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University of Nottingham

School of Chemical, Environmental, and Mining Engineering

IMPROVING CHEMICAL PLANT SAFETY TRAINING USING VIRTUAL REALITY

by

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Abstract

The chemical engineering industry often requires people to work in hazardous environments and to operate complicated equipment which often limits the type of training that be carried out on site. The daily job of chemical plant operators is becoming more demanding due to the increasing plant complexity together with increasing requirements on plant safety, production capacity, product quality and cost effectiveness. The importance of designing systems and environments that are as safe as possible to educate and train personnel is vital for the chemical process industries. Virtual reality offers the potential to expose personnel to hazardous situations in a safe, highly visual and interactive manner.

Virtual reality has been proposed as a technological breakthrough that holds the power to facilitate learning. The ability to visualise complex and dynamic systems involving personnel, equipment and layouts during any real operation is a potential advantage of such an approach. Virtual reality and multimedia training is commonly used in many industries, aiding understanding and memory retention and creating a more interactive learning experience.

Four desktop virtual reality training environments were developed for this research which highlighted issues related to chemical process dynamic simulation and plant safety. The pump training system is a virtual reality environment, which was built using the SAFE-VR virtual engine, to train personnel to operate two centrifugal pumps. The virtual hazard spotting exercise focuses on improving the users' safety awareness of electrical and occupational hygiene hazards. The virtual boiler plant is a complicated and high detailed virtual training environment, which is characterised by its flexibility and by a real time dynamic simulation of the steam generation chemical process. The virtual flooding and gas absorption experiment was based on an undergraduate laboratory experiment for the Chemical Engineering degree course at the University of Nottingham, focusing primarily on training and safety issues of students using the equipment. The dynamic features of the virtual absorption column simulation give high level of realism in the virtual environment.

Dedication

To my parents Dimitris and Theano

Acknowledgements

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Chapter 1

Introduction

1.1 Introduction

Most human activities carry specific risks. The risk profiles of industries change with time as certain hazards are overcome and new ones appear. The main hazards of the process industries arise from the escape of process materials, which may be inherently dangerous or become dangerous being present at high pressures and high or low temperatures. A review of worldwide chemical or chemical related incidents that have had major impacts on surrounding communities is summarised in table 1.1. This suggests the need for improved approaches to the handling of hazardous materials (King and Hirst, 1998).

Incident	Impact
Flixborough in United Kingdom (1974) Vapour cloud explosion	28 fatalities on-site; $232 million damage; damage to homes off site
Seveso in Italy (1976) Toxic material release	Widespread contamination on-site and off-site
Bhopal in India (1984) Toxic material release	300 fatalities, $20 million damage, mostly off-site
Mexico City LPG (1984) LPG Explosion	2500 fatalities many others injured off-site
Chernobyl in Ukraine (1986) Fire and radiation release	31 fatalities; 300 square miles evacuated; widespread contamination
Sandoz warehouse Switzerland (1986) Toxic material release	Major impact on ecology of Rhine River
Shell Norco refinery in United States (1988) Vapour cloud explosion	7 fatalities on-site; neighbouring town evacuated; damage exceeded $50 million; widespread damage to homes off-site

Table 1.1: Selected major incidents (after AICHE, 1989)

As chemical industries become increasingly complicated and automated, the gap between operators and processes becomes wider. Operators loose the ability to handle real processes as they manipulate plants through control panels, which include switches, alarms, recorders, monitors, and many other instruments. It is difficult for them to understand all the knowledge about relevant processes and emergency situations. Accidents in chemical processes arise mostly from operator error (Goh *et al*, 1998).

To reduce these errors in operating procedures, effective training methods must be developed. In the past the objective of operator training was only to prevent direct damage and to reduce the loss of lives and property from accidents but at present it includes the wider meaning of developing human resources and increasing the productivity, safety and efficiency of industries. The importance of operator education is emphasised now more than ever.

Training has always been considered an important factor in staying competitive in a global economy. Employees need to remain up to date with the latest methods and technology. Most would agree training is important, but there is an obvious cost in developing or purchasing training. Companies also lose productive employee time while they sit through training; not to mention travel costs if training isn't offered locally (Barton, 1997).

Training should involve an introduction to basic hazards and plant procedures in which the flammability, toxicity and the corrosive properties of chemicals are discussed. Also the use of personal protective equipment, fire alarm systems and work safety processes should be incorporated. The trainee should be assigned to a particular plant to work alongside an experienced operator, in order to receive practical instructions in all aspects of plant operation, including safety and emergency processes. These training methods in combination with available computer packages can be used to help the trainee to understand specialised aspects of process hazards such as emergency safety and permit-to-work systems.

There is a need to create hazardous simulations to provide a real world situation for such training without causing any harm to the trainee and the environment.

Three-dimensional simulation systems allow users to navigate in any direction within a computer-generated environment, decide what actions to take and immediately see the impact of those actions (Goh *et al*, 1998). These virtual reality training systems allow trainees to walk around the plant, see all the equipment that constitutes the process, have the possibility of starting, running and shutting down equipment and responding to error conditions without causing any damage to the equipment or harm to themselves.

1.2 Virtual reality as a training medium

Virtual reality is a rapidly growing technology, which utilises the increasing power of computers to simulate real or imaginary environments and situations with a high degree of realism and interactiveness. It is an emerging technology with potential applications in areas such as product design and modelling, process simulation, planning, testing and verification, real-time shop floor controls, training and maintenance. One speculation on virtual reality's development in manufacturing industry is a computing architecture that could provide virtual production environments within concurrent engineering contexts to achieve zero-defect and non-risk production. In fact, virtual reality has already been applied to a wide range of problems associated with manufacturing, industrial maintenance, post-production training and customer services in areas such as visualisation of complex data, robot control and remote operation of equipment, communication, training and planning, and virtual prototyping and design. The success of those applications has mostly relied on a realistic virtual environment.

Virtual reality technology is being used for training applications in a variety of process industries and fields such military, medicine, aircraft, art and business. Virtual reality offers the potential to expose personnel to simulated hazardous situations in a safe, highly visual and interactive way. Customised simulations of chemical plants layouts, dynamic process operations and comprehensive virtual environments can be set up allowing users to move around the virtual plants, taking operational decisions and investigating processes at a glance. The consequences of both correct and incorrect decisions can be immediately fed back to trainees giving them the opportunity to make mistakes and directly learn from them.

Users can interact with the virtual worlds using a variety of hardware devices such as joysticks and data gloves, and the impression of actually being in the virtual world can be enhanced by special optical and audio devices such as head mounted displays and three-dimensional, surround sound.

1.3 Statement of research problem

It is believed that virtual reality can be successfully applied to improve training and hazard awareness issues in the field of chemical engineering. Virtual reality can offer the potential to immerse personnel into an interactive and well-controlled virtual world containing simulated hazards. This may operate as an enhancement to existing training methods. The primary issues of this research will be the implementation of generic virtual reality systems, which will have been tested for a range of chemical plant prototypes with different safety scenarios. This artificial computer based training system is able to simulate the necessary components of chemical engineering processes obtaining an adequate level of realism but which is still able to run and perform satisfactorily on a personal computer based system.

1.4 Research aims

The overall aim of this project is to research and develop novel training techniques to improve the safety of chemical plant personnel. This has involved the development of a range of training scenarios for application in the chemical process industry. It is believed that the use of such systems will increase safety awareness and knowledge of safety procedures and therefore hopefully lead to reducing the plant accident rate.

Individual objectives can be classified in the following way:
- ??To investigate the general suitability and potential of virtual reality technology for training application in the field of chemical engineering
- ??To develop a range of virtual chemical plants environments in which to train operators for a range of different scenarios
- ??To identify components and characteristics of the chemical processes to be simulated in the virtual world for adequate realism and training acceptance

??To develop and test a number of virtual reality systems for a range of chemical plant scenarios

1.5 Thesis Overview

The contents of this thesis cover the following areas:

?? **Chapter 2**

This chapter discusses available literature relating to hazards and safety in the chemical industry. It also provides a short description of a number of incidents in order to show the consequences of such events, considers some of the main hazards in the chemical industries and discusses process safety issues, indicating methods to avoid and anticipate catastrophic events for chemical plants.

?? **Chapter 3**

This chapter presents a computer graphics and virtual reality literature review covering the definitions of computer graphics and virtual reality, general application areas of computer graphics and virtual reality and the current use of virtual reality for training aids. It outlines some common virtual reality software, especially the SAFE-VR development tool and furthermore focuses on the potential of virtual reality for safety training.

?? **Chapter 4**

This chapter details the development of the pump training system, which is a virtual reality training environment to train personnel to operate two centrifugal pumps. It describes the chosen model layout, its component objects and its functionality. This chapter also, presents a virtual reality hazard spotting exercise that is extracted from a multimedia training package, which was commercially delivered by the Institution of Chemical Engineers (ICHEME). Using advanced computer graphics, virtual reality and computer animated human figures, it was converted from a two-dimensional multimedia hazard spotting exercise into a three-dimensional computer generated environment.

?? Chapter 5

This chapter presents a virtual boiler plant environment, highlights some of the issues and problems relating to boiler operation and concentrates on issues relating to plant training and safety. This chapter also describes the dynamic simulation of the boiler plant and its implementation in SAFE-VR, and focuses on relevant process engineering and control issues.

?? Chapter 6

This chapter describes a virtual world based an undergraduate laboratory experiment for the Chemical Engineering degree course at the University of Nottingham. It concerns two packed columns, which are used to absorb ammonia from an air stream. It describes the dynamic mathematical model, the simulation and the virtual reality implementation of this gas absorption experiment. This chapter also discuses issues related to laboratory safety and explains the functionality of the current virtual reality experiment.

?? Chapter 7

This chapter reviews some examples of the evaluation studies that researchers and industry have conducted on their various uses of virtual environment technology. This chapter also discusses the results of simple evaluation trials for the virtual gas absorption simulator training using a number of subjects from the School of Chemical, Environmental and Mining Engineering of the University of Nottingham.

?? Chapter 8

This chapter presents the conclusions arising from this work and some recommendations for the use of virtual reality in the chemical engineering industry and in chemical engineering education.

Chapter 2

Safety in chemical industry

2.1 Introduction

This chapter discusses available literature relating to hazards and safety in the chemical industry. It also provides a short description of a number of incidents in order to show the consequences of such events, considers some of the main hazards in the chemical industries and discusses process safety issues, indicating methods to avoid and anticipate catastrophic events for chemical plants.

2.2 Safety culture

The increasing size and complexity of industrial processes creates increased scope for major disasters, leading to greatly increased public concern about industrial safety. The last century has seen a series of such disasters worldwide.

There is a widespread concern over the hazards of chemicals, not only to those who work with them but also to the environment and the general public. Unless a chemical plant is well designed, it is very difficult to prevent dangerous materials from escaping. Safety in chemical industries cannot be treated as a separate subject such as design, production or maintenance, but depends inextricably on both the technical competences and safety awareness of all staff and employees (King and Hirst, 1998).

Process safety has advanced over the last thirty years. In the 1970s the introduction of a number of checklists, such as the development of Hazop studies and the Dow's Fire and Explosions Index constituted a major breakthrough in the history of industrial safety. Dow's Fire and Explosions Index is a checklist method of hazard identification, which provides a comparative ranking of the degree of hazard posed by particular design conditions and its third edition is published as a manual by the American Institute of Chemical Engineers (Jones, 1992 and King and Hirst, 1998). In the 1980s came an increase in the regulation of chemical plants which culminated in an overall sociotechnical and audit

approach covering all aspects of design, operation and management of chemical plants (Wells, 1997).

The extent to which health and safety thinking is reflected in business activity and decision-making is an important determinant of effectiveness. The practical implications of safety policies must be thought through so as to avoid conflict between the demands of policy and other operational requirements. Management decisions where insufficient attention or weight is given to health and safety leads to (HSE, 1991):

?? Unrealistic time scales for the implementation of plans which put pressure on people to reduce supervision;

?? Work scheduling and rosters which fail to take account of problems of fatigue;

?? Inadequate resources being allocated to training;

?? Organisational restructuring which places people in positions for which they have insufficient experience;

?? Jobs and controls systems which fail to recognise or allow for the fact that people are likely to make mistakes and might have difficulties communicating with each other.

Beyond the technical issues, the influence of human error in the chain of events leading to an accident and the failures in the organisation and management of safety emerge strongly from inquiries. The most detailed set of safety rules and procedures are meaningless unless they are implemented and kept under regular review. It is essential that the immediate causes of accidents are seen in the wider context of the organisation and management climate in which they occur and it is important to focus on the design of systems and equipment in order to minimise the potential for human error.

The twelfth edition of Marsh and McLennan's annual review analyses the largest chemical industry losses, which refer to the cost of injuries and damage, since 1959 (Marsh and McLennan, 1988). The distribution of loss and the average value of losses over $10 million at 1988 values for various types of complex are shown in figure 2.1. Most of these losses occurred in oil refineries while the highest average losses occurred in natural gas processing plants.

The primary causes of loss, broken down into seven headings, are shown in the figure 2.2. Mechanical failure of equipment was the most frequent of these causes. Most of these could have been avoided by proper inspection and maintenance. The next most frequent cause was stated to be operational errors, which could have been avoided by providing more effective training of operators.
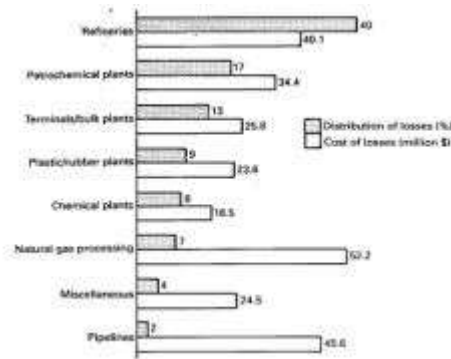
Figure 2.1: Distribution and average cost of large losses by type
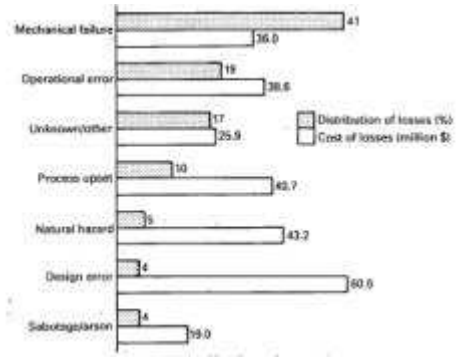
Figure 2.2: Primary causes of large losses
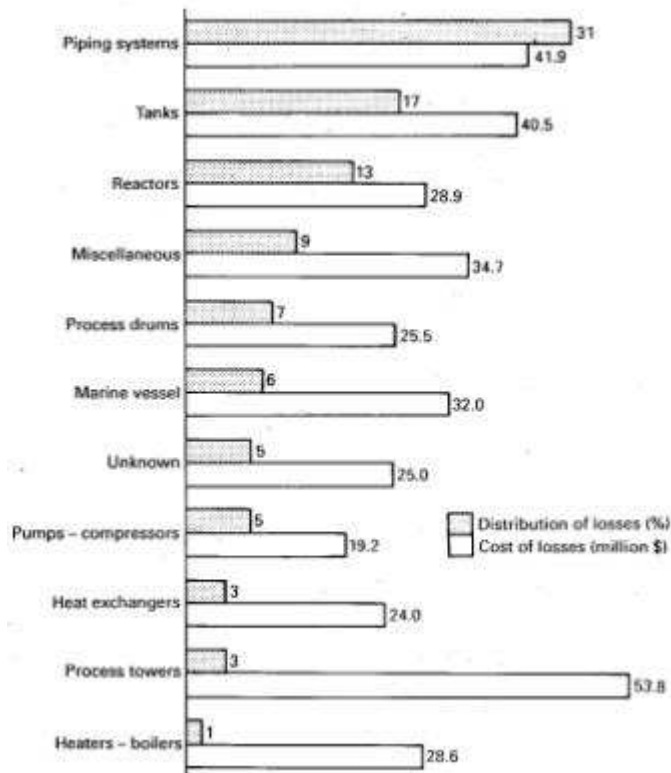
Figure 2.3: Types of equipment involved in large losses

The relative frequency of involvement of eleven different types of equipment in origin of loss is shown in figure 2.3. Piping systems, which include hose, tubing, flanges, gauges, strainers and expansion joints were the most frequent origin of loss. The low frequency of losses originating at pumps and compressors was unexpected (King and Hirst, 1998).

The public no longer regards processes industries as something remote from them, run by operators with an incomprehensive language of their own, but they consider them capable of giving rise to events which may directly affect ordinary people. Public opinion in the majority of countries is concerned about industrial accidents and their effects and will not tolerate fatalities on the scale that once existed.

2.3 Hazards in chemical industries

A hazard is a physical situation with a potential for human injury, damage to property, damage to the environment or some combination of these. Hazards as defined not only include process plant and associated materials but also major structures, and materials, which release ionising radiation (Jones, 1992). The hazards, which are commonly identified in chemical industries, can be grouped in several different categories. These categories include electrical hazards, health and occupational hygiene hazards, chemical reactions hazards, explosion and fire hazards, operational and control hazards and hardware hazards.

2.3.1 Electrical hazards

Electricity is a safe and efficient form of energy and is a convenient source for lighting, heating and power. The proper use of electricity is not dangerous but out of control it can cause harm if it passes through a human body by producing an electric shock. In the United Kingdom every year up to fifty people may be killed and up to thousand are injured at work as a result of an electrical accident (Ridley, 1994).

The effects of electric shock depend upon the type of circuit, its voltage, resistance, current, pathway through the body and duration of the contact. Effects

can range from a barely perceptible tingle to immediate cardiac arrest as shown in the table 2.1 (OSHA, 1997).

Current	Reaction
1 Milliampere	Perception level. Just a faint tingle
5 Milliamperes	Slight shock felt, not painful but disturbing. Average individual can let go. However, strong involuntary reactions to shocks in this range can lead to injuries.
6-30 Milliamperes	Painful shock, muscular control is lost
50-150 Milliamperes	Extreme pain, respiratory arrest, severe muscular contraction. Death is possible.
1000-4000 Milliamperes	Ventricullar fibrillation. Muscular contraction and nerve damage occur. Death is possible.
10000 Milliamperes	Cardiac arrest, severe burns and probable death.

Table 2.1: Effects of electric current in human body (after OSHA, 1997)

Employees whose occupation requires them to work directly with electricity must use the personal protective equipment required for their jobs such as rubber insulating gloves, hoods, sleeves, matting, blankets and industrial protective helmets. The basic procedures that should be followed when work is performed on electrical equipment can be summarised in the following points (OSHA, 1997):

- ?? Have the equipment deenergised
- ?? Ensure that the equipment remains deenergised by using some type of lockout and tag procedure
- ?? Use insulating protective equipment.
- ?? Keep a safe distance from energised parts.

Standard industrial electric installations are not designed to prevent sparks and hot spots, which may ignite a flammable gas or vapour. Special precautions are extremely necessary when electrical equipment is used in areas where such gases may be present. This often depends on plant standards and decisions have to be taken during the plant design stage. Once the plant is operating care is needed to ensure that extensions and replacements of electrical items comply with the

established system. Switches, motors and other items, which are liable to spark, should be contained in a strong enclosure such as two machined surfaces, which air can enter or leave only via a very narrow gap. The importance of maintaining the integrity of flameproof equipment must be appreciated. When a cover plate or a cable connection of a flameproof enclosure is removed it must be correctly replaced (King and Hirst, 1998).

2.3.2 Health and occupational hygiene hazards

Health and occupational hygiene is the science of anticipating, recognizing and controlling workplace conditions that may cause workers' injury or illness. Major workplace risks can include chemical, biological, physical and ergonomic hazards.

Harmful chemical compounds in the form of solids, liquids and gases exert toxic effects by inhalation, absorption or injection. Airborne chemical hazards exist as concentrations of mists, vapours, gases, fumes or solids. The degree of worker risk to any given substance depends on the nature and potency of the toxic effects and the magnitude and duration of exposure. Information on the risk to personnel from chemical hazards can be obtained from a material safety data sheet, which is a summary of the important health, safety and toxicological information on the chemical or mixture's ingredients (OSHA, 1998).

Biological hazards include bacteria, viruses and other living organism that can cause acute and chronic inflection by entering the human body. Occupations that deal with plants or animals or their products or with food processing products may expose workers to biological hazards. It is essential for an industry to provide proper ventilation, appropriate personal protective equipment such as gloves and respirators and adequate infectious waste disposal systems (OSHA, 1998).

Physical hazards include excessive levels of electromagnetic radiation, noise, illumination and temperature. In occupations where there is exposure to radiation time distance and shielding are important tools in ensuring worker safety. Danger from radiation increases with the amount of time one is exposed to it. Hence, the shorter the time of exposure, the smaller the radiation danger. Distance, also, is a

valuable tool in controlling exposure to radiation and the radiation levels from some sources can be estimated by comparing the squares of distance between the worker and the source. Shielding involves the placing of protective materials between the source and the person to absorb partially or completely the amount of radiation (OSHA, 1998).

Noise, another significant physical hazard can be controlled by installing equipment and systems that have been engineered, design and built to operate quietly or by enclosing or shielding noisy parts and by providing hearing protective equipment to personnel.

The part that lighting plays in ensuring a safe and healthy place of work is increasingly recognised. The standard of illuminance required depends on the visual efficiency necessary for the tasks involved and the decisions should be based on the recommendations of the code for lighting produced by Illuminating Engineering Society (Ridley, 1994).

Many working environments are uncomfortable owing to excessive heat. The heating protection in industries can be ensured by providing cooling systems and by installing reflective shields.

Ergonomic problems result from technological changes and arise from poorly designed job tasks. Ergonomic hazards such as excessive vibration and noise, eye strain, repetitive motion and heavy lifting problems can be avoided primarily by the effective design of a jobsite and well designed tool equipment in terms of physical environment and job tasks for the employees. Through worksite analyses, employers can set up procedures to correct and control ergonomic hazards. Evaluating working conditions from an ergonomics standpoint involves looking at the total physiological and psychological demands of the job on the worker.

2.3.3 Chemical reaction hazards

A chemical reaction that goes out of control and runaways can create a serious incident with the risk of injury to people and damage to property and the environment. The reactivity of chemicals in process industries is a potential

process hazard. The chemical reactivity of any substance should be considered in the following contexts (King and Hirst, 1998):

?? Its reactivity with atmospheric oxygen

?? Its reactivity with elements and compounds with which it is required to react in the process

?? Its reactivity with water

?? Its reactivity with itself

?? Its reactivity with other materials with which it may come in contact unintentionally in process

?? Its reactivity with materials of construction

Most hazards are caused by reactivity with atmospheric oxygen and the majority of problems arise from oxidative self-heating. In most continuous organic chemical reactors, which operate under pressure, air is automatically excluded. In some cases more stringent measures are taken not merely to prevent air entering the plant while it is running but also to remove it before the plant starts up and to remove oxygen from materials entering the process.

The reactivity between reactants in processes must be carefully studied and considered when a reaction system is designed, both from thermodynamic and kinetic aspects. From the safety point of view, it is extremely important whether a reaction is strongly exothermic, moderately exothermic, mildly exothermic, thermally neutral or endothermic. Exothermic reactions are usually difficult to control in continuous process involving gases and liquids and are most difficult to control in batch processes where the entire charge of reactants is added at the start of the batch, where both liquids and solids are present.

An exothermic reaction can lead to thermal runaway, which begins when the heat produced by the reaction exceeds the heat removed. The rates of most reactions increase rapidly with temperature leading to the danger of their getting out of control, with large rises in temperature and pressure and loss of containment of the process material. Importantly, the rate at which heat is removed usually increases linearly but the rate at which heat is produced increases exponentially as shown in the figure 2.4 (HSE, 1997).
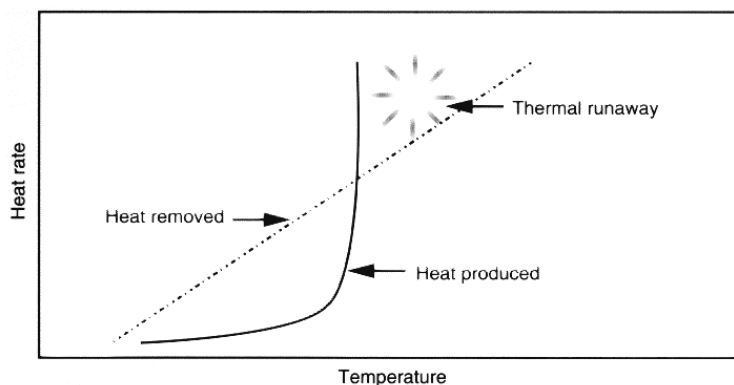
Figure 2.4: Thermal runaway in exothermic chemical reactions (after HSE, 1997)

The hazards of exothermic reactions occur particularly in storage of compounds, which tend to polymerise or decompose and in process reactors themselves.

A runaway exothermic reaction can have a range of results from the boiling over of the reaction mass, to large increases in temperature and pressure that lead to an explosion. Such violence can cause blast and missile damage and if flammable materials are released, fire or secondary explosions may result. There can be serious risk of injuries, even death, to plant operators and the general public and the local environment may be harmed as the accident at Seveso has shown (HSE, 1997).

An uncontrolled exothermic reaction occurred at the ICMESA, a small factory located in Seveso in the North of Italy in 1997. The plant was involved in producing trichlorophenol. The emission of a toxic cloud from a reactor into the atmosphere seriously contaminated the nearby area. The cloud was a mixture of various substances, including trichlorophenol, sodium-trichlorophenate, ethylene glycol and, as confirmed a few days later, large quantities of 2,3,7,8, - tetrachlorodibenzodioxin (TCDD or dioxin). An area of two square miles was declared contaminated, 250 cases of skin inflection were identified and over 600 people evacuated (Pesatori, 1998).

An analysis (Barton, 1998) of thermal runaways in the United Kingdom has indicated that these accidents occur because of:

?? Inadequate understanding of the process chemistry and thermochemistry

?? Inadequate design of heat removal

?? Inadequate control systems and safety systems

?? Inadequate operational procedures, including training.

2.3.4 Explosion and fire hazards

The term explosion is used to describe incidents where there is a rapid release of energy, which causes a significant blast wave capable of causing damage. The gases in a chemical explosion, which is formed as a result of chemical reactions, expand rapidly due to a sudden increase in temperature, thereby increasing the pressure relative to the surrounding atmosphere. The damage which arises from an explosion may be caused either by the effect of a blast wave or by projected fragments or items of equipment. All chemical explosions are very fast; they give out heat, and make a loud noise. They fall into two classes:

?? Explosive deflagrations, which are caused by chemical reactions, which are passed through the deflagrating materials at well below sonic velocity. They develop an appreciable pressure producing a blast wave with the potential to damage and the burnt products move in the opposite direction from that of combustion wave.

?? Detonations are caused by very rapid chemical reactions which pass through the exploding materials at speeds of 1-10km/s. High pressures are developed and the burst products move in the same direction as the combustion wave. Explosives, which normally detonate, are termed high explosives such as TNT (trinitrotoluene) and have high shattering power even when unconfined.

Fire is a process of combustion characterised by heat or smoke or flame or any combination of these. The simple facts of combustion, reactants and ignition source are commonly displayed as the fire triangle, which is shown in figure 2.5.
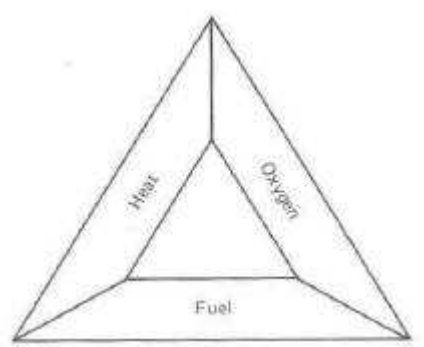
Figure 2.5: The fire triangle (after King and Hirst, 1998)

Almost all organic chemicals and mixtures whether in solid, liquid or gaseous stage are flammable and they are potential fuels. The main source of oxygen in a fire is air, which contains 21% oxygen. Other sources are oxidizing agents and combustible substances, which contain oxygen. As heat is the most common source of ignition anything, which will supply heat to a flammable material is a potential ignition source. Direct heating sources such as steam and hot-water pipes, hot air, stoves and boilers, open fires and electrical heaters are some of a long list of potential heat sources. Electrical discharge, which can take place when a circuit is made or broken, is another source of ignition. The heat from an ignition source can be transmitted to the flammable substance by conduction, convection or radiation.

Safety measures associated with fire fall into two broad categories: fire prevention and fire protection measures. Fire prevention measures are those intended to reduce the likelihood of a fire occurring and fire protection measures refer to those which seek to minimise the extent of a damage from fire should it occur. Fire protection systems may detect, extinguish, contain or allow persons to tolerate a fire (Jones, 1990).

The explosion at a cyclohexane plant in Flixborough in 1974 was the largest chemical accident in the United Kingdom. The accident resulted from the ignition and detonation of a huge quantity of cyclohexane, which escaped when a temporary bypass between two reactors broke. The bypass had not been properly engineered, as the company had not taken the possibility of such an accident into account. The fire from the explosion raged over an area of 45000 square meters

with flames over 100 meters in height. This accident in Flixborough killed 28 workers and injured 400 people (MacGrillen, 1999).

2.3.5 Operational and control hazards

There have been a number of recent and well-publicised accidents in which human error has played a prominent part. For example, in Texas city in 1969 the operators opened an escape valve in the overhead product line of an butadiene plant which was placed on total reflux whilst other parts were being serviced. As a result an unstable compound, vinyl acetylene, concentrated in the bottom of the column. Eventually two tonnes of vinyl acetylene in the liquid phase detonated, scattering large pieces of the column up to 900 metres and the fire burned for 60 hours (Wells, 1997).

In order to understand the contribution of human behaviour to the risk of accidents it is essential to examine the errors people make and what leads to such errors. The reduction of human error probability can lead to a reduction in the probability of accidents in chemical industries.

A useful classification framework identifies the human errors as slips-lapses, mistakes or violations. Slips or lapses typically occur through lack of attention or from stressful situations with the result that individuals fail to achieve what they intend to do. Slip or lapse human errors include forgetting to turn off power, becoming inattentive to important safety checks or forgetting important steps in work procedures, which may cause equipment damage (Ridley, 1994)

Mistakes can result from incorrect decisions, poor communications and infrequently practised operations. Typical mistakes include failure to appreciate the dangers of equipment and materials used, misunderstanding of operational procedures and emergency situations or failure to realise the implications of a process plant. Individual or team training is the most effective way to reduce these mistakes. Virtual reality training systems can help trainees to learn from their mistakes without causing any damage to equipment or themselves.

Violations are deliberate decisions to break agreed procedures. They can be associated with a steady drift into unacceptable attitudes, or can be deliberate acts by a workforce to adopt unsafe and unapproved practices. Some violation human errors include the deliberate use of unauthorised lifting equipment, the breaking of rules for an electrical unit or deviation from permitted work process.

The study of the relationship between employees and the equipment with which they work in parallel with the physical environment in which man-machine system operates is extremely important for the safe and effective operation of processes industries (AICHE, 1989).
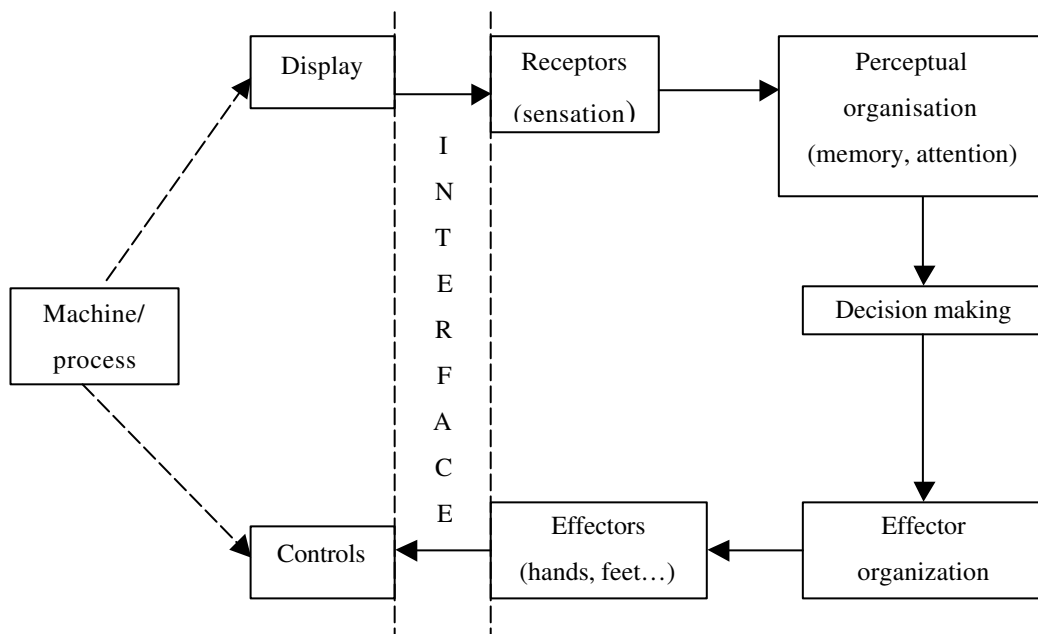
Figure 2.6: The man-machine interface (after AICHE, 1989)

The flow diagram shown in figure 2.6 emphasises the performance of the human information processing system. The broken lines emphasize that displays and control are links between the operator and machine. The flow diagram also focuses on the need for optimum information flow in order to aid the operator in monitoring and subsequent decision-making. Problems of misreading and misinterpretation of instrumentation and the incorrect activation of control elements can be considerable.

By incorporating human factors considerations into a process safety training program, the chances of incidents caused by human error can be reduced. During the design stages, a company should require incorporation of human factors principles into the design, instead of simply designing equipment and then motivating and training people to operate it (AICHE, 1989).

2.3.6 Hardware hazards

Even in the best designed machinery and plants, failures can occur. If the cause of failure is investigated the repetition can be normally prevented. Modes of failure relate to the type of stress under which the component has been working and the characteristic features of failures due to tension, compression, shear and torsion are well known. Sometimes the failure is related more to the operating process than to the stress. When particularly there is repeated stress cycling of the part and it can suffer fatigue failure (Ridley, 1994). Some of the causes of metal failure in process equipment are presented in table 2.2.

Cause	Percentage of failure
Fatigue	33.2
Overload	12.1
Abrasion, erosion or wear	12.1
Poor welds	9.8
Cracking plating	6.9
Creep or stress-rupture	4.2
Overheating	4.2
Cracking, heat treatment	4.2
Defective material	3.6
Embrittlement, strain, age	2.9
Brittle fracture	2.7
Cracking, weld	1.3
Cracking thermal	1.3
Leaking through defects	0.9
Warpage	0.9

Table 2.2: Causes of metal failure in process equipment (after Ridley, 1994)

Operators must be taught the hazards associated with a machine before being allowed to operate to it. Examples may include the criteria that no machinery guard may be adjusted or removed without the authority of the responsible supervisor or by the person responsible for maintaining it. Employees may be forced to appropriately dressed and must not start any machine unless the guard is in position and functioning properly. A written permit system should be used before any maintenance is done on any machine to ensure that it is isolated from electrical power, other services and process materials.

The disaster on the Piper Alpha oil platform in North Sea in 1988 began when a primary propane condensate pump failed. The backup condensate pump was under maintenance and the workers had removed its pressure safety valve the day before. The people in the control room, who were in charge of operating the platform, decided to start the backup pump, not knowing that it was under maintenance. Gas products escaped from the hole left by the valve with such force that workers described it as being like the scream of a banshee, and then the gas ignited. The resulting explosion destroyed the fire control and communication systems and demolished a firewall. Some survivors escaped by jumping into the sea from a height of up to 50 meters but 167 oil workers were killed (Cullen, 1990 and BBC Online, 2000).

2.4 Risk assessment and hazard identification

Risk is the likelihood of a specified undesired event occurring within a specified period or in specified circumstances. It may be either a frequency (the number of specified events occurring in unit time) or a probability (the probability of a specified event following a prior event), depending on the circumstances (Jones, 1992).

Cooper and Chapman (1985) define risk as the exposure to the possibility of economic or financial loss or gain, physical damage or injury, or delay, as a consequence of the uncertainty associated with pursuing course of action.

A further definition of risk, which is used as the basis of many risk assessment techniques, is similar to the one quoted by Horton (1991) and says that the term

risk is used to cover the combination of an unfavourable result and the possibility of it occurring. It is used as recognition of future uncertainty and implies that a given set of circumstances has more than one possible outcome.

2.4.1 Risk Assessment

Improvement in safety performance has often meant looking to reduce the number of potential accidents. The process of risk assessment attempts to minimise or eradicate the probability of an accident occurring. Risk assessment has been used informally throughout history, whenever there is a decision to be made, or an action taken there is always an associated risk. The outcome of the decision is in the future and is therefore uncertain, different actions might mean different outcomes; some outcomes might be more desirable than others.

The wide variety of industrial activities has created a wide variety of different definitions and hence a blur between terms such as risk assessment, risk analysis and risk estimation. Jones (1992) gives one of the clearest definitions:

?? Risk assessment is the quantitative evaluation of the likelihood of undesired events and the likelihood of harm or damage being caused together with value judgements made concerning the significance of the results.

?? Risk analysis is an imprecise term that infers the quantified calculation of probabilities and risks without taking any judgements about their relevance. As such it is equivalent to risk estimation.

The assessment of risks is necessary in order to identify their relative importance and to obtain information about their extent and nature. This will help in deciding on methods of control. Knowledge of both areas is necessary to identify where to place the major effort in prevention and control, and in order to make decisions on the adequacy of control measures (HSE, 1991). Assessing risks will demand a thorough knowledge of all the activities and working practices. The knowledge of the employees and safety representatives involved often proves valuable. Competent people should carry out risk assessments, and professional health and safety advice may be necessary in some cases (HSE, 1991).

Determining the relative importance of risks involves deciding on the severity of the hazard and the likelihood of occurrence. There is no universal formula for rating risk in relative importance but a number of techniques have been developed to assist in decision-making.

2.4.2 Hazard identification

The identification of hazards is the vital element of risk analysis and its effectiveness requires a deep understanding of the process, which is clearly dependent on the knowledge, experience, engineering judgement and imagination of the team to whom the task is assigned. It can also be seen as a useful discipline in its own right. For example, identifying hazards at an early stage will often allow them to be eliminated by a modification of the design or system (HSE, 1992).

Hazard identification is the process of determining what hazards are associated with a given operation or design, as it is operating. In existing operations, hazard identification is performed periodically to determinate the implications of changes to process knowledge and to recognise changes to process, equipment and materials.

2.4.2.1 Reliability and failure analysis

Reliability can be defined as the probability that a component will perform a required specified function. This may depends on the components success in commencing to operate when required, continuing to operate subsequently, not operating on demand, and not continuing after the demand has ceased. The reliability of a multi-component system depends on the incidence of failures in the components. Data on such failure may be fitted to statistical distributions for use in reliability analysis (Lee, 1980).

2.4.2.2 Fault Tree Analysis (FTA)

Fault Tree Analysis is the technique that can be used to determine failure sequences and probabilities in complex systems. In a FTA a logic diagram or "fault tree" is developed to determine the causes of an undesired event. A fault tree may be constructed for virtually any undesired event that can occur within the

system. Once an undesired event has been selected, it is shown at the top of the diagram and all the circumstances that lead to it are determined by reasoning backward from this event. These circumstances are then broken down into events that can produce them, and so on. The process is continued until all events that can ultimately lead to the undesired event are identified.

Special symbols are used in FTA to represent events and their logical relationships. Circles, rectangles, diamonds and house-shaped figures are the symbols, which are used for events and indicate certain characteristics about them. Other symbols, called "logic gates" show the manner in which events at one level of fault tree combine to produce an event at the next higher level (Rankin and Tolley, 1978).

2.4.2.3 Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effects Analysis is based on identifying the possible failure modes of each component of a system and predicting the consequences of the failure. In this procedure each item used in the system, which might include the people, equipment, materials, machine parts or environment, is listed on an FMEA. The analyst should consider the exact modes in which each item can fail. For example if a control valve fails to open it could result in too much pressure or the wrong ratios of flow (ICHEME, 1985).

The analysis is continued by determining the effects of each failure combination. Both the effects on other items within the system and those on overall system performance are considered and evaluations are then made concerning the seriousness of each failure or failure combination. Finally, the means of detecting each failure is determined and any additional remarks regarding the failures are recorded. (Rankin, 1978)

2.4.2.4 Hazard and operability analysis (Hazop)

The most widely known technique is that published by H.G. Lawley and later by the Chemical Industries Association in the United Kingdom under the title "A guide to hazard and operability studies" (ICHEME, 1985). Hazard and operability studies can be applied to existing process plants, in particular when modifications

are being considered, but are most effective when carried out at a design stage where a wide range of possible actions still exist.

The method uses guidewords such as "too much" and "too little", which can be applied to the process parameters to generate "what if" questions. The guidewords that are used must be relevant to the stage of design and must be sufficiently comprehensive to be capable of identifying the hazards involved. While this method can be used without direct reference to engineering standards it requires a broad documentation of the points studied to demonstrate the quality of the study.

Experience has shown that this technique is most effective when carried out by a team of designers, operators, and other specialists as appropriate, at a series of study meetings (Jones, 1992).

2.5 Training

Evidence from everyday life shows that well trained and careful workers may avoid injury on a dangerous job whilst untrained and careless workers may be injured under the safest possible conditions. Before any employee can work safely they must be shown safe procedures for completing their tasks. The purpose of safety training should be to improve safety awareness in employees and increase their performance on their jobs without endangering themselves and their fellow employees. Acknowledgement of the hazards, their effects, and the required techniques to avoid or ameliorate those effects, must be provided to all personnel in a process industry (Schofield *et al*, 2001).

Training helps people to acquire the skills, knowledge and attitudes to make them competent in the health and safety aspects of their work. It may include formal off-the-job training, instructions to individuals and groups, and on-the-job coaching and counselling. Ensuring that people are competent may demand more than formal training, for example a period of supervised experience to practice and develop new skills.

The Institution of Chemical Engineers (ICHEME) in United Kingdom and the American Institute of Chemical Engineers (AICHE) provide a variety of training

packages, which include courses, slides and video tapes on detailed technical information about safety and environmental aspects of chemical plants. For example, "human error" is a safety training package of ICHEME, which contains 70 slides and examines 15 accidents wrongly attributed to human error and explains how the real causes are faults in management, control, design, systems of work, training, labelling and notices (ICHEME, 2000). AICHE produced a CD-ROM training package called "The Distillation in Practice" which gives the trainee a unique innovative way to learn the essentials of distillation. For practicing engineers at all levels, this CD-ROM illustrates complex theories and concepts through colourful, animated graphics (AICHE, 2001).

An employers training duty is set out in section two of the Health and Safety at Work Act (HSE, 1974) and requires, "the provision of such information, instruction, training, and supervision as is necessary to ensure, so far as is reasonably practicable, the health and safety at work of his employees." In regulation eleven of the Management of Health and Safety at Work (MHSW) regulations (Health and Safety Commission, 1992) employers are also required to take account of the health and safety capabilities of employees when entrusting tasks to them. They should be particularly aware of training during induction, change of job responsibility, or the introduction of, or change in work equipment. It calls for repeat training, and the adoption of training to take account of changed risks to health and safety. The activities in a typical training cycle are shown in figure 2.7.

Job and task health and safety analyses help to identify health and safety needs. These analyses can involve:
?? Consideration of accident, ill health and incident records relevant to those jobs to identify how such events have occurred and how can be prevent.
?? Information from employees about how jobs are done, the sequence of tasks involved and the tools, materials and equipment used.
?? Observing and questioning employees to understand what they are doing and why. In complex process plant the analysis needs to take account of human error.

```
                    ┌──────────────────┐
                    │  Decide if training │◄──────────┐
                    │  is necessary      │           │
                    └──────────────────┘           │
                            │                       │
                            ▼                       │
                    ┌──────────────────┐           │
                    │  Identify training │◄──────────┤
                    │  needs            │           │
                    └──────────────────┘           │
                            │                       │
                            ▼                       │
                    ┌──────────────────┐           │
                    │  Identify training │◄──────────┤
                    │  objectives       │           │
                    └──────────────────┘           │
                            │                       │
                            ▼                       │
                    ┌──────────────────┐           │
                    │  Develop learning │◄──────────┤
                    │  activities       │           │
                    └──────────────────┘           │
                            │                       │
                            ▼                       │
                    ┌──────────────────┐           │
                    │  Carry out training│◄──────────┤
                    └──────────────────┘           │
                            │                       │
                            ▼            Feedback loop to
                    ┌──────────────────┐  improve training
                    │  Evaluate         │──┐  process
                    │  effectiveness    │  │
                    └──────────────────┘  │
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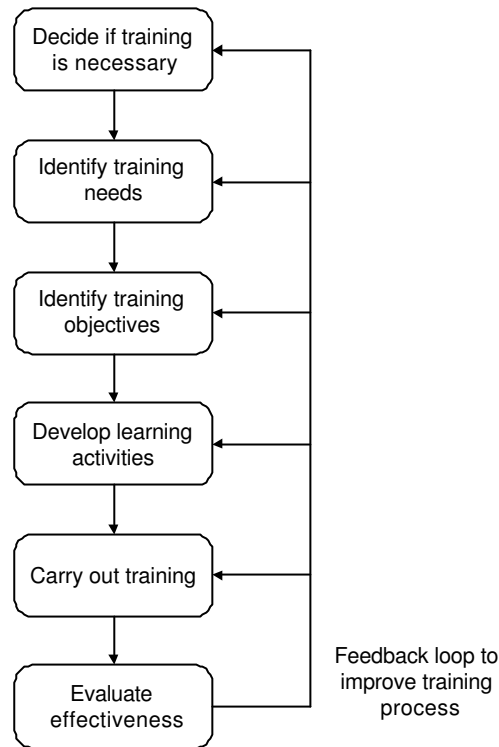
Figure 2.7: Typical training cycle (HSE, 1991)

Analysis can be applied to complete jobs or subsidiary tasks. Complete analysis is essential for new workers, but with existing employees the need may be to improve performance on their tasks.

2.5.1 Training techniques

Training is comprised of both formal and informal teaching. Formal training describes that which is undertaken in a workshop or classroom and is essentially off-the-job. These include induction courses for new starters, as well as those designed to update and reinforce employee's knowledge of safety techniques and practices. Informal training is essentially practical in nature and will normally take place on-the-job; an example may include an individual receiving tuition on a one-to-one basis with their supervisor.

A successful training programme must bring together both the theoretical (formal training) and the practical (informal training) aspects of the job. The methods used in both formal and informal training normally follow accepted training and

educational techniques. Bird has summarised the two basic goals of job instruction as follows (Bird, 1974):

?? To make sure the employee knows the importance of doing the job correctly.

?? To be certain that the employee knows how to do it correctly.

In reality, a training programme will normally have more ambitious goals with regards to improving safety and efficiency. It was observed, in connection with the effectiveness of different training methods, what people generally tend to remember (Kubias, 1982):

10% of what they read.

20% of what they hear.

30% of what they see.

50% of what they see and hear.

70% of what they say.

90% of what they say as they do a task.

This has shown that trainees retain the job information best if they follow oral and visual instructions by doing the job themselves and recalling the important points of the job as they proceed.

Ridley draws from this that involvement sessions are of most benefit and he cites a number of techniques used during training sessions.

?? Prepared notes, programmed learning.

?? Lectures, talks, taped commentaries.

?? Slides, posters, overhead transparencies.

?? Films, slide/tapes, video presentations.

?? Discuss case studies, possibly with working models.

?? On the job training, simulation exercises, role playing.

According to Ridley (1994), there are benefits of active participation by the trainee. This participation can best be achieved by using training aids that suit the circumstances of the industry, the company and the trainee. Heinrich (1980) echoes this, saying that particular types of training are best suited to certain types

of subject matter.   In reality an employees training will often involve an amalgamation of the above techniques.

2.5.2 On-the-job training

Three on-the-job training tools that are applied systematically include the following (King and Hirst, 1998):

?? Job Safety Analysis (JSA).   This is a technique for identifying potential hazards in each step of a job and eliminating them by altering the procedure or using different equipment or tools.

?? Job Instruction Training (JIT).   After the job has been described and demonstrated to the trainee, the trainee is invited to carry out the operation on their own after being told where to go if they need help.   The trainee is impressed with the phrase, 'if you are not sure – don't do it'.   Using this method the supervisor checks frequently that the trainee is progressing adequately.

?? Over-the-shoulder coaching.   The supervisor remains present whilst the trainee undertakes the job and provides guidance as and when needed.   This can be extremely effective though is time consuming and often expensive.

On-the-job training allows each training situation to be customised for the learner. Any questions the learner has are addressed quickly. The learner may, or may not, gets hands-on experience during the training period. This approach may work well if there are one or two learners but it is ineffective for larger numbers. Also, if the employees were dispersed at multiple locations, the instructors would have to travel to those locations so the cost and the time of the training increases.

2.5.3 Training media and methods

For years, classroom training was the most cost effective way to teach. The instructor follows a course outline to ensure covering required content. A classroom-training programme may use several different types of media to deliver its content (King and Hirst, 1998).

2.5.3.1 Printed media

Books and notes are easily produced and whatever other methods are used to deliver the training programme a booklet or manual is usually provided for reference. The written word is quickly forgotten, and books are passive learning aids. Although the trainee may respond to the book, it cannot detect any difficulties the trainee is having.

Written exercises may require answers, however, there is little to stop the student from cheating or losing interest unless the book is used in conjunction with another delivery method. A pre-requisite for using books and notes is the literacy of the student, the student must be able to comprehend and understand what is being written.

2.5.3.2 Personal instruction

This ranges from individual coaching to lecturing to a large audience. Instructors are able to sense trainees' difficulties and alter their delivery accordingly. However, the spoken word is not a good medium as it can be easily misheard, misunderstood or forgotten. This medium can be reinforced with additional demonstrations or visual aids such as projection slides or videos, notes are also often provided for reference.

2.5.3.3 Films and video cassettes

These are a very powerful medium, as they combine moving, real-life images with the spoken word, this helps to overcome the confusion or misunderstanding of a situation. Films and videos require considerable skill, resources and planning to produce. However, there are many safety videos and films that can be purchased from safety institutions such as the Health and Safety Executive (HSE) in the United Kingdom or the National Institute for Occupational Safety and Health (NIOSH) in the United States. Some example screenshots from a safety training video can be seen in figure 2.8.

Figure 2.8: Filmed on working offshore platforms, rigs, and support vessel (after Safety Advantage LLC, 2001)

During video training the trainees are watching an expert perform a task. Video trainees have not the opportunity to practice or engage anyone in their learning, but they do watch a more knowledgeable person at their own pace. Watching an expert demonstration does not result in acquiring a familiarity with the task at hand. Given that the nature of the task is to gain declarative knowledge and situation awareness, the act of watching is essentially a passive activity and therefore should not be considered as effective as virtual reality learning.

2.5.3.4 Computers

Computers were introduced as a training aid to extend the availability when teachers were in short supply. According to King and Hirst (1998) they are used in three principal ways, Computer Assisted Learning (CAL), Computer Managed Learning (CML) and for keeping student records.

CAL encompasses a wide array of teaching methods, from simply reinforcing and teaching knowledge through simple question and answer (similar to class room test), to the full-scale simulation of an entire environment.

Recently developed CAL systems may contain a hidden model of a real-life situation to which the trainee must respond. By providing a number of these situations the trainee can more fully understand the environment. This type of instruction can be particularly useful for situations that are complex and do not necessarily have one correct answer.

CML and the keeping of student records deals with the general administration of student records. It might help to identify potential shortcomings in students and help to target additional training sessions to overcome or readdress these.

The use of computers in a training program will require that each person (both student and teacher) become familiar with the system used. This may place a burden on the resources if the time required to achieve this is significant.

Modern CAL systems contain sophisticated training simulations of real-time situations that allow trainees to develop skills and experiences under a range of circumstances. Such simulators may be used to train operators of complex chemical plant. The recent developments of computer graphics techniques can make training more realistic, and give trainees detailed information about the simulated system.

2.6 Summary

The dangerous nature of the chemical industry and the accidents, which had occurred in the past, in particular those caused by human error, are placing increasing emphasis on improving safety training on chemical process plants. There is a need for continuous updating and upgrading of chemical process education and training methods. As automation and mechanisation increase in complexity the human interface with systems becomes critical if safe and effective performances are to be achieved.

Training must reinforce from the top, cascading down line management and line supervision to all levels. Safety training should be automatic for newly employed-staff and nobody should start work without knowledge of the safety aspects of their job. Conventional training methods have difficulties in helping employees to understand and experience unusual or potentially dangerous occurrences from a position of safety. It is also extremely difficult for conventional training methods to simulate processes in the chemical production field giving the opportunity for trainees to practice and test their abilities and their knowledge. Using traditional methods of training trainees are not able to experiment with the different types of equipment involved in the chemical process, without actually taking the

equipment off line. These shortcomings indicate that there is an opportunity for a new approach, which may improve safety and hazard awareness training in the chemical industry.

Chapter 3

Computer graphics and virtual reality

3.1 Introduction

This chapter reviews available literature relating to computer graphics and virtual reality covering the definitions and general application areas of computer graphics and virtual reality. It also presents current uses of virtual reality for training aids, outlines some common virtual reality software, especially the SAFE-VR development tool and focuses on the potential of virtual reality for safety training.

3.2 Computer graphics

A picture is said to be worth a thousands words. Computer graphics have the capability to express this statement in a modern way. Computer graphics is commonly understood to mean the creation, storage and manipulation of models and images. Such models come from a diverse and expanding set of fields including physical, mathematical, artistic, biological, and even conceptual (abstract) structures.

Engineers and scientists have always capitalised on the value of pictures by expressing the results of their design work and calculations in the form of engineering drawings, charts and graphs (Demel, 1984).

3.2.1 Computer graphics history

Computer graphics has a history extending back to 1960s and has evolved through various types of technology such graph plotters, vector display systems, storage tube displays and raster based screens, which still remain the most popular methods of displaying images. The term "computer graphics" was coined in 1960 by William Fetter to describe new design methods he was pursuing at Boeing. He created a series of widely reproduced images on a plotter exploring cockpit design using a three-dimensional model of a human body. Ivan Sutherland created the first truly interactive graphics system, shown in figure 3.1, which was called sketchpad, at MIT in 1963 for his Ph.D. Thesis. (van Dam, 2000)

Figure 3.1: The first interactive graphics system in 1963 (after van Dam, 2000)

Computers graphics became an important part of computing from its earliest days, but it was only in the late of 1970s and early 1980s that computer graphics became cost effective. The introduction of Cathode Ray Tubes (CRT) for displaying pictures by Tektonix in 1968, the significant drop in the cost of computer memory in the seventies and the widespread use of low priced personal computers at the beginning of the eighties led to the rapid development and the dramatic cost reductions of computer graphics. In the mid eighties, graphics moved from its status as a limited purpose tool to become an internal part of many computer systems. The Macintosh computer with its extensive use of graphics and the mouse, has helped integrate every aspect of computer use, from the developing data relationships in databases to debugging programs. Personal computers with more memory than mainframe computers of the seventies are found in most offices and homes, which makes computer graphics a mainstream form of computing. Finally companies, which developed graphics software packages, have made Computer Aided Design (CAD) software cost effective for a wide range of companies (Mielke, 1991)

3.2.2 Computer graphics theory

The term "computer graphics" refers to a set of computer applications, which can be used to produce images, and animations, which would have been impossible with the technology available only a few years ago. Computer graphics uses numerical models of real world objects to create artificially created views. Each object is reduced to a representation consisting of points, edges and flat sides (Hollands *et al*, 1999).

The kernel of three-dimensional computer graphics might be defined as the principles of modelling and rendering. Modelling is the creation of the geometry of the object to be rendered. The geometric primitives might be polygons or surface patches. The primitives might be created by defining the three-dimensional co-ordinates of the vertices of the polygons or might be created via interaction with a computer program such as a CAD program or a simple program, which allows a user to create surfaces of revolution. Rendering, on the other hand, is the process of displaying the image of the object on the screen of a video display monitor, i.e. determining which pixels will be displayed and what the shade (i.e. colour) of each pixel will be. Rendering might be accomplished via hidden-surface techniques, ray-tracing techniques, radiosity techniques or some combination of these methods (Pierre, 1997). A more advanced feature available at the higher end of the graphics market is the ability to create sequences of rendered frames and thus display these as an animation, or film.

3.2.2.1 The graphics rendering pipeline

Rendering is the conversion of a scene, which is composed of models in three-dimensional space into an image. Models are composed of primitives supported by the rendering system (Bell, 2001).

Models are typically composed of a large number of geometric primitives. The only rendering primitives typically supported in hardware are points, line segments and polygons and polynomial curves and surfaces. A software renderer may support these modelling primitives directly, or they may be converted into polygonal or linear approximations for hardware rendering (Bell, 2001).
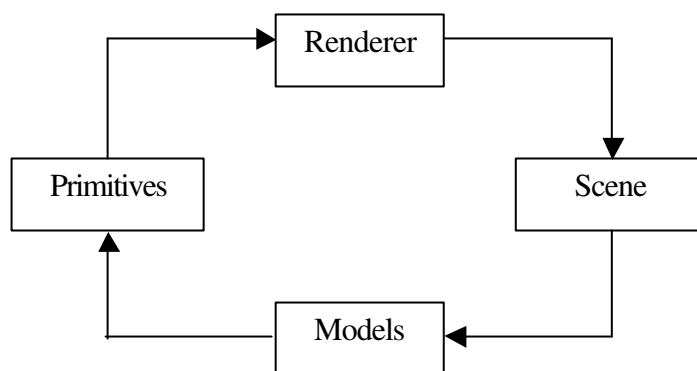
Figure 3.2: The graphics rendering pipeline (after Schofield, 2000)

The conversion from model to image is broken into stages and some of them are implemented in graphics hardware to allow real time simulation. These stages include:

?? The conversion of primitives, which are in the modelling co-ordinate system to primitives in the device co-ordinate system

?? The addition of shading, texture, shadows.

?? The removal of invisible primitives.

?? The conversion of primitives in the device co-ordinate system to pixels in a raster image.

3.2.2.2 Faces and polygon mesh models

A model is made up of a number of faces, which form a representation of the shape of the object. A face can be regarded as a list of points that are all planar and which define its outline, where each point is defined relative to a local origin.
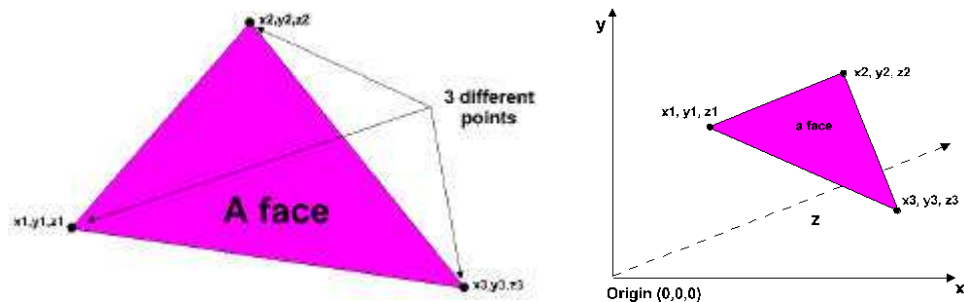
Figure 3.3: Example of a triangulated face (after Schofield, 2000)

Faces are made of materials, which give the underlying colour of the face. The individual points, which make up a face, have a position relative to the origin (0,0,0) as shown in the right hand part of figure 3.3. Faces are the primary building blocks for shapes and models. Multiple faces can be used to build up more complex shapes and models to define position in a virtual world. The faces, and hence complete models or elements of models are defined around a local origin.

A popular representation of three-dimensional objects is the wireframe model where the object is displayed as a set of straight lines that join the vertices together. Compared to shading an object, drawing a wireframe model is very fast.

This will use a few hundred calls to the basic line-drawing utility, and the complete model will be drawn in a fraction of the time taken for a shaded representation.
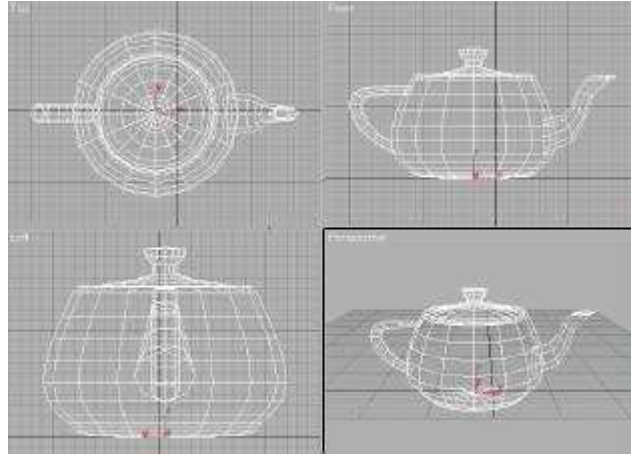
Figure 3.4: Example of a wireframe model

The speed of use is the main reason for the ubiquity of wireframe models. Hidden lines can be removed or left in as required and the interpretation of wireframes can be enhanced by the judicious use of colour and depth cueing, which is referring to changes of colour and intensity of an object's surface, depending on the distance from the viewer.

Wireframes are often used as a preview facility when the final image is to consist of a scene made up of shaded objects and they are used extensively in CAD applications both as a preview and as a final representation. Three-dimensional computer animation also makes extensive use of wireframe previews because the choreography of objects and the virtual camera can be worked out and evaluated using wireframe sequences. Current computers cope easily with wireframes of complex scenes in real time, and the images impart sufficient information for the animator to evaluate the sequence. In fact, wireframes are a pure analogy of the pencil or line tests employed by traditional animators. Here sequences are drawn with no colour to test the dynamics of the movement.

A wireframe model is the simplest visualisation of an object represented as a polygon mesh model. Although a polygon mesh model is a simple concept, its

exact form and the data structure in which it is embedded depend on the use to which it will be put. To produce a wireframe model a simple data structure suffices for the polygon mesh and the individual faces of that mesh (Schofield, 2000).

3.2.2.3 Lighting and reflection

A reflection model describes the interaction of light with a surface, in terms of the properties of the surface and the nature of the incident light. A reflection model is the basic factor in the look of a three-dimensional shaded object because it enables two-dimensional screen projection of an object to made it look real. The purpose of reflection models in computer graphics is to render three-dimensional objects in two-dimensional screen space giving them realistic features. The higher the degree of reality required, the more complex the reflection model and the greater the processing demand.

For example, simple models are often used in computer-generated imagery for games and flight simulators. Even large multiple processing systems may still be constrained by accuracy of the reflection models and the geometric representation of the solids. In a computer game, an accurate shading reflection model may not be as important as the texturing on a surface. Textures are important depth cues in games and simulators and texture mapping can place more demands on the processor than the reflection modelling. In contrast a film special effect or television commercial, which uses a short animated sequence may demand, for aesthetic reasons, a much richer reflection model and more time to be spent generating each frame in the sequence on a single processor.
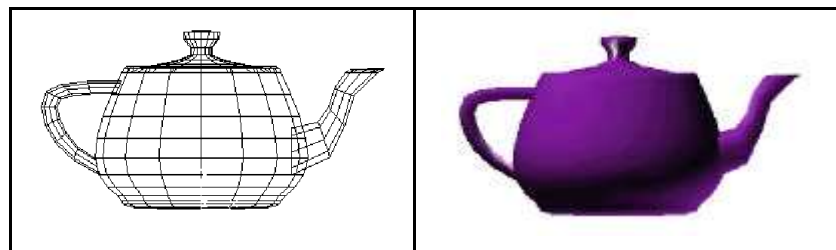
Figure 3.5: Wireframe and shaded solid representation of a CAD model

An engineering component or plan is designed in CAD packages interactively often using solid modelling capability. In order to visualise the completed object, or proposed plan, most three-dimensional CAD systems have a shading option, which use a basic reflection model to shade the surfaces of an object. An example of both a wireframe and a shaded representation is shown in figure 3.5.

Conversely, an illumination model defines the nature of the light emanating from a source and the geometry of its intensity distribution. Most commercial computer graphics artists use simple reflection models and extremely simplified illumination models because these produce acceptable results using currently available hardware power and display devices (Schofield, 2000).

The attributes of the light sources are extremely important in the realistic representation of complex environments. The light source geometry, its luminous intensity and its spectral distribution should have been taken into account. Lighting or atmospherics effects are provided to illuminate geometry in views and are very important to the final appearance of a three-dimensional computer generated world. There are four main types of light sources, ambient, infinite, point and spot, which can be used to give different atmospheric effects. Ambient light is general background lighting, without any radiation direction.

| Infinitive light source | Point light source | Spot light source |
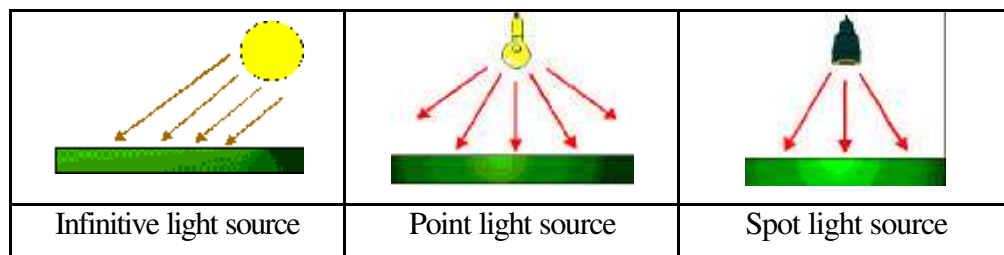
Figure 3.6: Different types of light source

Infinite light sources define the direction in which the light radiates. An example of an infinite light source is the sun, as seen from the earth. Point light sources have a position somewhere in the world, and this type of light source radiates light in all directions. An example is a naked light bulb. Spot light sources combine the different properties of both infinite and point light sources and is defined as the

light, which is radiated from a given point in a given direction. Figure 3.6 shows a representation of different types of light sources.

3.2.2.4 Shadows, materials and texture

Shadows are an important addition to the repertoire of techniques used to visualise three-dimensional objects using computer graphics. Simple shadows can be used to dissolve the perceptual effect of objects floating above the ground and they are far less expensive to compute and are more necessary for simple images than, for example, the accurate modelling of ambient illumination. Shadows can vary tremendously as a function of the lighting environment. They can be hard edged or soft edged and contain both an umbra and a penumbra area. The relative size of the umbra-penumbra is a function of the size and shape of the light source and its distance from the object.

Materials and textures play a large part in lending realism to the scene by improving the outward appearance of objects. Individual faces and subsequent shapes are made from materials, which define the appearance of a shape or model on screen. Materials can be made up of several surface properties such as base or emission colour, transparency and light reflectance.

Additionally images can be added to materials as textures. A texture is simply a raster image that can be 'mapped' onto part or the whole of a face or faces to bring realism to an object. For example changing a green face to a textured one to give the effect of grass, or using a brick effect for buildings. Figure 3.7 shows some examples of different types of texture mapping.

Texture mapping was one of the first developments towards making images of three-dimensional objects more interesting and apparently more complex. Most texture mapping methods modulate the colour of a surface using repeating motifs or a frame grabbed image. Textures on 'real' objects usually exhibit both surface and colour modulation.

ambient map	reflection map	specular map
opacity map	bump map	shininess map
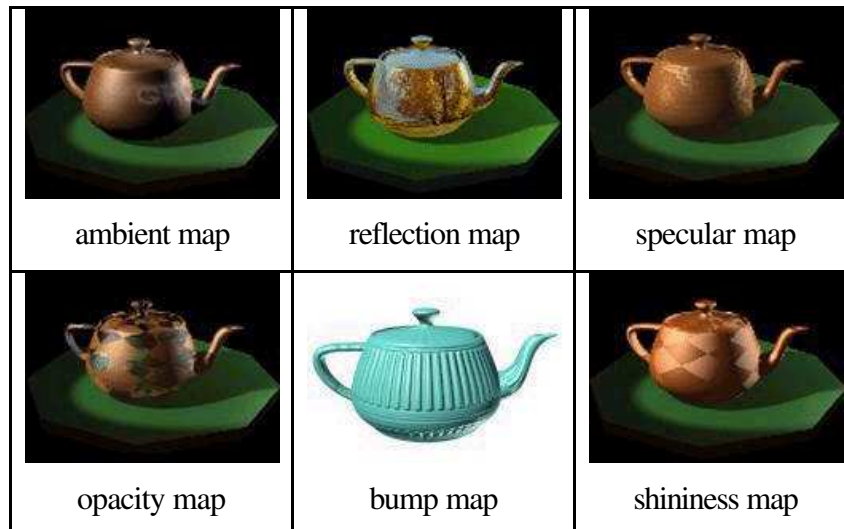
Figure 3.7: Examples of different types of texture mapping (after Kinetix, 1999)

The images assigned to materials are called maps and they can offer a high level of realism. There are several different types of maps, which are used, including standard bitmaps such as .bmp, .jpg, or .tga files, procedural maps, such as repeating checker or marble designs, and image-processing systems such as compositors and masking systems. Maps can be assigned to most of the components that make up a material. By assigning the maps to different attributes of the materials, computer graphics artists can affect the colour, the opacity, the smoothness of the surface, and much more.

3.2.2.5 Hierarchies, kinematics and animations

Three-dimensional scenes are typically made up of multiple complex objects, which are often modelled individually. Building up large, complex scenes without any recognised structure would be extremely difficult. The use of "geometry hierarchies" can simplify the organisation of multiple objects. There are two key benefits from the use of hierarchies, which are the handling of very large, multi, sub-shape models and the manipulation of articulated models.

A hierarchy is created as objects are introduced into a scene and linked together. These objects can be displayed as a tree of elements, traditionally in a vertical arrangement where an icon may represent each element allowing the user to see how different objects are related, and how they are built up in a scene. The top level of the hierarchy can be thought of as a container for sub-objects within the

world. This level is sometimes called the "root", since this can be considered as the base. Normally, any number of objects can be attached to others in a hierarchy and their behaviours and their actions can also be assigned in a similar way.

The basic principles employed by forward kinematics include the hierarchical linking from parent object to child object, the placement of pivot points to define the connecting joint between linked objects and the inheritance of position, rotation and scale transformations from parent to child. Forward kinematics allows considerable control over the exact placement of every object in the hierarchy. However, the process can become tedious with large and complex hierarchies. Before linking anything but the simplest hierarchy time should be taken to plan the linking strategy. The choice of root object and the way the branches will grow out of the leaf objects will have important effects on the usability of the model. An example of forward kinematics structure is shown in figure 3.8.
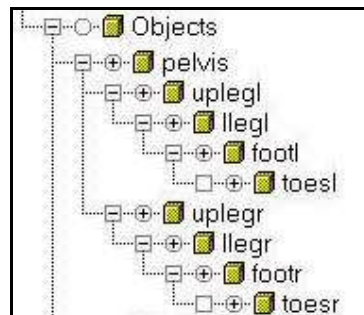
Figure 3.8: Example of forward kinematics structure

Inverse kinematics is a method of manipulating linked structures where the animator positions objects at the end of the linkage and the program calculates the positions and orientations of all other objects in the linkage. Inverse kinematics uses a goal-directed method, wherein the animator positions a child object and the program calculates the position and orientation of the parent objects. Inverse kinematics starts with linking and pivot placement as its foundation and then follows the principles of the constraints of joints with specific positional and rotational properties and the determination of the position and orientation of parent object by the position and orientation of child objects. Due to these added constraints, inverse kinematics requires greater thought about how objects are

linked and pivots located. Where many different solutions for linking objects may be suitable for forward kinematics, there are usually just a few good solutions for any given inverse kinematics approach. The best solution depends on both the nature of the hierarchy and how that hierarchy will be animated. Inverse kinematics is often easier to use than forward kinematics allowing complex motions to be created relatively quickly. The drawback is that the animator must give up some control to the inverse kinematics functions.

Figure 3.9 shows an inverse kinematics structure with its end effector resting on top of a box. The interpolated animation of the end effector follows a natural looking curved path. The positions and rotations of all the objects in the kinematic chain are interpolated between the keyframes to produce the curved result.
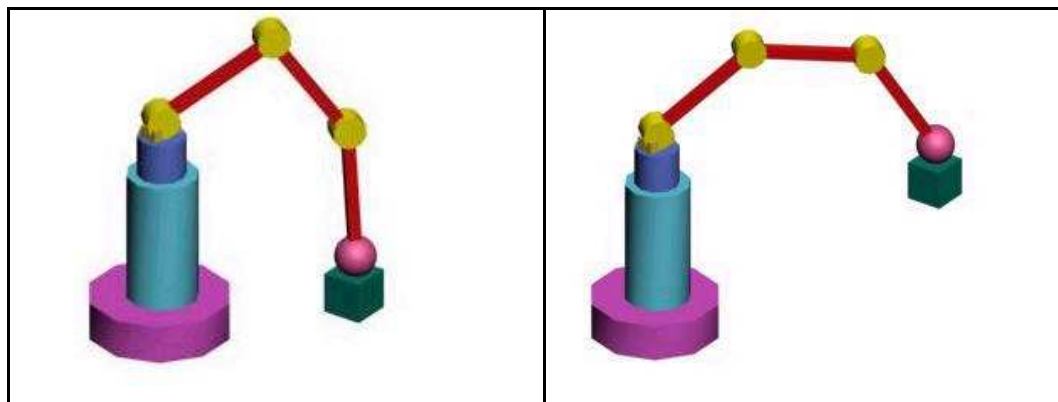
Figure 3.9: Inverse kinematics structure

Inverse kinematics is extensively used in character animation. Modern software packages provide inverse kinematics interpolation engines allowing the production of natural looking motion with a combination of physical dynamics based on gravity and simulation techniques which mimic the motion mechanics displayed by real world two, or four, legged animals. The sophisticated interpolation algorithms result in natural looking motion that is quick to create. In spite of this sophistication, many software packages still require an artist's touch to refine the motion and create something truly expressive.

Until recently, almost all three-dimensional computer animation was produced for the entertainment or advertising industry. Flight and military simulators were an

exception to this, but apart from some efforts in animating scientific phenomena, most applications were produced for films or television. This situation is beginning to change with more scientific applications being developed. Undoubtedly the major research effort in computer graphics has been devoted to more realistic image synthesis and three-dimensional animation has been attracted and developed by the high rewards of the entertainment industry.

It is evident that there is a place for three-dimensional computer animation in engineering simulation and scientific visualisation. High colour animated three-dimensional graphics are used to visualise and provide insight into complex phenomena characterised by massive data sets, such as fluid behaviour in liquids and gases. Animation of phenomena such as shock waves, vortices, shear layers and wakes, all of which depend on time, is of major importance.

The production of a completed animated film sequence includes the modelling of the three-dimensional objects, the scripting of their motion and the motion of the camera and finally the rendering of the frames in the sequence.

3.2.3 Computer graphics software

The first decades of computer graphics were dominated by engineering applications but since the cost of graphics systems has decreased, the number and the variety of computer graphics applications have grown. A wide range of computer graphics software is available.

3.2.3.1 Computer-aided design (CAD)

One of the most powerful early CAD software products was CATIA, which has its roots in the aerospace industry. It was first developed at Dassault Systems as their internal CAD system in the early 1980's and backed by IBM. It has supported digital design processes from concept to reality in manufacturing industries. It offers design flexibility, which accommodates the product designs, involving hybrid-modelling techniques, while preserving the ability to make late engineering changes and delivers one of the largest process-oriented application portfolio supporting best concurrent engineering practices to optimise design productivity, shorten design cycles while improving product quality and reducing

design cost (Dassault Systems, 2000). A screenshot from CATIA software is presented in figure 3.10.
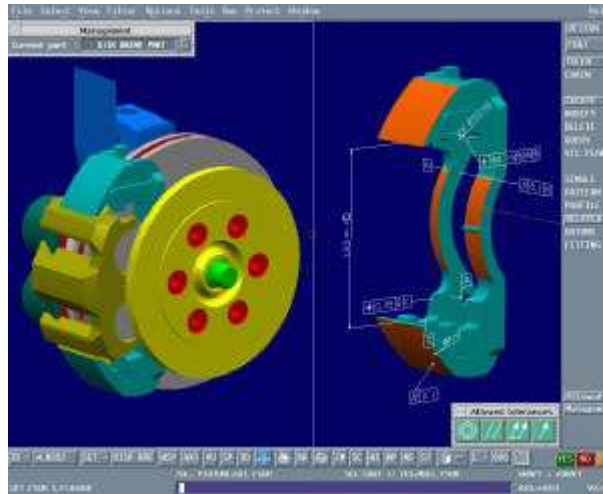
Figure 3.10: A screenshot form CATIA software (after, Dassault Systems, 2000)

SDRC is another company in the industrial design market that developed and brought out the I-DEAS software, which has the ability to develop digital master product models with computer aided design software. SDRC's CAD software is a three-dimensional design system, and its drafting capabilities can be used as a tool for documenting solid models or as a standalone two-dimensional drafting system. The graphical interface product line includes dynamic surface modification and diagnostic solutions processes, including capabilities for geometry based building and inspections (SDRC, 2000).

PTC is a company that is promoting industrial design in an advanced CAD package, which is called Pro/ENGINEER. This single package provides integrated capabilities for creating detailed solid and sheet metal components, building assemblies, designing weldments, and producing fully documented production drawings and photo realistic renderings (PTC, 2000). Shape Studio also is a high-end CAD software package from Unigraphics Inc., which offers advanced designing tools for detailed mechanical design and provides graphics capabilities by including an extensive suite of visualisation and rendering tools (Unigraphics, 2000).

AutoCAD is currently the most popular CAD package worldwide. AutoCAD is designed for use on single-user, desktop personal computers and graphic workstations. It was first released in 1982 under the name MicroCAD by Autodesk. That first AutoCAD release created a change in drafting and design. AutoCAD is a medium priced CAD package that will run on a variety of different types of machine (Apple Macintosh, IBM PC, or UNIX) and provides a range of basic CAD tools. AutoCAD is translated into eighteen languages and currently used by million of users worldwide.

Rebis is a company that is developing AutoPlant, a piece of CAD software for plant design and plant data management. AutoPlant provides plant designers with a set of integrated software tools, such as three-dimensional modelling, dynamic animation and visualisation, which offer advanced design tools for chemical plant design. Autoplant provides various types of equipment in pre-built libraries such as pumps, tanks, heat exchangers, pressure vessels, and after common equipment can easily be constructed. Complete animation and visualisation capabilities are provided in this software as a tool for design review, and also as a tool to visually assess plant congestion and potential interferences (Rebis, 1999). Figure 3.11 shows a screenshot from Autoplant software.
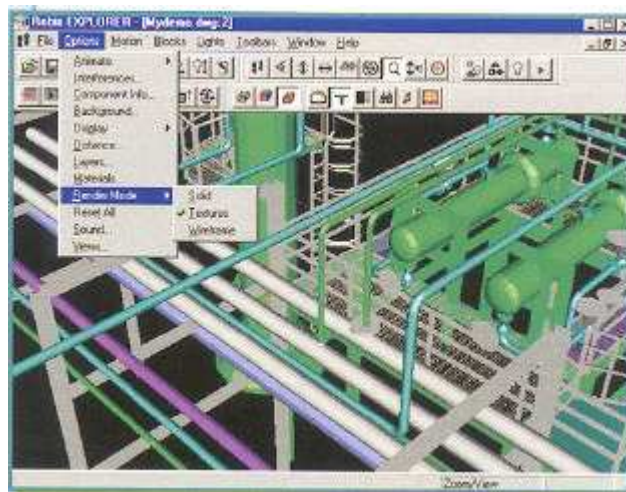
Figure 3.11: Picture from AutoPLANT 3D Modelling (after Rebis, 1999)

Intergraph plant design system (PDS) is a computer-aided design and engineering application for the process and power industries. Corporations worldwide use

PDS for projects ranging from revamping small plants to building multibillion-dollar offshore platforms. PDS creates and maintains an accurate database that provides engineers with valuable information for regulatory compliance, streamlining operations, maintenance, and downstream retrofit projects. PDS consists of integrated two-dimensional and three-dimensional modules that correspond to engineering tasks in the plant design workflow (Intergraph, 1999). Figure 3.12 shows a screenshot from Intergraph's PDS software.

Figure 3.12: Picture from Intergraph's PDS (after Intergraph, 1999)

3.2.3.2 Modelling and animation

In the field of three-dimensional modelling and animation there are many software packages, which allow computers graphics artists to produce complex structures and realistic animations for commercial applications.

Alias Wavefront is a company in the modelling and animation software field and its tools are used for designing products ranging from house-ware to automobiles.

Figure 3.13: A screenshot from LightWave 3D software (after NewTek, 2001)

3D Studio Max from Discreet is a professional three-dimensional modelling, animation and rendering software package, delivering a unified, object-oriented platform for the creation of visual effects, character animation and three-dimensional environments. Since its introduction in 1996, 3D Studio Max is currently used by more than 140,000 computer graphics artists

Rhino from Robert McNeel and Associates is low cost, modelling tool for industrial, product, and scene designers. Rhino is flexible and accurate modelling software, which allows the creation and rendering many combinations of freeform curves, surfaces, and solids Robert McNeel and Associates, 2001

Softimage 3D is three-dimensional modelling, animation and rendering system. It includes advanced features for creating realistic character animations. Softimage

has been used in numerous, well-known film productions such as Jurassic Park, The Mask, Jumanji, and Casper (Softimage, 2001). Figure 3.14 shows an image from Softimage 3D software.
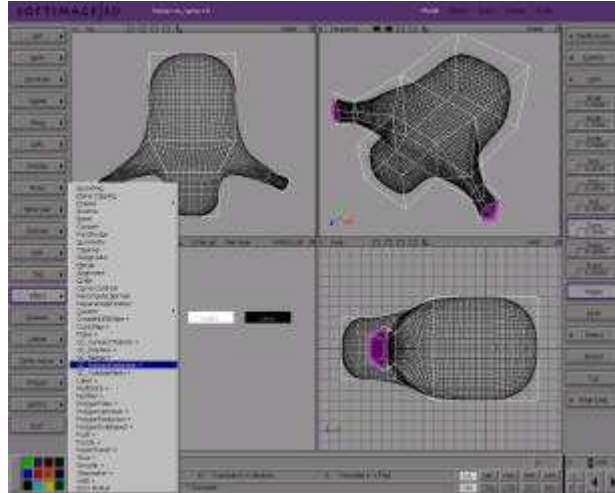
Figure 3.14: Picture from Softimage 3D software (after Softimage, 2001)

3.2.4 Computer graphics applications

Today computer graphics are used routinely in such diverse areas as science, engineering, medicine, business, industry, government, art, entertainment, adverting, education, training and accident reconstruction. The following sections discuss some of the applications areas of computer graphics and present examples of such applications.

3.2.4.1 Design Engineering

A major use of computer graphics is in design processes, particularly for engineering and architectural systems. CAD methods are routinely used in the design of buildings, automobiles, aircrafts, computers and many other products. Objects in a design application are first displayed in a wireframe outline form, which shows the overall shape and internal features of objects and allows designers to quickly see the effects of interactive adjustments to design shapes. Software packages for CAD applications typically provide the designers with a multi-window environment. Most of them have the ability not only to model but to be able to create design iterations quickly and collaborate in an iterative process (Wheeldon, 1994).

Real time manipulation and animations of objects using wireframe displays on a video monitor are often used in CAD applications and they are useful for viewing the three-dimensional objects. When object design is complete, realistic lighting model and surface rendering are applied to produce displays that will show the appearance of the final product. Examples of realistic lighting effects and background lighting in an architectural context are demonstrated in figure 3.15.

Figure 3.15: A realistic three-dimensional perspective view from the Borough of
Hackney Project. (after Skidmore, Owings and Merrill, 2001)

Architects use interactive graphic methods to lay out floor plans which show the positioning of rooms, doors, windows and other building features. Realistic displays of architectural designs permit both architects and their clients to study the appearance of a single building or a group of buildings. Furthermore, electrical engineers working from the display of a building layout can try out arrangements for wiring, electrical outlets and fire warning systems.

The Aims research unit has developed computer graphics techniques to quantitatively assess the visual impact of proposed developments on the landscape. One recent project was the development of the new Birmingham University hospital and the reallocation of the psychiatric hospital. Within a few

weeks a 2km squared area of the proposed site and surrounding area was modelled in order to produce rendered views of the new hospital and the relocated psychiatric hospital from various key locations. The percentage change in view was also calculated for the psychiatric hospital project section from these key locations. Figure 3.16 shows an image of the hospital, which was produced using computer graphics.

Figure 3.16: View of the psychiatric hospital of a residential tower block

3.2.4.2 Computer art

Computer graphics methods are widely used in commercial art applications. Artists use a variety of computers methods including special purpose hardware, artist's paintbrush programs, CAD and animation packages and desktop publishing software that provide facilities for designing objects, shapes and specifying object motion. A paintbrush system with a Wacom cordless, pressure-sensitive stylus was used to produce the electronic painting in figure 3.17 that simulates the brush strokes of Van Gogh. The stylus translates changing hand pressure into variable line widths, brush sizes and colour gradations.

Computer generated art is widely used in commercial applications. Various designs of logos and advertisements are produced with computer graphics systems and are often used in television (Heard and Baker, 1994).

Figure 3.17: A Van Gogh reproduction created by graphics artist Elizabeth
O'Rourke (after Heard and Baker, 1994)

3.2.4.3 Presentation graphics

Another major application area is presentation graphics, which are used to produce illustrations of work or to generate slides or transparencies for use with data projectors. Presentation graphics are commonly used to summarise financial, statistical, mathematical, scientific and economic data for research and managerial papers or bulletins or various types of reports. Typical examples of presentation graphics are bar charts, line graphs, surface graphs and other displays showing relationship between multiple parameters. An example of a three-dimensional graph is shown in figure 3.18.
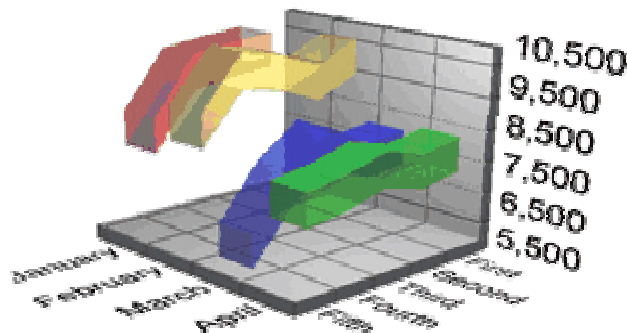
Figure 3.18: Three-dimensional line graph (after Three D Graphics Inc, 2001)

3.2.4.4 Entertainment

Computer graphics methods have been widely used to make motion pictures, music videos and television adverting spots and shows. Sometimes the graphics scenes are displayed by themselves and sometimes computer generated objects are composited with the actors and live action scenes. Photorealistic rendering techniques are frequently used in advertising and television commercials. These animations can be produced by rendering each frame of a simulated motion, which are then saved as image files. When all frames in an animation sequence have been rendered, the frames are transferred to film or stored in a video buffer playback. Figure 3.19 shows a scene generated with advanced modelling and surface rendering methods for the film "A Bug's Life".

Figure 3.19: A computer generated scene from the film "A Bug's Life"(after Pixar, 1998)

3.2.4.5 Visualisation

Computer graphics make vast quantities of data accessible. The use of computer graphics technology allows scientists and engineers to produce graphical representations of large data sets. Numerical simulations carried out on computers frequently produce data files containing thousands and even millions of data values. Instead of scanning these large sets of numerical data, scientists use graphics techniques, which convert them to a visual form, and then they can easily determine relationships, trends and patterns within their models. There are many different kinds of data sets, and effective visualisation schemes depend on the characteristics of the data. A variety of different techniques including colour

coding, surface rendering, contour plots and image processing operations can be combined with computer graphics to produce different data visualisations. Mathematicians, physical scientists, engineers and others use visual techniques to analyse and processes large amounts of data values. Figure 3.20 shows a triple-helical DNA in a bath of sodium ions a triple-helical DNA in a bath of sodium ions, simulated by Pettitt's group at the University of Houston (Greenberg *et al*, 1995).
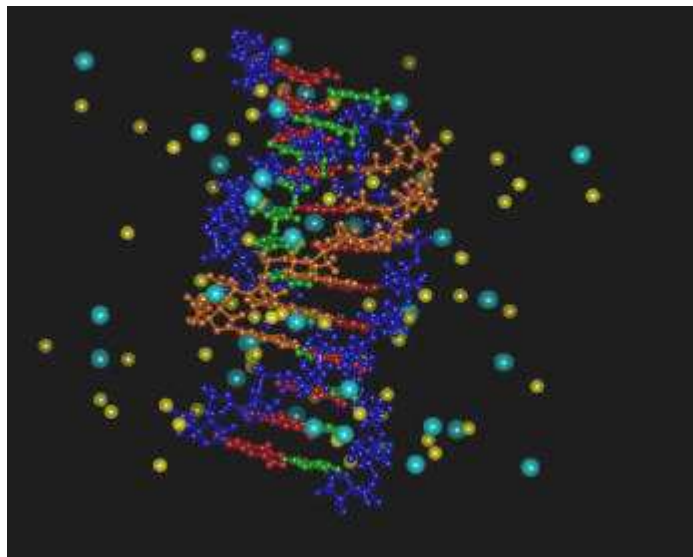
Figure 3.20: The triple-helical DNA in a bath of sodium ions (after Greenberg *et al*, 1995)

3.2.4.6 Education and training

Computer generated models of physical, financial and economic systems are often used as educational aids and they can help trainees to understand the operation of the real system. Simulators and other specialised systems which provide graphics screens for visual operation are often used for practice sessions or training of ship captains, aircraft pilots, heavy equipment operators and air-traffic control personnel.

Figure 3.21 shows a screenshot from a driving simulator, which is used to investigate the behaviour of drivers in critical situations. The drivers' reactions are then used as a basis to optimising vehicle design to maximize traffic safety.

Figure 3.21: A picture from an automobile simulator used to test driver reaction
(after Evans & Sutherland, Inc., 2001).

The AIMS Research Unit has produced a number of training video's using the computer graphics techniques. An example of this type of video is a free-steered vehicle awareness video produced for British Coal and a still from this animation is shown in figure 3.22.

Figure 3.22: Still from a British Coal safety video (after Schofield, 1997)

This was aimed at educating pedestrians who work in free-steered vehicle roadways of the dangers associated with the vehicles. Computer graphics were exclusively used to produce this video in which dangerous situations and accidents were recreated, accidents were viewed from various viewpoints, the driver's lines of sight were shown as graphical three-dimensional objects, marking

the danger zones. A range of analogies from everyday life was used to reinforce the safety message.

This computer generated training video was of approximately four minutes duration. These animations are produced and laid down on high band, broadcast quality tapes. Narratives and atmospheric soundtracks are added to produce a finished item. The cost of producing a computer generated training film is surprisingly low when compared to the costs incurred by the difficulties of 'real' underground filming. In addition, computer graphics can be used to demonstrate hazardous situations that would involve significant risk to operators if reproduced in real life for filming purposes (Schofield, 1997).

3.2.4.7 Accident reconstruction

The AIMS Research has been pioneering the use of computer graphics technology for both traffic and industrial reconstruction accidents in the United Kingdom. Based on the accident survey data, the exact position of objects such as vehicles, environment details, landscape features and other relevant items are duplicated from the data within the 3D software. All objects are sized precisely and are coloured, embossed with images and textured to produce a lifelike appearance. Figure 3.23 shows a view of three-dimensional environment, from an accident, which involved a vehicle that lost control as the driver took a bend too quickly in Australia (Schofield *et al*, 2000).

Figure 3.23: A view of the 3D computer model built, based on digital survey data and photographs (after Schofield *et al*, 2000).

The ability to represent a range of accident scenarios on a computer screen and view those scenarios from any angle enables accident investigators, and lay people, to understand the underlying causes of an accident. Figure 3.24 shows a view of a reconstructed accident, which happened in Nottinghamshire. The three-dimensional computer model was built based on police digital survey data and photographs of the scene. The motion of both cars involved in the accident, based on police calculations, is clearly shown. Also various witness vehicles are included in the animations, based on locations and timing from witness statements.

Figure 3.24: Vehicles in skid marks from an accident reconstruction application

(after, Schofield *et al*, 2000)

As can be seen in the computer graphics used for film and television, realism in these 'virtual' environments is increasing. As computer-processing power increases and the software tools develop realism increases within the computer generated environments used in forensic animations. It is possible that the environments surrounding the accident site will be included within the models. For example the animation may not only show the vehicles on the road but also the position of the vehicles in relation to houses and other roadside features, as the accident reconstruction in figure 3.25 shows (Schofield *et al*, 2000).
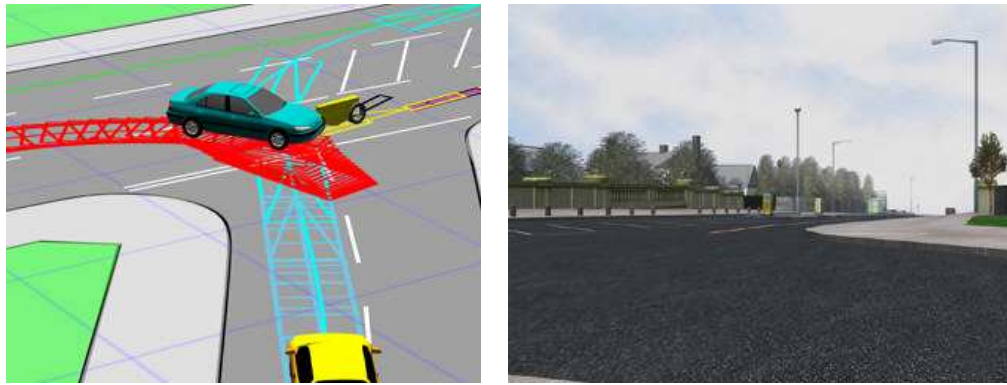
Figure 3.25: A simple three-dimensional model and a rendered model of the landscape of an accident scene (after Schofield *et al*, 2000)

The main purpose of these computer models is their presentation in trials, industrial hearings, public enquiries or for settlement attempts. The ability to represent a range of crime or accident scenarios and view those scenarios from any angle enables investigators, and jury members, to better understand the underlying causes of an accident.

3.3 Virtual reality

Virtual reality encompasses many technologies and application areas, hence it is difficult to describe virtual reality in a single, concise definition. Certainly virtual reality technology shares a lot in common with computer-generated visual simulation systems but virtual reality applications generally support more intensive interaction between the human participants and the simulation system. The common capability among virtual reality systems is that they all use computers and other spatial digital hardware to present a simulation to a human participant via visual and other sensory outputs such that the humans experiences an interaction with the virtual world. Virtual reality is a significant extension to the way we interact with computer systems, improving individual and shared understanding of real or imaginary environments. Applications of its use in the business community have been emerging for the last decade and have given competitive business advantages. Users are able to interact in real time with computer-generated environments in a simple, "natural" manner, without the need for extensive training (Kalawsky, 2000).

There has been a steady increase in the potential for virtual reality techniques for many training applications. In particular the ability to provide cost effective access to high fidelity computer simulations is a very important attribute. The potential of a virtual reality based system can be very impressive and as costs for the enabling technologies fall there is likely to be an acceleration in the uses of this technology. It is not too difficult to see that virtual reality will have a major influence on training processes by providing training establishments with a powerful new approach to training and research. It will soon be feasible to provide access to sophisticated chemical plant facilities in a virtual format. The exact form that virtual training aids will take depends very much on the nature of the training program to be delivered. A broad spectrum of technology based concepts are available and it will be extremely important to understand where and how to apply these to achieve an effective training medium (Kalawsky, 2000).

3.3.1 Virtual reality systems

A virtual reality system allows a participant to:

- ?? Become immersed in a completely synthetic computer generated environment.
- ?? Achieve a sense of presence in the environment.
- ?? Become un-inhibited where conventional laws of physics can be controlled in a way that assists greater understanding.
- ?? Achieve a sense of non-real time, where situations can be presented in slow or fast time.
- ?? Achieve a high degree of interaction that can equal or exceed that achievable in the real world.
- ?? Interact in a completely natural and intuitive manner with the synthetic environment.
- ?? Repeat the task until the desired level of proficiency or skill has been achieved.
- ?? Perform in a safe environment

It is important to note that a virtual reality system is essentially an interactive simulation that can represent a real or abstract system. The simulation is a

representative computer based model, which provides appropriate data for visualisation or representation of the system (IMO, 1995). A generic description of a virtual environment is shown in figure 3.26 (Kalawsky, 2000).
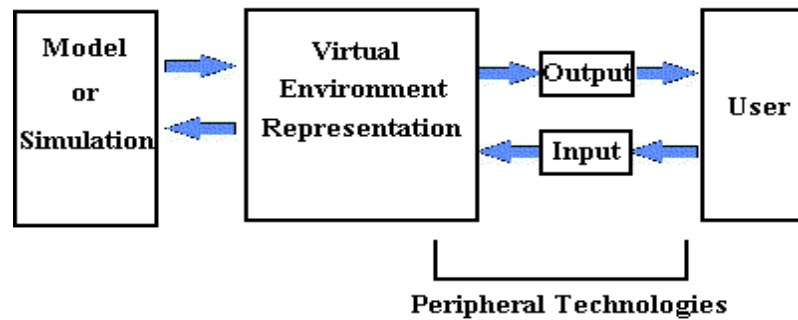
Figure 3.26: Generic model of a Virtual Environment System

The virtual environment can take many forms and for example, it could be a realistic representation of a physical system. Geometric accuracy and the attributes of colour, texture and lighting are very important. Three-dimensional software may be used to construct such an environment employing engineering drawings, architectural plans and the incorporation of important physical dimensions (Vince, 1995).

The virtual environment consists of collection of objects and light sources which are manipulated by animation and physical simulation procedures. In parallel with these activities, collision detection algorithms monitor collision between specified objects. The object within a virtual environment can be static or dynamic.

3.3.3.1 Model or Simulation

The model or simulation is a mathematical representation of the system being used. It needs to take account of dynamic behaviour in response to the user's input. For example, a mathematical model can be produced that represents the dynamic behaviour of a petrol engine under different load conditions. Very sophisticated mathematical models can be written but it is the way that these are associated with an auditory and visual representation of the system that is important (Kalawsky, 2000).

The simulation can also make it possible to explore "what if" situations that would otherwise be impossible or dangerous to perform. This further improves the user's level of understanding. It would even be possible to let the user explore a system and make mistakes. In this way the trainee will get the best possible understanding of the system operation. No other type of training allows trainees to experience and react to dangerous situations in this manner. When an unexpected condition arises, operators must react instinctively (Kalawsky, 2000; IMO, 1995 and Ferney, 1991).

3.3.3.2 Peripheral technologies

It is the peripheral technologies that most people closely associate with virtual reality since they represent the user's interface with the virtual reality system. The peripheral technologies are the input and output devices, which allow the user to interact with and control the actions in a virtual reality system.

The input devices refer to the interaction devices that are used to input the position and orientations of the user's head and hand. They include a standard mouse, keyboard, joystick, space ball, touch screen monitor, data glove and tracker devices. The selection of the input devices depends on level of interaction and flexibility of movement required. Figures 3.27 and 3.28 shows a joystick and a dataglove respectively.

Figure 3.27: Joystick input device (after Flight Sim Central, 2000)

Figure 3.28: Data glove input device (after Virtex, 2000)

The output devices provide stimuli to user and include standard or touch screen monitors, head mounted displays (HMD), three-dimensional shutter glasses combined with a monitor and three-dimensional sound systems, as shown in figure 3.29, 3.30. The advantages of this types of output devices such as HMD is that it completely blocks any external any external influences from the real world by enclosing the user's visual and auditory senses. This creates a strong sense of immersion and presence, as the user is unaware of any other environment than virtual environment. The choice of the output devices depends on the level of immersion and the resolution of image required.

Figure 3.29: Head-mounted display output device (after Forte, 2001)

Figure 3.30: Shutter glasses output devices (after Stereographics, 2001)

3.3.2 Types of virtual reality systems

A major distinction of virtual reality systems is the mode in which they are interfaced to the users. The participant in a virtual reality system has both a physical and a cognitive interaction with the virtual reality system. The physical interaction is provided by the hardware interface, which comprises the senses, which allow the users to update the virtual environment and the effectors via which they obtain information from it. The cognitive interaction is via the virtual world, which is built within the virtual reality system.

3.3.2.1 Immersive virtual reality systems

Immersive virtual reality systems use output devices to map as directly as possible to user's perceptual organs. The user in an immersive virtual reality system is required to wear a head-mounted display that tracks the wearers movements and conveys them to the computer which responds accordingly relaying the information (both audio and visual) back to the headset. Head mounted display encases the audio and visual perception of the user in the virtual environment and cuts out all outside information. Head mounted display may be stereoscopic which means that two lenses present slightly different information to each eye or binocular which refers to two screens presenting the same display or monocular. However, head mounted display technology is fairly crude, and rather expensive, and has a number of disadvantages including encumbrance, isolating experience and occasional simulator sickness (Kalawsky, 2000 and Hitchner, 1995).

3.3.2.2 Projection virtual reality systems

Projection virtual reality systems are a variation of the immersive systems and use single or multiple projection displays to create a room in which the viewer is able to stand or sit. The use of multiple projection based systems can have a significant cost but can result in high resolution images produced. An early implementation of this was called "The Closet Cathedral" (Vince, 1995) which had the ability to create the impression of an immense environment within a small physical space. Projection virtual reality systems are similar to desktop virtual reality systems but allow a wider audience to view the interaction, although they may not all directly participate. This is ideal for group presentations where direct interaction is either not suitable or unnecessary (Hitchner, 1995).

3.3.2.3 Desktop virtual reality systems

Desktop virtual reality systems are the most popular type of virtual reality systems and are based upon the concept that the potential user interacts with the computer screen without being fully immersed and surrounded by the computer generated environment. They provide a lower level of presence and perhaps interaction, than immersive systems but they have many advantages. The greater graphics quality, the flexibility of world building toolkits and lower capital cost of hardware, software and peripherals give many advantages to desktop virtual reality systems making them an attractive compromise to many end users. Desktop systems utilise standard computer hardware using a mouse, joystick or three-dimensional space mouse as the input medium to interact and manipulate the virtual environment using a monitor and speakers to view and listen to the results. The feeling of subjective immersion in desktop virtual reality systems can be improved through some form of shutter glasses, which give the extra dimension of stereoscopic three-dimensional space. Desktop virtual reality systems provide a low cost option for high-resolution visualisation for design, training and education applications. A typical desktop virtual reality system is presented in figure 3.31.

Figure 3.31: A typical desktop virtual reality system (after Wilson *et al*, 1996)

The rapid development in personal computer technology and the huge potential market for desktop virtual reality systems in a wide range of fields means that this is the area where some of the fastest developments are occurring. Multi-national corporations are investing hundreds of millions of pounds in ensuring that desktop virtual reality system performance increases. Whilst the technology drive has largely been focused on the home computer games market the spin-offs into

engineering have resulted in high quality systems becoming available for serious applications (Aukstakalnis and Blatner, 1992 and Wilson *et al* 1996).

As hardware costs and the performance of personal computers has reached sensible levels, this has resulted in continuous reductions in software development costs. As the market for virtual reality applications in chemical engineering increases this will result in major reductions in the unit costs of complete training systems. Hence, the argument that virtual reality is an expensive technology no longer holds, and the opportunity for mass training using virtual reality opens up as unit costs drop dramatically.

3.3.3 Benefits of virtual reality systems

The major applications areas of virtual reality can be broadly classified into understanding, experiencing, entertainment and learning. In all four cases, virtual reality provides a safe, and frequently highly cost effective environment for individuals to fulfil their professional, training or recreational needs.

There are many areas where virtual reality could be used to support training. The advantages of virtual reality training compared to traditional methods of training can be summarised in the following section:

?? Ability to observe system operation from a number of perspectives aided by high quality visualisation and interaction (Kalawsky, 2000).

?? Observation of system features that would be either too small or too large to be seen on normal scale system (Kalawsky, 2000).

?? Ability to control timescale in a dynamic event. This feature could operate like the fast forward or rewind preview in a modern video recorder (Kalawsky, 2000).

?? Most people learn faster by "doing" and virtual reality systems provide much greater levels of interactivity than other computer based system. Provided that the interfaces are intuitive and easy to use then the degree of interactivity can be very beneficial (Kalawsky, 2000 and Vince, 1995).

?? The inherent flexibility of a virtual reality system comes from the underlying software nature of the virtual environment. A virtual reality

system can be put variety of uses by loading different application environments. This means that it is feasible to use a virtual reality system for a range of training applications (Kalawsky, 2000 and UKVRFORUM, 2000).

?? The sense of immersion is a powerful characteristic in the field of engineering design and virtual reality environments provides that. For example, architecture is an area where the sense of scale is required to visualise the impact of a building design on the surrounding environment and the habitants. It is obvious that virtual reality systems are able to provide rescaling in three-dimensional designs, which is extremely important for engineering (Kalawsky, 2000).

?? Virtual training environments allow users to train themselves to engineering processes without actually being there and before plant has been built. Furthermore, the trainee is able to point out areas, which would have been very difficult to access (Fluor Daniel Ltd, 1998).

?? Using virtual reality training environments trainees can gain experience in actual chemical plant operations because start-up and shutdown scenarios can be gone through repeatedly in the virtual world in a fraction of time that they could not have happened on the real operating chemical units (Basta, 1995 and Elshout *et al*, 1987).

?? Virtual training systems are powerful engineering tools because anyone can learn to use most of the interfaces in as little as five minutes and can become quite proficient under half an hour. They often provide an intuitive interface that can give access to vast quantities of data at a glance (Fluor Daniel Ltd, 1998).

?? The trainees can be anywhere in the world. Using telecommunications facilities, remote workers can work together in the same virtual area, on a chemical plant or a building site for example, even though they may be physically a great distance apart. As a result, travel costs could be reduced and interactive programs with multiple sites networked for group learning and communication could be developed (IMO, 1995 and Warwick, 1993).

?? Virtual reality training systems can allow trainees to experience unusual or potentially dangerous occurrences from a position of safety. Conventional

training must be very careful when putting trainees into situations, which could be hazardous. An example might be brake failure or a potential derailment situation (Vince, 1995).

The above points show how virtual reality systems are ideal for demonstrating to trainees the correct or incorrect procedures that they should follow. Codes of practice or local rules can be demonstrated and virtual reality also allows for testing of retained knowledge (Cydata Limited, 2000).

3.3.4 Virtual reality software

There are currently a great number of many different efforts to develop virtual reality technology. Each of these projects has a different goals and approaches to the overall virtual reality technology. A number of academic groups, companies and government organization around the world have been developing virtual reality systems and associated simulation technologies. These range from industry-supported laboratories, such as the Human Computer Interface Laboratory (HCIL) in Seattle, to academic units such as the VIRART research team and the Communication Research Group (CRG) at the University of Nottingham in the United Kingdom. VIRART is a research and development group and in conjunction with the Institute for Occupational Ergonomics (IOE), it carries out substantial research into design and evaluation of virtual environments and virtual reality technologies. The CRG researches the use of computer and communications technologies including virtual reality, distributed systems and multimedia to support human communications and especially the work of physically distributed groups.

There are two major categories for the available virtual reality software: toolkits and authoring systems. Toolkits are programming libraries, generally for C and C++ that provide a set of functions with which a skilled programmer can create virtual reality applications. Authoring systems are complete programs with graphical interfaces for creating virtual worlds without resorting to detailed programming (Isdale, 1998).

3.3.4.1 Alice

Alice is a three-dimensional interactive graphic programming environment for Windows 95/98/NT built by the Stage 3 Research Group at Carnegie Mellon University. The Alice project is a public service to the wider computing and artistic communities; their hope is to make it easy for novices to develop interesting three-dimensional environments and to explore the new medium of interactive three-dimensional graphics. The current version of the Alice authoring tool is free to everyone and runs on computers that are commonly available for reasonable prices. Worlds created in Alice can be viewed and interacted with inside of a standard web browser once the Alice plug-in has been installed (Stage 3 Research Group, 2000). Figure 3.32 shows an application developed using the Alice software.

Figure 3.32: Launching a fighter jet from an aircraft carrier using the Alice software (after Stage 3 Research Group, 2000)

Alice is primarily a scripting and prototyping environment for three-dimensional object behaviour. By writing simple script codes, Alice users can control object appearance and behaviour, and while the scripts are executing, objects respond to user input via a mouse and keyboard. Alice is not a three-dimensional modelling program, but it does import many common three-dimensional file formats including .dxf and .obj formats. Objects can be converted to Alice format from .3DS or .max format using a special 3D Studio Max plug-in. The Alice core distribution includes a large library of textured models.

3.3.4.2 DIVE

The Distributed Interactive Virtual Environment (DIVE) is an internet-based multi-user VR system where participants navigate in three-dimensional space and see, meet and interact with other users and applications. The first DIVE version appeared in 1991 and it is a research prototype covered by licenses. It is popular among computer science departments at many universities because academic licenses are freely available for a number of platforms. DIVE supports the development of virtual environments, user interfaces and applications based on shared three-dimensional synthetic environments (Frécon and Stenius, 1998). A screenshot from a DIVE application is shown in figure 3.33.

DIVE is especially tuned to multi-user applications, where several networked participants interact over a network. DIVE reads and exports VRML and several other three-dimensional formats. It is integrated with the World-Wide-Web and is HTTP/FTP/HTML/MIME compliant.

Figure 3.33: Screenshot from a DIVE application

DIVE applications and activities include virtual battlefields, spatial models of interaction, virtual agents, real-world robot control and multi-modal interaction. The CRG group in University of Nottingham uses DIVE software and had developed a range of virtual reality training environments.

3.3.4.3 VRML (Virtual Reality Modelling Language)

VRML stands for Virtual Reality Modelling Language, this evolved shortly after the definition of HTML as a standard way of presenting and navigating three-dimensional scenes, or worlds, on the Internet. It is an open, extensible, industry-standard scene description language but it is not a programming language. At one level VRML is simply a generic file format for describing geometric data, which can be read by many different browsers on different platforms. VRML files are not compiled, but are simple ASCII text files, which can be parsed by a VRML interpreter. These interpreter programs are often called VRML browsers.

Since VRML code is interpreted, the visible results of the code may vary from one browser program to another. Furthermore, VRML is extensible, which means that browser developers, for example, can add new, non-standard functionality to the language, using standard components of the language. If a browser can parse the extensions to the standard VRML language, which it encounters in a world file, then the new functionality described by the extensions will be interpreted for the user as that scene is rendered.

By using textures and lighting it is possible to create realistic environments. The image in figure 4.34 came from a research project of the Computer Integrated Construction Group at National Institute of Standards and Technologies (NIST) in United States and involves a emission control system, which has been modelled in VRML as a test to show how construction process information can be made available through an advanced web-based three-dimensional user interface.

Figure 3.34: Emission control system in VRML (after NIST, 2001)

Architects and engineers can export buildings and structures to a virtual world to allow web surfers to explore existing buildings and proposed developments. In this instance VRML is mainly used as a viewing tool as it has limited use as a design tool. The original drawings and design work are carried out using powerful drafting tools such as AutoCAD or Microstation. Celtic football club in Glasgow use VRML to show how the Park Head stadium will look following on going developments (McGrath, 2000). This is shown in figure 4.35.
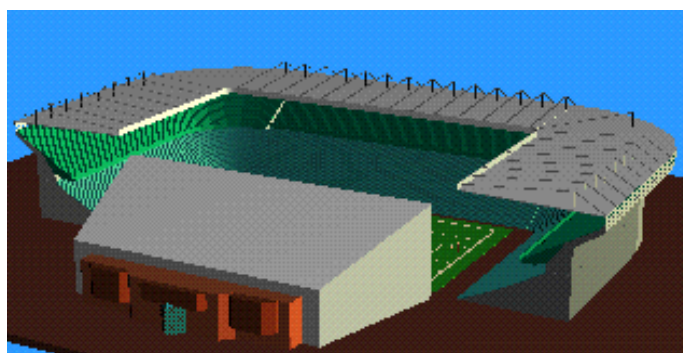
Figure 3.35: The Park Head stadium in Glasgow in VRML (after McGrath, 2000)

Science and medicine have also found uses for virtual 3-D environments. Complex crystal structures, such as that show in figure 4.36, can be modelled and then viewed across the Web. VRML is being used in cancer research to model biomolecules. These models allow researchers and students alike to view chemical structures from many different angles.
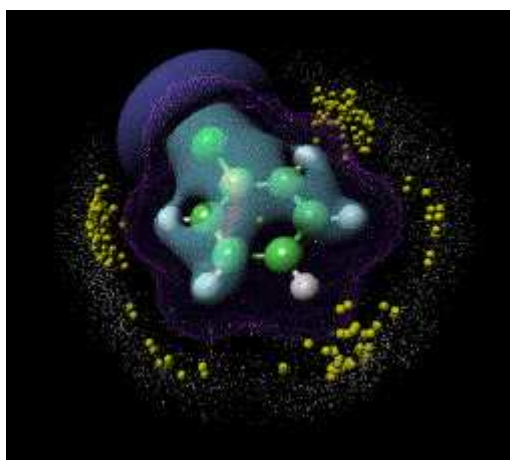
Figure 3.36: Scatterplot showing oxygen contacts to the centroid of chlorobenzene

(after Casher *et al*, 1995)

3.3.4.4 Sense8's WorldToolKit

Sense8's WorldToolKit (WTK) is a library of C functions that can be used to write C programs for developing and interacting with virtual worlds. The user writes a C program referencing the functions, which then become a WTK application. A typical program consists of an initialisation phase followed by a simulation loop. Initialisation consists of setting up the interaction, initialising sensors, identifying objects, configuring the illumination and initialising the viewpoint, while the simulation loop supports an interactive virtual reality session. The update rate of the display depends on how many times the simulation loop is evaluated per second. Figure 3.37 shows a screenshot from a visualization prototype created with Sense8's World Toolkit from the French Space Agency (Sense8 Product Line, 2000)
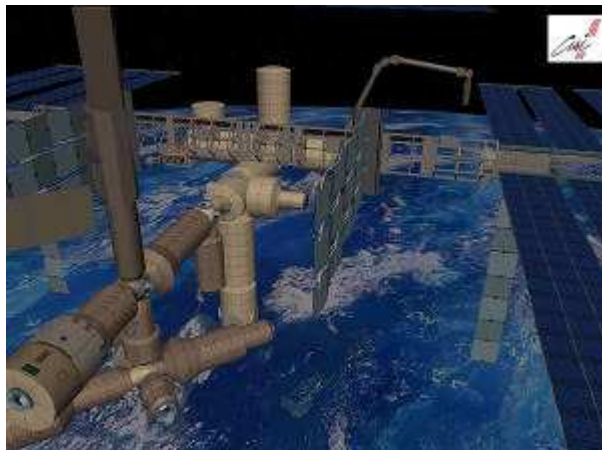
Figure 3.37: Screenshot from an application created with Sense8's WorldToolKit
(after Sense8 Product Line, 2000)

3.3.4.5 Superscape's Virtual Reality Toolkit (VRT)

Superscape's VRT is an integrated virtual reality system consisting of several editors, the most important of which are the shape editor and the world editor. The shape editor provides interactive tools for building polygonal objects, while the world editor organises the construction of the virtual world from these objects. The shape editor uses vertices and facets to create three-dimensional objects, which can be coloured, duplicated, transformed and animated. Superscape's virtual reality toolkit employs the concept of dynamic points, which can be animated when the object is eventually displayed. The world editor uses object

descriptions from the shape editor to build the virtual worlds organized as a tree of objects. It is also used to assign the physical attributes such as velocity, gravity, climbing and restitution. It also organises animations cells from the shape editor into animation sequences that will occur when the scene is rendered (Superscape, 2000).

Other editors are available for customising screen layouts, editing textures and sounds and controlling menus and dialogue boxes. One of those is the visualiser, which is used to display the virtual world and give the ability to user to move around the virtual environment and interact with it. When it used in a desktop virtual reality systems, a spaceball may be used to control the picking of objects and to control the user's viewpoint. Figure 3.38 shows a safety training application, which was created using Superscape's VRT for UAW-Ford partnership. The application addresses the problem of pedestrian safety in an industrial assembly environment.

Figure 3.38: A safety training application using Superscape's VRT (after Superscape, 2000)

3.3.4.6 dVISE

Division Ltd. sells a virtual reality programming environment, which is called dVS. This package runs on SGI systems, IBM RS/6000 workstations and a proprietary Division workstation. They also sell a complete world authoring and simulation program called dVISE. Division also offers interactive product

simulation tools, which is the process by which manufacturers use dVISE to create, interact with, share, manipulate and analyse an in-progress design (Division Ltd, 1998).

The simulation of a product's functionality is one of the most important applications of Division's interactive product simulation as consumers as well as engineers can experience the benefits of understanding the virtual product before making production and purchase decisions.

Division's dVISE software allows CAD data to be turned into a functioning, interactive virtual product, which reduces physical prototyping by testing the virtual product. It also allows testing and understanding how users and others will interact with the design by using joints, animations, and "Smart-Parts" – virtual parts that behave like real parts. Users are able to move parts and assemblies allowing them to understand and test maintenance procedures and sequences, taking advantage of concurrent involvement, access, and interaction with a functional design. Finally, it provides a facility for management to train new personnel by providing "hands-on training" (Division Ltd, 1998). Figure 3.39 shows an image from an engine, which is built using dVISE software.
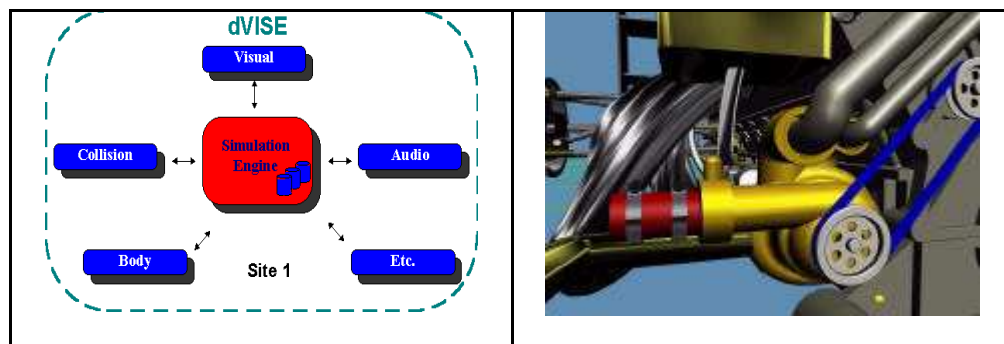
Figure 3.39: Image from an engine, which is built using dVISE software (after Division Ltd., 1998)

3.3.4.7 Evans and Sutherland

The Evans and Sutherland (E&S) company develops and manufactures hardware and software to produce highly realistic three-dimensional synthetic worlds. It produces high-quality visual systems for simulation and training in defence and commercial applications as well as high-performance systems for digital theatres

and other applications throughout the world. Among Evans and Sutherland's products is a full range of sophisticated visual systems for simulation, training, and virtual reality applications. It also produces high-performance, professional level graphics acceleration technology.

E&S produces simFUSION, which is a PC-based visual system to offer real simulation features. It is fully OpenGL compliant and can be easily configured. SimFUSION provides a range of suitable features to create realistic and effective training applications, such as high image quality graphical rendering under real simulation conditions.

Figure 3.40 shows a screenshot from a training application using simFUSION. This application is used to improve training and safety in the maritime and shipping industry. This particular training application simulates the operation of large, complex, and expensive equipment.

Figure 3.40: Picture from a PC-based simulation for maritime training (after Evans & Sutherland, 2000)

EaSIEST is a set of tools for creating virtual environments for real-time display on Evans and Sutherland's ESIG line of image generators. The name EaSIEST is an acronym, for Evans and Sutherland Interactive Environment Simulation Toolkit. EaSIEST has been used for years by many commercial and government organisations to create virtual environments for driving and flight simulation,

education applications including anatomy and new medical technique instruction and heavy equipment simulations for training in controlled environments.

Figure 3.41: Image from a commercial flight training application (after Evans & Sutherland, 2000)

Evans and Sutherland visual systems sell flight training simulators which replicate in-flight conditions that are crucial to effective pilot training. These simulators represent realistically simulating scenarios including fog, rain, and snow and pilots are able to virtually experience reality, before they ever leave the ground. An image from a commercial flight training application is shown in figure 3.41.
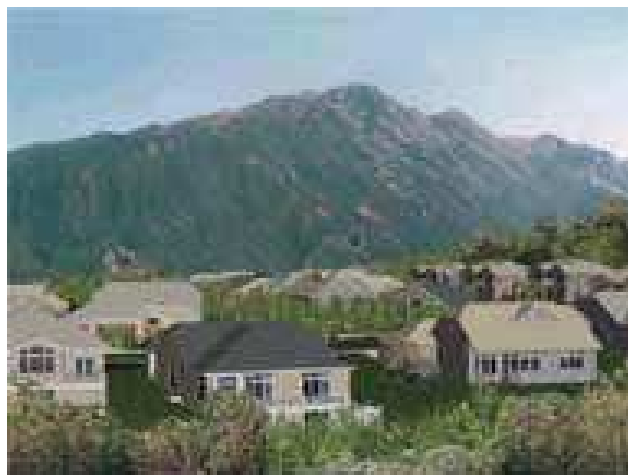
Figure 3.42: RAPIDsite Producer software (after Evans & Sutherland, 2000)

Another piece of software from Evans and Sutherland is RAPIDsite Producer, which is a synthetic environment construction and real-time rendering system. The integrator combines popular third-party tools in an easy-to-use system that

simplifies large scale graphical database creation. This software system integrates database elements from a wide variety of sources into rich three-dimensional synthetic environments. Integrator also features powerful database optimisers and scene renderers for interactive desktop rendering on Windows NT and real-time rendering on Harmony, Evans and Sutherland's newest high-performance image generator. Figure 3.42 shows a picture from a RAPIDsite software application.

3.3.5 AIMS Research Unit

The AIMS Research Unit at the University of Nottingham, in the UK, is a leading researcher into virtual reality based systems for a range of engineering industries. AIMS have taken advantage of the advances in hardware and software to research and develop a variety of graphical based systems for safety and training in a variety of industries. The unit has found that systems developed using PC technology are more easily ported into industry due to the reduced costs, the existing user base and the familiarity of PC technology (Schofield *et al*, 1994). In particular it now appears that the technologies have developed sufficiently and costs reduced to levels that mean that even the smallest companies can consider them seriously.

A number of virtual reality applications have been developed at Nottingham, these include environmental visualisation, safety awareness training systems, ergonomic design, simulation systems, driving simulators, training systems and hazard awareness systems (Schofield, 1997).

An example of an underground application created by the AIMS Research Unit is shown in figure 6.43. This system was developed for a major equipment manufacturer to assist in the introduction of new mining technology into countries which are new to such systems and train the operators in safe methods of working. A fully configurable mining simulator used to simulate underground room and pillar operations. The user can configure the number of entries and the size of the pillars, the software will then automatically create the mine layout. The user then selects which equipment is to operate within the mine layout, the system is pre-programmed with the intelligence and behaviour of the different items of equipment.
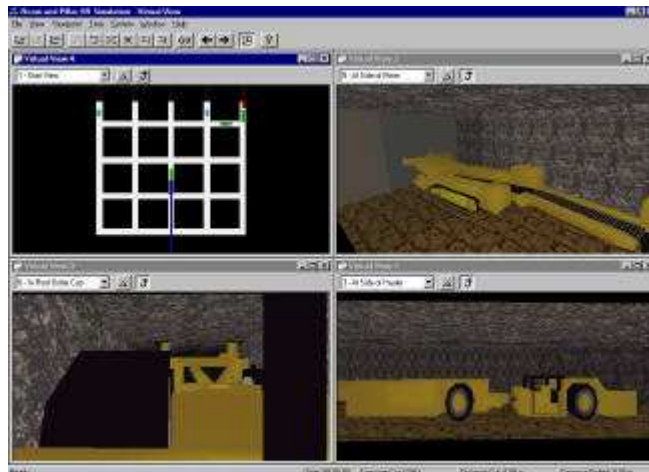
Figure 3.43: Image from a room and pillar training system (after Crawshaw *et al*, 1997)

Figure 3.43 shows a the system being used with multiple windows - the upper left window shows a map of the room and pillar operation with the locations of all the items of equipment in the mine, this map is dynamically updated. The upper right window is a floating viewpoint allowing the user to walk or travel around the mine. The lower two windows are anchored to items of equipment. The lower left window is linked to a hauler and follows the vehicle as it travels around the mine. The lower right window is an overhead view of continuous miner operation (Crawshaw *et al*, 1997).

Virtual reality technology has been investigated for application in the South African mining industry to provide improved hazard identification training for underground workers. This work was conducted as a jointly funded two years project of the Safety in Mines Research Advisory Committee (SIMRAC) and the mining technology division of CSIR. The developer of this project completed a Ph.D. in virtual reality in the AIMS Research Unit at the University of Nottingham while developing this application (Squelch, 1998).

Hazards represented in the South African stope model currently include falling rocks and moving machinery. An image from the system developed is shown in figure 3.44. Each hazard is triggered by the trainee 'walking' into its region of influence if no prior corrective action has been performed. In each case the

implication of responding incorrectly to or recognising the hazard is depicted to the trainee through sound and visual effects, which includes video clips where appropriate (Squelch, 1998). The success or failure of a trainee is recorded for each hazard during their session in the virtual world, and can be rated subsequently for evaluation purposes and future comparison.

Figure 3.44: CSIR's gold stope training system (after Squelch, 1998).

This stope model has been developed and tested with the aid of 'field' trials at gold mine training centres in South Africa. These trials have indicated an encouraging level of relevance, understanding and acceptance of the virtual reality generated mine environment among the trainee target group of underground workers. Current indications are very favourable that virtual reality technology can be successfully applied to mine safety training (Squelch, 1998).

3.3.6 SAFE-VR

AIMS have ten years experience of creating a variety of virtual reality training systems. Over this period, it became apparent that a large number of virtual reality training applications developed shared a common set of requirements:

?? Generate a three-dimensional representation of a working environment.

?? Place representations of hazardous objects or situations within the world.

?? Allow the user to find, identify and categorise any hazards present.

?? Simulate the operation and dynamics of objects and equipment within the virtual world.

?? Allow the user to carry out actions within the virtual world.

?? Tag or report any actions that result in a hazardous situation.

In order to be able to develop such applications without the advanced programming skills normally required, AIMS have developed SAFE-VR, a Graphical User Interface (GUI) application development tool. Using SAFE-VR, virtual worlds can be created and populated with hazards simply by using the mouse and a simple point and click interface.

SAFE-VR is a generalised PC-based training system that provides a graphical user interface to enable users to import CAD and other files defining the machinery or environment to which the training is related. A screenshot from SAFE-VR application tool is shown in figure 3.45. Navigation around the computer generated virtual environment can be achieved using keyboard, mouse joystick or touchscreen.
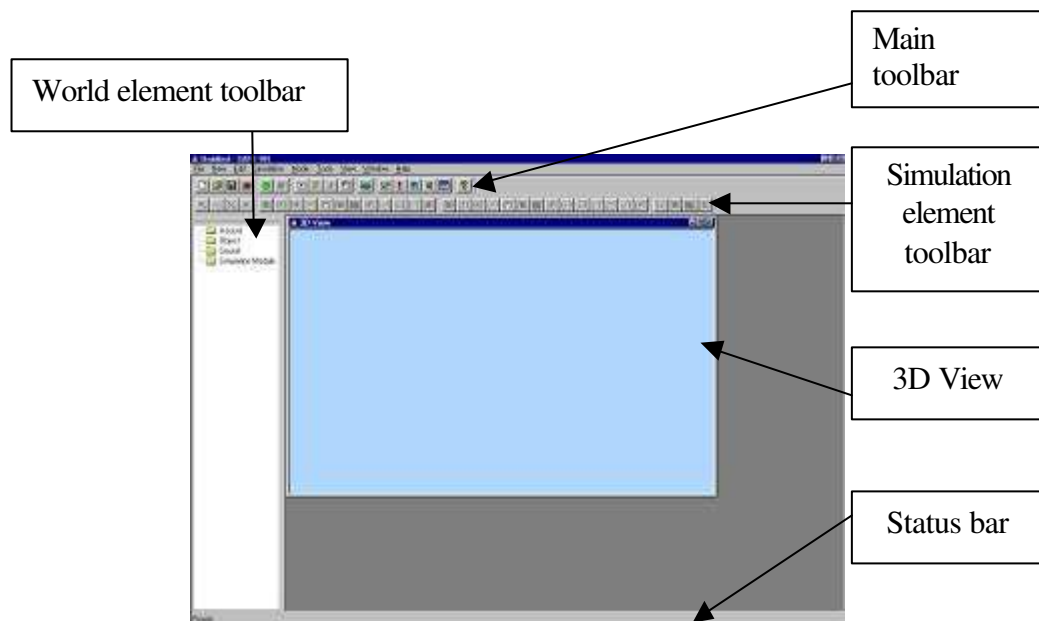
Figure 3.45: Screenshot from the SAFE-VR development tool

SAFE-VR separates the virtual world to three component types, which are hazards, objects and sounds, as shown in figure 3.46. These components can interact with each other. Objects are the three-dimensional shapes representing real world objects and can be placed at any position within the virtual world. The user is able to move throughout the world and view them from any position and orientation. Any object within the SAFE-VR world may have a number of sounds associated with it. A sound is simply a noise that would be associated with an

object within the real world, for example the diesel engine on a hauler or the electrical motor of a pump.
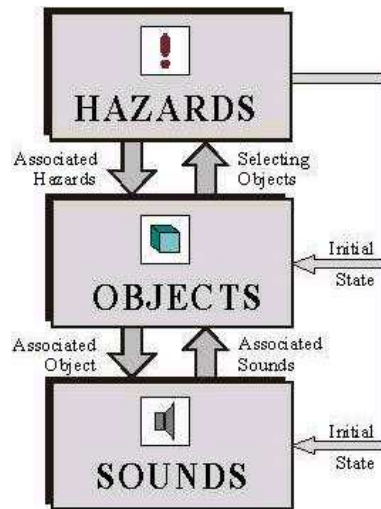
Figure 3.46: The world components of SAFE-VR (after Hollands, 1999)

The key components within a SAFE-VR world are the hazards each containing a description of an individual hazard condition. This description is divided into a series of categories appropriate for the specific application type, for example identification, consequence, probability and solution in a standard hazard assessment. The user can define for each hazard a probability of its occurring during the simulation and can assign a number of different solutions in a multi-choice response list. When the trainees spot a hazard, they must then choose the most appropriate description from a hazard identification list and the suitable solution for it, as shown in figure 3.47. All text entries can be supplied with user-defined pictures or different sound files can also be associated with the text providing spoken commendatory where language could be a problem (Hollands *et al*, 1999).

Each hazard may have additional files associated with it, providing information about a certain hazard. So, various multimedia files or other applications can be automatically activated and displayed on the screen. Figure 3.48 shows an example of a session report from a pre-shift truck inspection, showing hazard location and multimedia (Hollands *et al*, 1999).
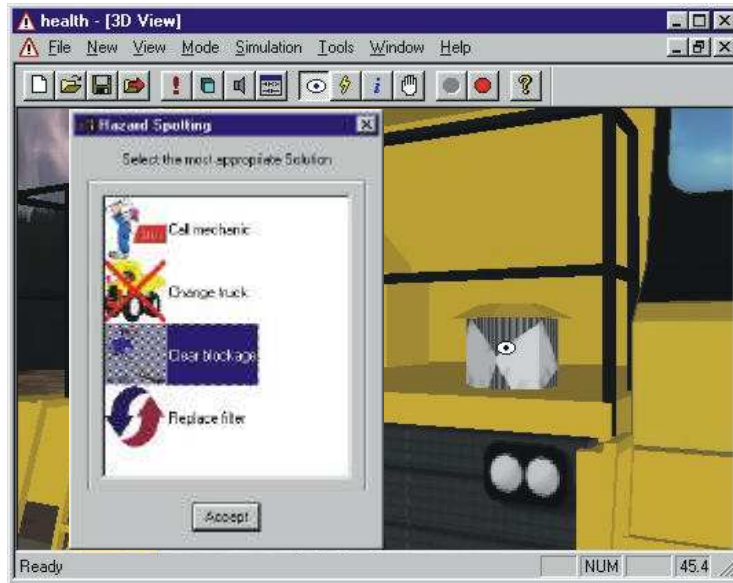
Figure 3.47: Example of a user-interface multiple choice list (after Hollands *et al*, 1999)

The standard world building tools supplied with SAFE-VR provide an effective method for creating visual simulations of the virtual worlds containing a variety of random hazards. SAFE-VR's simulation modules allow the creation and editing of complex simulations, including fault trees and procedural simulations. Each of these simulation modules contains a selection of the intuitive simulation elements combined in a simple ladder-logic combination.
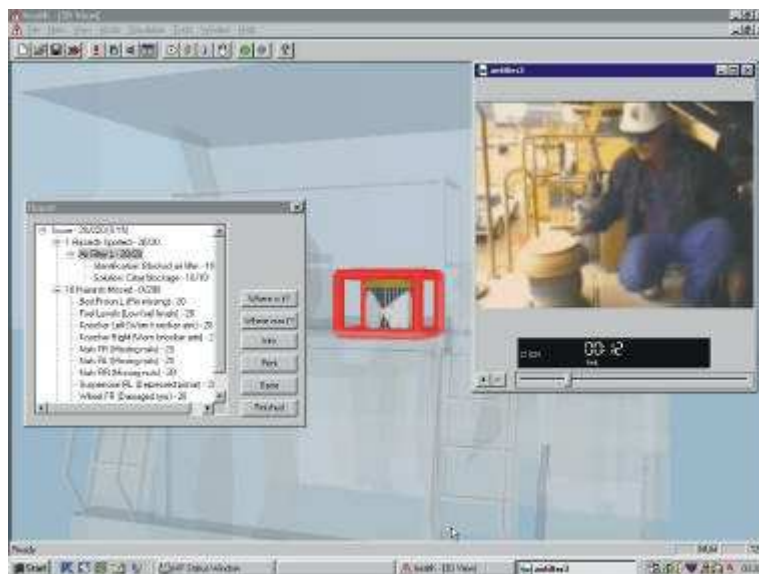
Figure 3.48: Example session report from a pre-shift truck inspection, showing hazard location and multimedia (after Hollands *et al*, 1999).

The simulation structure is based on ladder-logic, commonly found in industrial Programmable-Logic-Controllers (PLCs). In ladder-logic the simulation is made up of a series of rungs, as in a ladder. Each rung contains a series of elements representing switches and relays, as shown in figure 3.49.
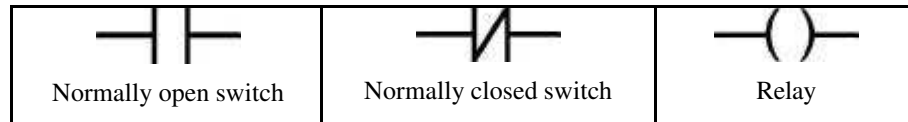
Figure 3.49: Elements, which represent switches and relays in a ladder-logic diagram (after Hollands, 1999)

The ladder can be thought of as an electrical circuit, with the left-hand as being at an active supply voltage, and the right-hand rung at ground. The supply voltage then runs from left to right along the rungs. If a switch element is on the rung, then the switch must be closed for the voltage to continue. If two paths meet, then an active voltage from either will provide an active voltage for the rest of the rung. Anywhere an active voltage reaches a relay element will activate the relay to perform some action. Figure 3.50 shows some examples of ladder logic diagrams.
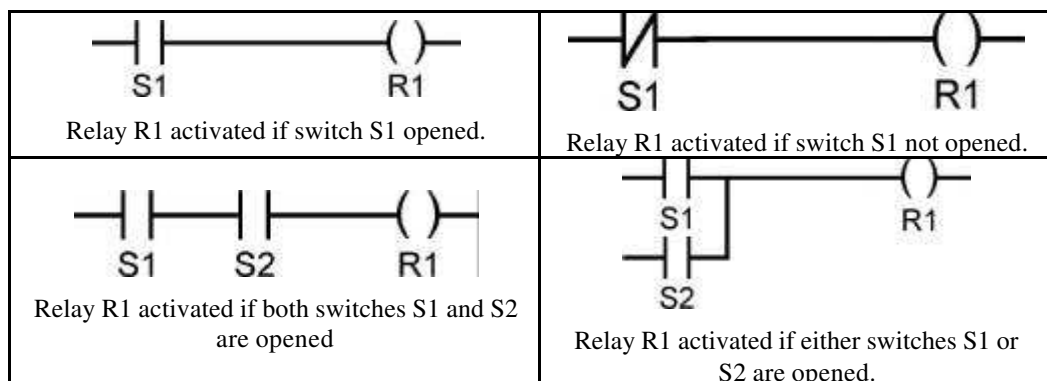
Figure 3.50: Examples of ladder-logic diagrams (after Hollands, 1999)

SAFE-VR uses the same basic approach as ladder logic, but expands it to a system that handles the wide variety of objects within the virtual world more simply. Traditional ladder logic tends to have a regimented approach to its rung structure, with a vertical rail at the left and right, rungs running in a straight line from one rail to the other, and no more than one output (relay) element to a rung (although rungs could be branched to support more output elements). SAFE-VR takes a more flexible approach to the structure. The vertical rails are disposed off,

so rungs can start and finish at any horizontal position (although they do still run from left to right). Any element which has its left side disconnected is assumed to have an active input state (as though connected to the old left-hand rail). Similarly the flow of signals stops wherever an element has its right side disconnected (as though connected to the old right-hand rail) (Hollands, 1999).

In traditional ladder logic, there tends to only be one output element per rail, and that is always located on the right hand side. In SAFE-VR, the output elements can be placed anywhere on the rail, and have any number on the same rail. Although output elements affect the world components, they are completely invisible to the simulation signal flow, similar to a permanently closed switch.

Creating dynamic simulations of real world processes, SAFE-VR contributes to the realistic representation of them. Figure 3.51 shows a very complex simulation module of a SAFE-VR application.
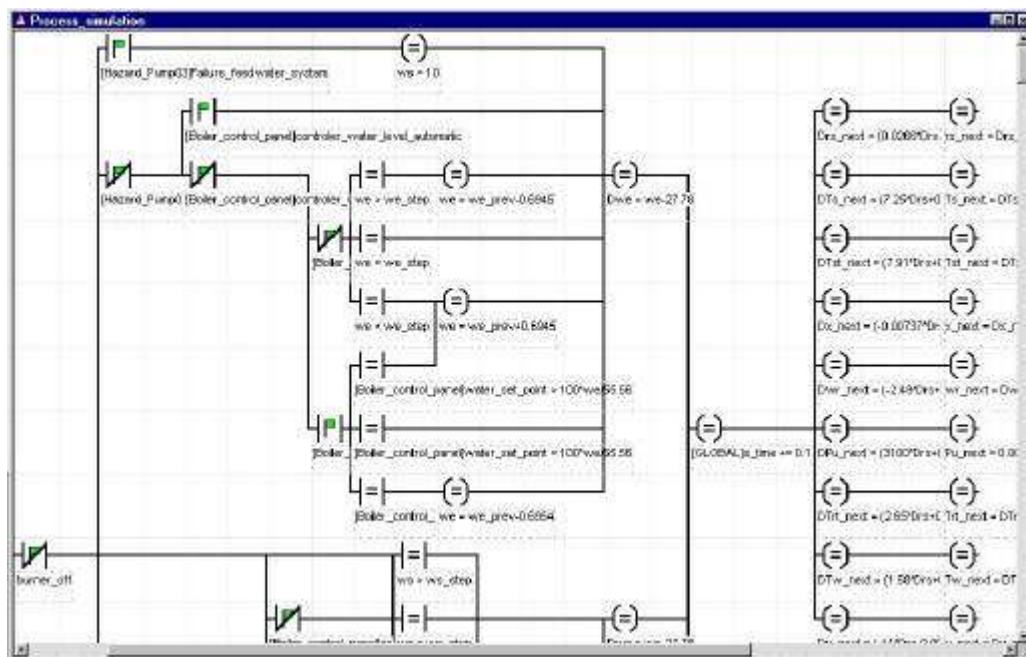
Figure 3.51: Example of SAFE-VR ladder logic simulation module

At the end of each hazard spotting session the system provides a comprehensive summary report of the training session, indicating how the total score has been calculated, where any marks have been dropped and what the best replies would

have been. The trainee is able to see a list of hazards, which were missed and have the possibility to point out their locations.

3.3.7 Virtual reality applications areas

Research and development into virtual reality applications can be found in many places, all over the world. The applications being developed in the field of virtual reality run across a wide spectrum, from games to construction and from business planning to flight simulations.

3.3.7.1 Engineering

The engineering applications using virtual reality technology include: CAD and computer aided manufacturing techniques, product design, system design, architectural design, human factor and ergonomic issues.

After the computer aided design phase of an engineering component there is often the need to build full-size or scale mock-ups of the project. Virtual reality can be used to visualise as animated objects descriptions of engineering components that have previously been viewed as lifeless drawing or static perspective projections. Virtual reality technology is able to produce a virtual engineering space where the objects can be manufactured, inspected, assembled, tested, and subjected to a range of simulations. This form of application is being considered in the concept design and evaluation of motors cars and the planning of new telecommunication services. (Vince, 1995)

The Rover group has been assessing virtual reality technology for the visualisation of new plant layouts in order to enhance communication and simulation processes. One of the facilities to be modelled consists of an existing building to be refurbished and the virtual model helps to show the proposed changes to the building and where equipment would be placed. Figure 3.52 shows one view of the virtual environment, which created by Rover group. Engine assembly and storage plant can be viewed with ancillary rooms on the right and the pallet storage area in the distance (Wilson *et al*, 1996).

Figure 3.52: View of the virtual environment created by Rover (after Wilson *et al*, 1996)

3.3.7.2 Entertainment

Most people get their first introduction to virtual environments in the form of entertainment. A number of virtual environment entertainments are available with more being announced all the time. In the field of entertainment virtual reality has applications in the areas of games, computer animation and television.

Virtual reality is a natural extension of the computer games industry's well developed usage of computer graphics. Many larger scale applications take the form of immersive simulator rides, some of which are interactive. The computer graphics link exists with computer animation where virtual reality is able to give lifelike behaviour to virtual characters by coupling a human model directly to the graphics system. The use of virtual reality in television range from real-time computer cartoons animated at transmission time by a puppeteer, to virtual sets being integrated with real sets to provide extra levels of detail in the finished product, and to training, experimentation or rehearsal with virtual sets and studios layouts (Vince, 1995).

3.3.7.3 Science

The use of computer graphics for scientific visualisation of various types of data sets is well established for interpretation in fields such as cartography, remote sensing, archaeology, molecular modelling, medicine and oceanography. Using powerful computer graphics workstations some of the images in these domains

can be rendered in real time and when a parameter is adjusted within the simulation exercise, an immediate response appears in the image. If the user is interfaced to the images through the immersive technology of virtual reality, user's actions are interpreted as three-dimensional events on a screen based display device. These techniques offer a very effective problem-solving environment and provide many benefits to scientists.

3.3.7.4 Training

Virtual reality is a powerful tool for training since people comprehend images much faster than they grasp lines of text or columns of number. Some aspects of training can be acquired in a classroom or from a book but there is no substitute for training with the real thing. It is believed that virtual reality is an excellent substitute of the real thing and many industries have produced virtual reality training simulators, which are used for planes, submarines, power plants, tanks, helicopters, ships, trains, surgery, and air traffic control. These simulators use a replica of the real operational environment and real time computer simulations to model its dynamics.

Virtual reality training through simulation provides significant benefits over other methods because the simulators allow the trainees to make mistakes having the opportunity to experience first hand why certain procedures must not be used in the real world. Virtual reality training systems have also the flexibility to structure different training scenarios and they can monitor and measure the progress of every training session.

The electronic equipment manufacturer Motorola uses virtual reality for training its employees on new productions and assembly lines in order to avoid the expense of shutting down actual production facilities. Figure 3.53 shows a screenshot from one robotic work cell from the Motorola virtual reality model of the assembly line. The virtual environment created included a conveyor system, robotic work cells for assembling pagers, a machine vision inspection system and a laser marking system for etching identification numbers on each product (Wilson *et al*, 1996).

Figure 3.53: Screenshot from Motorola virtual reality model (after Wilson *et al*, 1996)

3.3.7.4.1 Aircraft and vehicle training

This category of virtual reality application is concerned with creating a virtual environment that replicates all or some of the features involved in the operation of a vehicle or an aircraft. The real control components can be integrated with the virtual environment giving a realistic training experience. Pilots or drivers can experience the virtual reality simulation training systems without causing any harm to the vehicle or aircraft and to themselves (Carr, 1992).

Virtual environments have played a significant role in flight training over the past two decades and they will continue to do so in the future because their use has demonstrated significant advantages over physical scale systems. The flight simulator is one of the earliest implementations of virtual reality technology. These simulators generate a highly realistic virtual environment so that pilots trained on them may be capable of fling the real aircraft at the first attempt. Using flight simulators pilots can be trained for new types of aircrafts and they can practice flying under emergency conditions without involving a real aeroplane or airport (Vince, 1995 and Iovine, 1995).

At the Defence Helicopter Flying School (DHFS) at Shawbury, operators use virtual reality flight simulators to train United Kingdom Royal Air Force pilots. These virtual reality training systems replicate in-flight conditions that are crucial to effective pilot training and realistically simulating scenarios including fog, rain,

and snow, pilots are able to virtually experience reality, before they ever leave the ground (FBS Ltd, 2001). A screenshot from such a flight simulator is shown in figure 3.54.

Figure 3.54: Screenshot from a flight simulator (after FBS Ltd, 2001)

3.3.7.4.2 Medical training

Medicine has become a computer integrated high technology industry. Virtual reality and telepresence may have much to offer with its human computer interfaces, three-dimensional visualisation and modelling tools. Advanced three-dimensional modelling tools can be used to develop useful models of the human body and in the design of artificial organs. Medical professionals can use virtual reality to study the body by navigating in and around it. Telepresence techniques could allow surgeons to conduct robotic surgery from anywhere in the world offering increased accessibility to specialists. Prototypes have been tested that let the surgeons experience all the sensory feedback and motor control that would be felt in person (Dutton, 1992 and Nilan, 1993). The development of virtual reality training simulators can help surgeons to practice without harming animals or humans.

The Human Interface Technology Laboratory (HITL) at the University of Washington has developed human controlled robot manipulators, which can provide numerous advantages in performing surgical tasks, especially in microsurgery and minimally invasive surgical procedures. Virtual interface technology combined with robotic manipulators can potentially re-map this

relationship between the surgeon and patient, and thereby provide additional degrees of freedom to the surgeons' movements and senses, and close the gap between inside and outside, large and small (HITLab, 2001). Figure 4.55 shows screenshots from this virtual reality application.
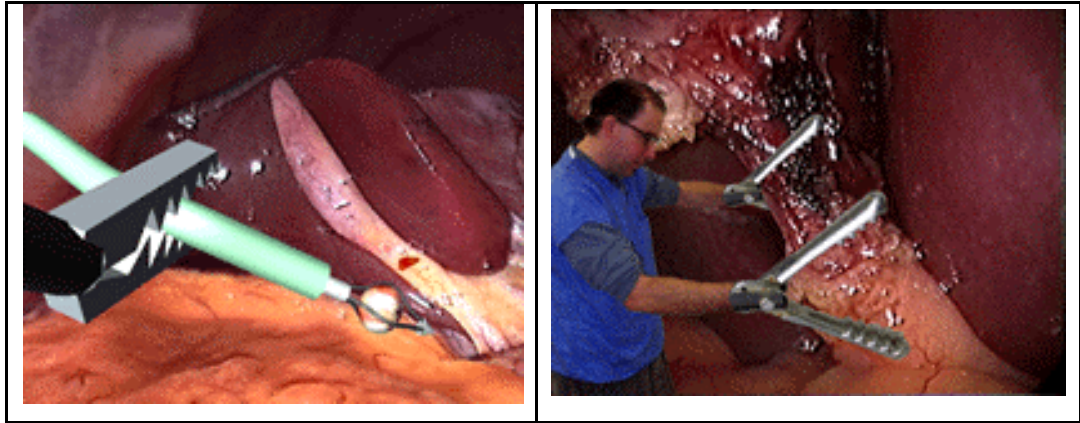
Figure 4.55: Virtual prototyping of medical robotic interfaces

(after HITLab, 2001)

3.3.7.4.3 Military training

One of the first areas where virtual reality found practical application is in military training and operations. One of the earliest uses of simulators in a military environment was the flight trainer built by the Link Company in the late 1920's and 1930's. These trainers looked like sawed-off coffins mounted on a pedestal, and were used to teach instrument flying. The darkness inside the trainer cockpit, the realistic readings on the instrument panel, and the motion of the trainer on the pedestal combined to produce a sensation similar to actually flying on instruments at night. The Link trainers were very effective tools for their intended purpose, teaching thousands of pilots the night flying skills they needed before and during World War II. In a dynamic combat environment, it is imperative to supply the pilot or tank commander with as much of the necessary information as possible while reducing the amount of distracting information (Baumann, 2000).

Virtual reality techniques are being explored to evaluate how today's soldiers can master new weapons and tactical procedures without the support of the physical environment. It is hoped that the virtual environment will be able to offer all the

realism associated with the real world without the obvious drawbacks of cost, organisation, weather, time of the day and so on. The virtual domain is repeatable, interactive, three-dimensional, accurate, reconfigurable and networkable and provides an excellent medium for military training.

The Evans and Sutherland company has produced a range of computer based virtual reality systems for military planning and mission simulating. These virtual reality training applications can train personnel for security planning and scenario analysis, urban planning and law enforcement training. Figure 3.56 shows an image from a virtual reality training system used for military applications.

Figure 3.56: Virtual reality training for military applications (after, Evans and Sutherland, 2000)

3.3.7.5 SAFE-VR applications

The Aims Research Unit has developed a great number of hazard spotting training applications using the SAFE-VR application tool. Figure 3.57 shows an image from a hazard spotting system involving a surface mine haulage truck. This world consists of a simple truck with around twenty-five hazards, which associated, with different components of the truck. The system makes use of samples from existing training videos to explain the repercussions of missing any hazards. Whilst missing securing pins may cause the entire load bed to drop from the truck, litter around the air intake could cause the vehicle to stall, either causing the driver to lose control, or to be stuck at a particularly dangerous point on the haul road (Hollands *et al*, 1999).

Figure 3.57: Pre-shift truck inspection

AIMS have also created an underground roof support application using SAFE-VR as shown in figure 3.58. This application allows the user to perform an inspection of a section of roadway in an underground coal environment. The trainee is expected to spot a range of hazards such as badly installed roof bolts, unsupported areas, water seepage and to identify deviations from the mines support regulations in both the roadway and at junctions.
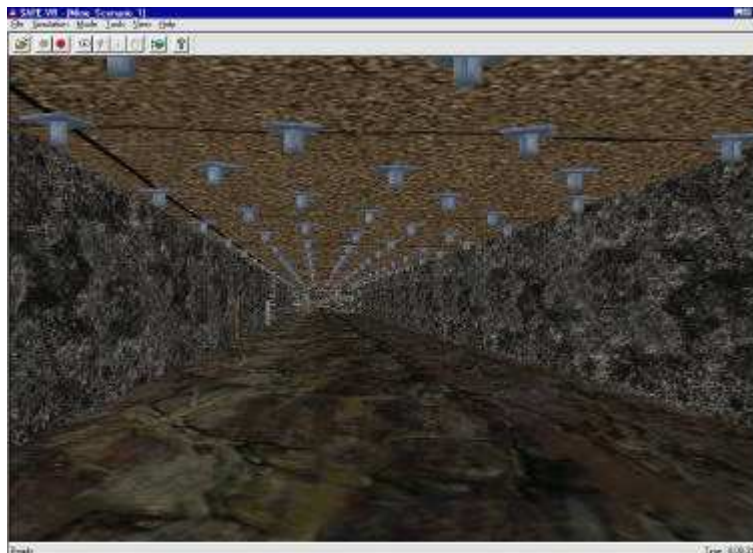
Figure 3.58: Roof bolting inspection system

Figure 3.59 shows a shot from a SAFE-VR simulation of a Universal MkII 650 Drill Rig. These rigs can be complex to operate and extremely hazardous if

handled incorrectly. This simulation combines hazard spotting with an operational simulation of the rig. This allows trainees to familiarise themselves with control locations and functions before being allowed on real equipment. In addition, the trainees may operate the controls to take a rig through a standard drilling procedure. Where controls are operated in the wrong sequence, the simulation will log the errors and inform the user. Similarly, should the user forget any safety related procedures, such as applying locking bars, the omission will be logged and the trainee's score penalised.

Figure 3.59: Screenshot from a virtual drilling rig operation

Figure 3.60: Oil rig model

Figure 3.60 shows the interior of an oil rig production module built as a SAFE-VR environment by AIMS Research. The computer model was loosely based on information from the Piper Alpha platform, which was located 110 miles northeast of Aberdeen. Unfortunately the platform was destroyed by an explosion in July 1988, claiming the lives of 165 of the 226 persons on board. This accident demonstrated, very well, the dangers associated with an offshore oil environment and the need for improving training procedures (Hollands *et al*, 1999).

The user can control the operation of the main oil line pumps. Within the production module, there are four main oil line pumps. These are positive displacement pumps and contain no safety interlocking, so the correct procedure is required to start up and shut down these crucial items of equipment. The user is also able to 'launch a pig', pigs are also known as scrapers, or spheres. A pig is defined as "a device that moves through the inside of a pipeline for the purpose of cleaning, dimensioning, or inspecting". In the virtual environment the user is required to vent the pig launcher, open the door and insert the pig, close the door, pressurise the launcher and release the pig into the main oil pipe line. A number of hazards are associated with this task including incorrect operation of valves (denoted by lights on the control panel), oil leakage from the launcher and damaged pigs (Hollands *et al*, 1999).

3.4 Limitations of virtual reality training applications

There has been considerable speculation and enthusiasm among would-be users regarding the potential of virtual reality technology, much of it more wishful thinking than actual applications. The popular media typically make exaggerated claims about the current state of the technology. A more responsible view is that, whereas virtual reality has considerable potential for many applications in industry and commerce, it is neither appropriate nor desirable in all cases (Wilson, 1997).

Because of its many advantages, virtual reality seems to be an ideal training medium. However, inherent to virtual reality training and education is the assumption that the training that takes place within a virtual environment transfers to the real world. Most reports regarding transfer are anecdotal and there has been

insufficient effort expended toward demonstrating under what conditions transfer takes place, if at all (Rose *et al*, 1998).

Among the studies that have attempted to examine transfer from computer-generated to real environments, many have focused on flight simulation which, until recently, has been the best known and most sophisticated commercial application of computer-simulated training. In general, simulator training leads to better flight performance, but this depends on the type of task. In terms of spatial learning and navigational rehearsal, for example, Wickens and Baker (1995) concluded that greater realism in navigational rehearsal flights did not lead to better performance in a transfer environment. Thus, if a helicopter pilot rehearsing a dangerous rescue mission wants to learn the specific features of the approaching ground terrain and the rescue site, simply studying a two-dimensional map can lead to retention and performance that is as good or superior to training in a virtual environment. It may be that the mental effort allocated towards other aspects of on-line performance takes away from the mental effort that is directed solely toward navigational learning (Wickens and Baker, 1995).

The findings from flight simulation research have also been demonstrated in more general studies of spatial learning. Wickens and Baker (1995) examined how well people understood the shape of a complex three-dimensional surface. Previous experience with a highly realistic presentation (3-D, stereo) of aspects of the surface was better than a less realistic presentation (2-D, mono) at helping subjects answer questions about it as they were viewing it. However, it did not help much for later memory and understanding of the surface shape. Furthermore, the addition of stereo to the three-dimensional perspective view had no added benefit to later understanding. A more recent study found that passive, monocular viewing of a complex layout of objects from a single vantage point led to greater ability to reproduce the array than active, binocular exploration of a virtual replica (Arthur *et al*, 1997). Again, these studies demonstrate that virtual reality visualisation is not always an advantage.

Virtual reality is considered a valuable tool for rehearsing critical actions, in preparation for performance in the real world. It is therefore advocated for

training individuals to perform tasks in dangerous situations and under hostile environments, such as in chemical plants. However, rehearsal in a dangerous situation may have unwanted consequences. The user, who makes mistakes and only experiences safe, simulated consequences, could become desensitised to, and less fearful of dangerous scenarios. This lessening of anxiety can be an important asset in enabling workers to maintain their cool under duress, but it may also lead to a loss of respect for a real-life danger, particularly where the hazard is experienced in a game format. Similarly, if occupational health and safety efforts present a virtual representation as accurate when, in fact, the simulation is not credible, the participant could leave the experience with the impression that the hazard event is really not of much concern (Mitchell, 1997).

3.5 Summary

Virtual reality aims to provide a three-dimensional computer generated representation of a real or imaginary world with which the user can have real time interaction and experience some feeling of being present in that world. Computer graphics and virtual reality technology is currently well developed and can be cost effective even for small organisations or companies which are considering their use. The flexibility of virtual reality based training systems makes them so competitive and valuable that the majority of them can be configured quickly and produced relatively cheaply.

Virtual reality based simulator systems will form an increasingly important element of the training systems of the future. The ability to simulate complex chemical engineering processes in real time allows the trainee to have experience of an environment that changes over time. Using computer models of real equipment is risk free and allows endless experimentation without ever taking the real equipment off line and risking production. Allowing users to learn within computer generated environments provides the opportunity for them to make mistakes and suffer the consequences without necessarily putting themselves at risk.

Virtual reality is neither not appropriate for all users nor for all situations. While virtual reality appears to have significant potential in some cases, it is clear that it

must accomplish a particular objective in a substantially better way than traditional techniques. Virtual reality may save staff time and money and be a superior way to train staff as compared to accomplishing a goal by more traditional approaches. However, if the skills do not transfer to the real world and if users get bogged down in technical difficulties or poor simulation, then virtual reality may fail to live up to its promise.

The following chapters present a variety of chemical engineering based virtual worlds. The majority of these virtual worlds focus primarily on simulating chemical processes, which corresponds to the real world processes, and secondly on presenting hazards and emergency situations that arises due to mechanical and operational errors.

Chapter 4

Initial virtual reality training systems

4.1 Introduction

This chapter details the development of a pump training system, a virtual reality training environment to train personnel to operate two centrifugal pumps. It was built using the SAFE-VR development environment. It describes the chosen model layout, its component objects and its functionality. This chapter also, presents a virtual reality hazard spotting exercise that is based on a multimedia training package, which is offered commercially by the Institution of Chemical Engineers (ICHEME). Using advanced computer graphics, virtual reality and computer animated human figures, the original was converted from two-dimensional multimedia hazard spotting exercise into a three-dimensional computer generated environment. This chapter details the construction of these virtual environments, their hazards and explains their functionality.

4.2 Pump training system

To improve the reliability of pumps, it is often necessary to improve the reliability of the people who run them. That means developing a generation of operators who understand the operational procedures of starting up and shutting down of machinery. Well-trained operators can run equipment reliably and can spot trouble and hazards before they grow to catastrophic proportions (Parris and Camerom, 1999).

This particular project involved a solid dryer procedure that dried wet materials utilising a superheated solvent, which is being evaporated as the fluidising and the heat transfer medium. After reaching equilibrium, the scrubber condenser removes an amount of solvent from the wet material and the remainder is recycled through the heater and to the dryer. The flow sheet of the chemical process is shown in figure 4.1.
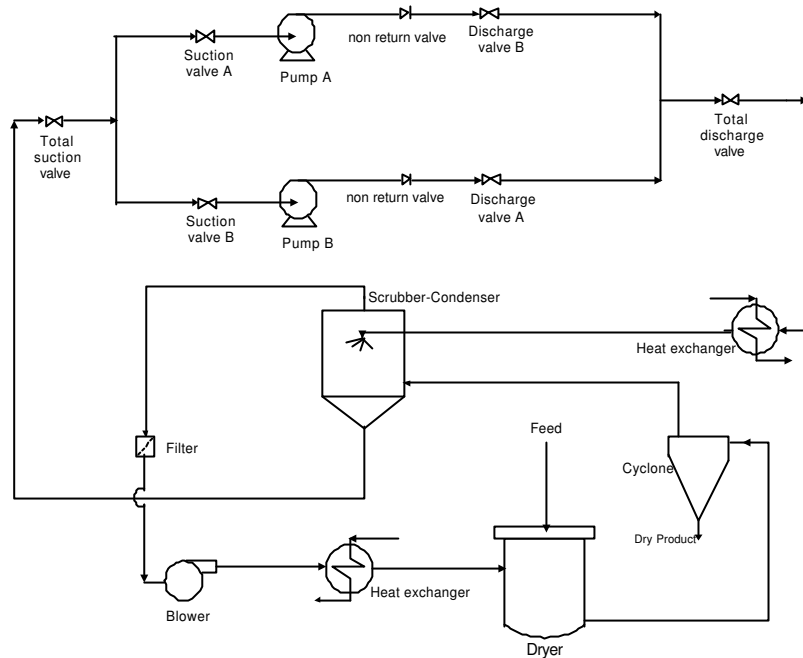
Figure 4.1: The flow sheet of the chemical procedure

The simulation system is focused on the operation of two centrifugal pumps, which are connected in parallel, and recycle the solvent to a scrubber-condenser.

4.2.1 Pump basics

A pump is a machine that expends energy to increase the pressure of a fluid and move it from one point to another. There are various classifications of pumps but one main classification is according to the method that energy is imparted to the liquid. As a result, pumps are classified into two general categories: kinetic energy or centrifugal pumps and displacement pumps. (Perry *et al*, 1984)

Centrifugal pumps accomplish the generation of pressure by the conversion of velocity head into static head. Centrifugal pumps are devices, which convert driver energy to kinetic energy in a fluid by accelerating it to the outer rim of a revolving device known as an impeller. The amount of kinetic energy given to the liquid corresponds to velocity at the edge of the impeller. The faster the impeller revolves or the bigger the impeller is, then the higher will be the velocity of the liquid at the edge of the impeller and the greater the energy imparted to the liquid.

A displacement pump has an expanding cavity on the suction side of the pump and a decreasing cavity on the discharge side. Liquid is allowed to flow into the pump as the cavity on the suction side expands and the liquid is forced out of the discharge as the cavity collapses.

4.2.2 Development of virtual reality pump training system

The construction of the objects used to build the virtual chemical environment are discussed and described in this section. Using a number of modelling techniques, all the objects to be used in the virtual world will be first created by using 3D Studio Max. Adobe's Photoshop software was used to manipulate and design the textures, which were applied to objects. GAMUT-DXm software from Animetix Technologies, is a set of plug-ins applications for 3D Studio Max. This was needed to convert the three-dimensional objects into *.x or *.agt formats, to be imported into the SAFE-VR development system with all their textures intact. The flowsheet in figure 4.2 shows the procedure, which was used for the creation of the virtual objects.
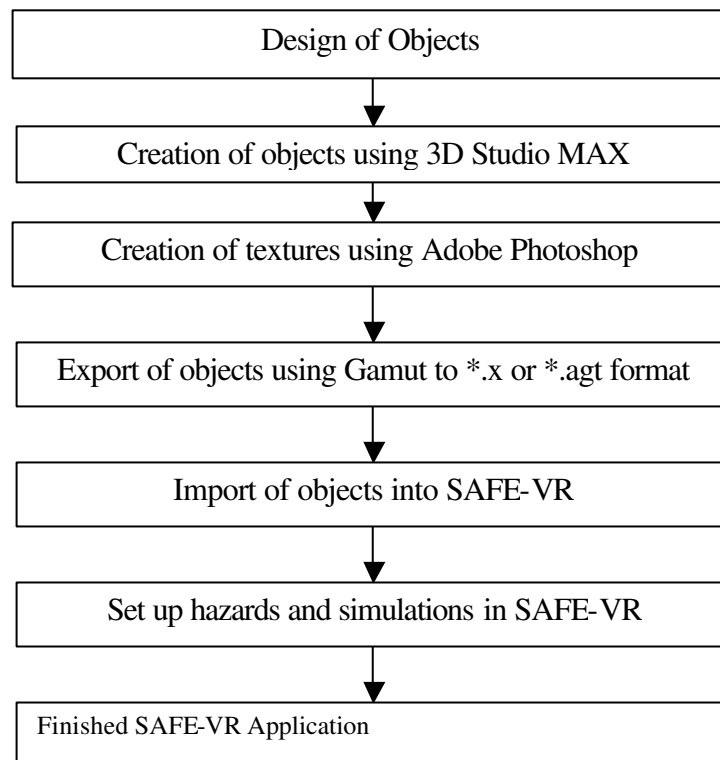
Figure 4.2: Flow chart showing the procedure for the creation of virtual object

It was recognised that, in building a viable virtual environment, care needed to be taken to keep the total number of polygons used to a minimum, as this has an impact on the rendering speed of each frame. Objects therefore, needed to be constructed as simply as possible with the minimum number of polygons and yet be easily recognised. Where appropriate, judicious use was made of textures to increase the apparent level of detail and elsewhere the correct choice of plain colours was utilised.

To strike a balance between a sufficiently detailed virtual environment and a reasonable operating speed, some decisions and compromises have had to be made. A model geometry representing a portion of a typical chemical plant environment was finally decided upon as being a reasonable self-contained unit of manageable size and providing sufficient scope for a walk-through environment containing typical chemical engineering equipment.

4.2.2.1 Centrifugal pump

The two main components of a centrifugal pump are the impeller and the volute as shown in figure 4.3. The impeller produces liquid velocity and the volute forces the liquid to discharge from the pump converting velocity to pressure. This is accomplished by offsetting the impeller in the volute and by maintaining a close clearance between the impeller and the volute at the circular casing. A centrifugal pump impeller forces the liquid out of the volute (Cook and Cullen, 1980).
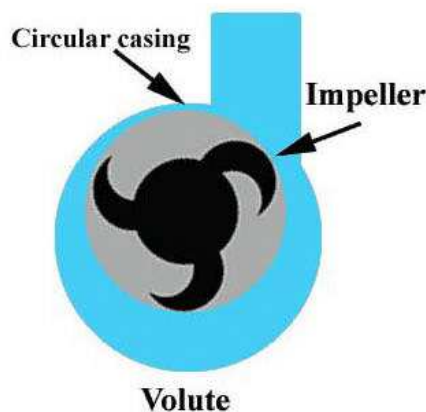
Figure 4.3: The main components of a centrifugal pump (after Cook and Cullen, 1980)

The primary advantages of a centrifugal pump are simplicity, low cost, small floor space, low maintenance expense, quiet operation and adaptability for use with a motor or a turbine drive.

The three-dimensional computer model of the centrifugal pump is shown in figure 4.4 and was constructed using 3D Studio Max. It contained 418 polygons and the three textures used are presented in figure 4.5. Figure 4.4 shows that the pump is placed on a common concrete plinth with starter support.
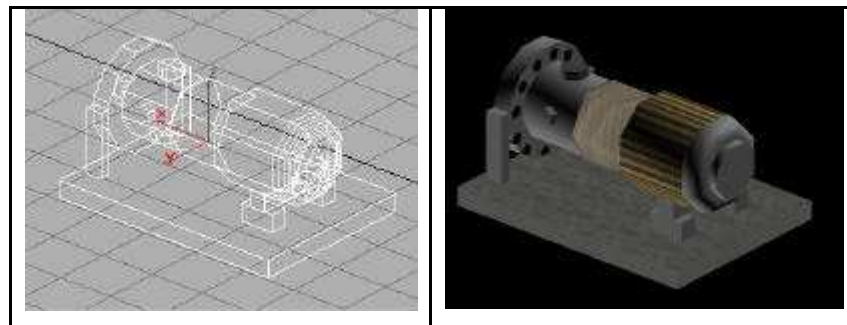
Figure 4.4: Wireframe and rendered representation of the pump object
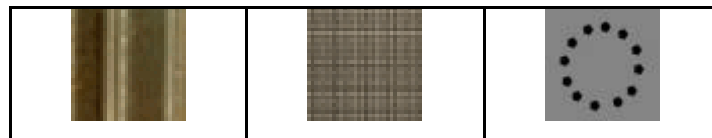
Figure 4.5: Textures used in pump object construction

The control panel of each pump is placed in front of them, each has a start button, a stop button and an ammeter, which indicates the power of the pump motor. The four different texture maps, which are used for the buttons, and the image applied in the ammeter's object are shown in figure 4.6. A three-dimensional animated object for the ammeter's pointer was built in 3D Studio Max. A perspective view of pump's control panel, which was extracted from the three-dimension model is presented in figure 4.7.
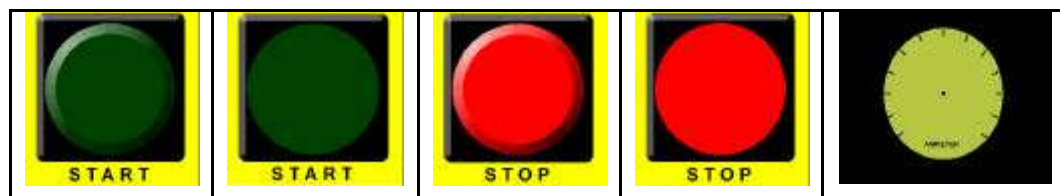
Figure 4.6: Textures used for the pump's control panel
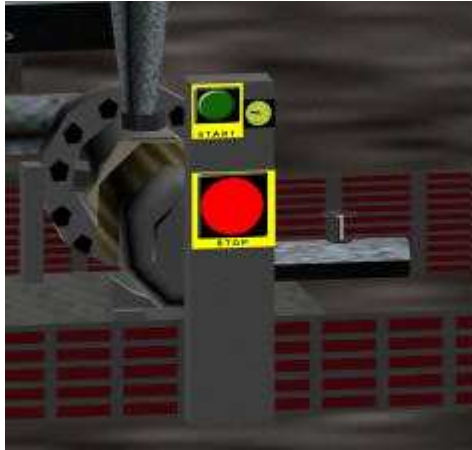
Figure 4.7: Perspective view of pump's control panel

4.2.2.2 Pipes and pipe stands

Most of the pipes were made of six sided cylinders objects in 3D Studio Max. In order to make them more realistic a smoothing modifier was used and a texture depicting smokiness and dirtiness was applied to them. Figure 4.8 shows a screen shot of the pipelines as shown in the perspective view port of 3D Studio Max.
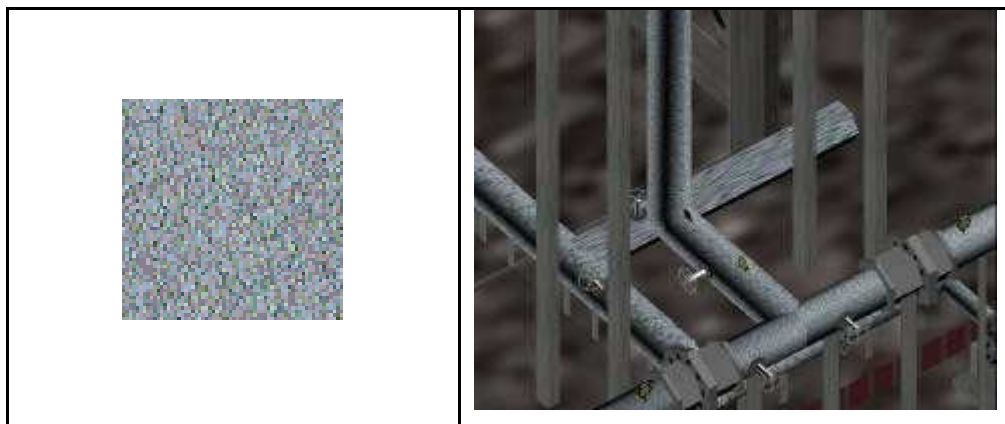
Figure 4.8: Pipe's screen shot from 3D Studio Max

Instead of building a large number of objects that represent the columns holding the pipes within the virtual chemical environment, it was considered good practice to design the pipe stands using a simple texture mapping and make the black colour transparent. This meant that the total number of polygons used for the stands was extremely low. An example of the texture map, which was applied to the simple box objects, is shown in figure 4.9.
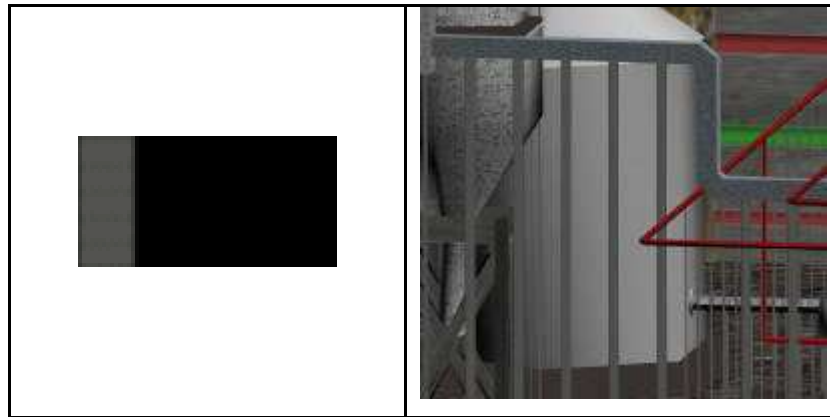
Figure 4.9: Pipe stand texture

4.2.2.3 Valves

A three-dimensional valve object constructed in 3D Studio Max contained too many polygons to be practical. To alleviate this problem, a texture image was created and applied on the top and the bottom of a simple box object with the black colour again set as transparent. The image, which was used, is shown in figure 4.10. The three-dimensional object that represents the valve now contains a small number of polygons. There are eight valves in this three-dimensional chemical environment.
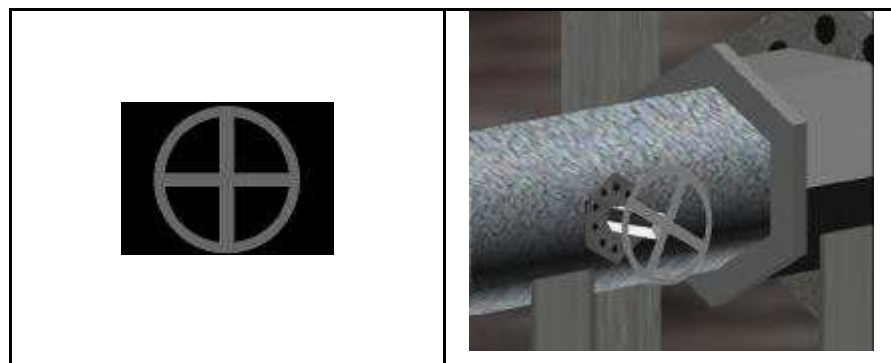
Figure 4.10: The texture for the valve object and a perspective view
of discharge valve A

4.2.2.4 Pressure and flow meters

The construction of digital measurement equipment was considered too complicated and extremely difficult for this type of virtual environment and the available virtual reality engine. The necessity of keeping the number of polygons as low as possible led to the design of simple measurement equipment for the flow and pressure. So, a six-sided cylinder object with an arrow shape object on its

plate was designed to represent flow and pressure meters. The texture, which was used, is shown in figure 4.11.
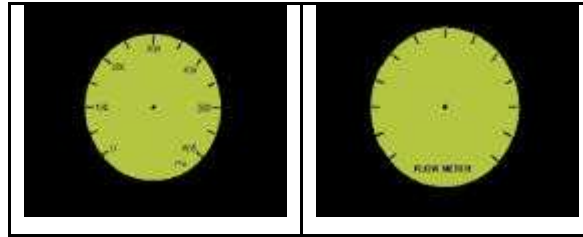
Figure 4.11: The textures used for flow and pressure meter construction

Figure 4.12 shows a screen shot of the pressure meter, which is placed on the discharge pipeline of pump A. The pointer on the pressure meter's faceplate indicates the value of the pipeline pressure.
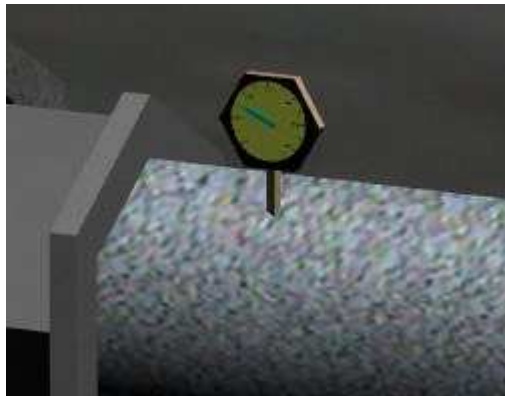
Figure 4.12: Perspective view of a pressure meter

4.2.2.5 Heat exchanger

Heat exchangers are commonly used in a variety of plant processes to transfer energy from one fluid or gas to another without mixing the two substances. There are two main types of heat exchangers: shell-and-tube exchangers and plate-type exchangers. Shell and tube exchangers were used in the current project, because are the most common type found in industry and they consist of round tubes mounted in cylindrical shells.
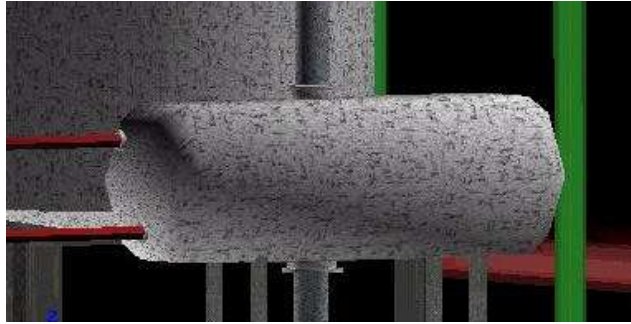
Figure 4.13: The heat exchanger object

The three-dimensional object of the heat exchanger constructed using 3D Studio Max, is shown in figure 4.13.

4.2.2.6 Cyclone separator

Cyclone separators are widely used to separate solid particles from both gas streams and liquid streams. The equipment is a settling chamber in the form of a vertical cylinder, so arranged that the particle laden air spirals round the cylinder to create centrifugal forces which throw the particles to the outside walls (Hutter, 1997). A schematic representation of a cyclone is shown in figure 4.14.
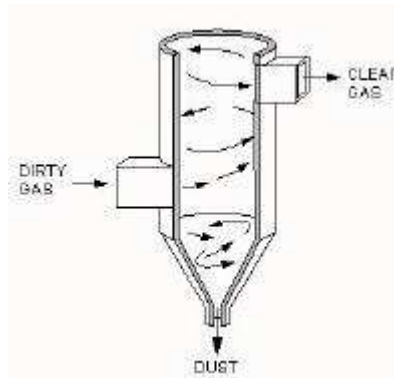
Figure 4.14: Cyclone separator schematic representation (after Hutter, 1997)

A cylinder object was constructed using 3D Studio Max software for the cyclone separator. By applying various modifiers to the initial cylinder object and a texture map, which is shown in the following figure, it was made to look more realistic. The images in figure 4.15 show a perspective view of the cyclone separator object and the texture image that was used for mapping.
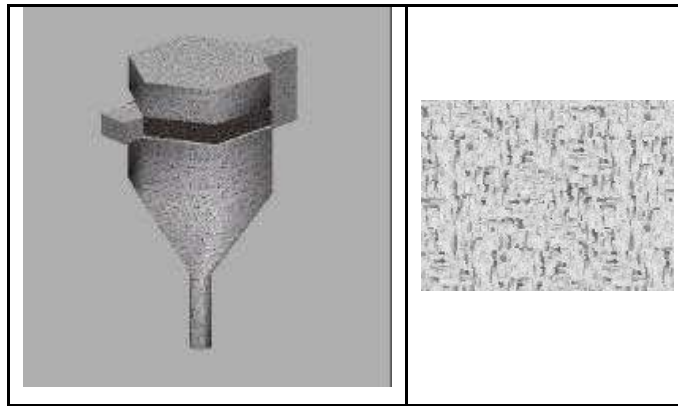
Figure 4.15: Perspective view of cyclone separator and the texture

map, which was used

4.2.3 The virtual reality pump training system

The converted *.agt files from 3D Studio Max were imported in the SAFE-VR software in order to develop the computer-generated environment of the chemical plant. Figure 4.16 shows a general view of the virtual chemical plant environment developed using SAFE-VR.
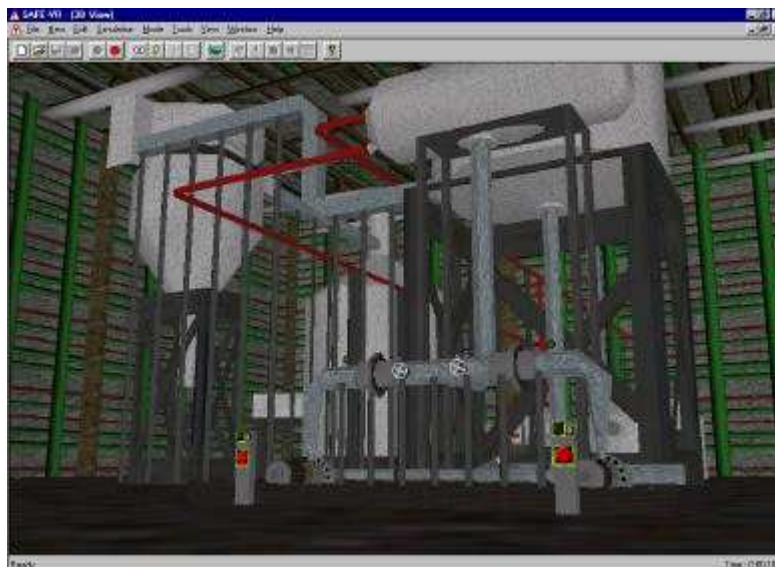
Figure 4.16: General view of the virtual chemical plant environment

in SAFE-VR

To control the operation of the pumps the trainees must move around the plant opening and closing valves, checking pressures in discharge pipelines and pressing buttons on the control panels. Some of the valves open and close in stages, so the trainees should decide how far to open or close each particular

valve. Flow meters and pressure meters are placed around the plant. The users should watch the values of these instruments and if something goes wrong, they should be able to open or close the appropriate valves in order to avoid hazardous situations in the plant.

4.2.3.1 Running the virtual pump training model

Primarily the trainees fed immersed within the virtual environment because they are placed in a chemical plant environment among pumps, heat exchangers, scaffolding and pipe work. They are able to walk around the equipment and can practice how to open / close valves and start or shut down the pumps. Some valves are open or closed in stages, and the user must decide how far to open or close each particular valve. The reading of flow meters, pressure meters and ammeters that are placed around the plant are very important for the proper operation of the training scenario. The user has to watch the values of pressure and flow in order to avoid any hazardous situation occurring in the plant.

Hotkey	Position
Key 1	Total suction valve position
Key 2	Suction valve A position
Key 3	Control panel of pump A position
Key 4	Suction valve B position
Key 5	Control panel of pump B position
Key 6	Position of the escape valve
Key 7	Position of drains for pump A
Key 8	Position of drains for pump B
Key F1	Position of pressure meter on the discharge line of pump A
Key F2	Position of the flow meter on the total discharge line
Key F3	Position of pressure meter on the discharge line of pump B
Key F4	Position of the pressure meter on the total discharge line

Table 4.1: Navigation hotkeys for the pump training system

To move around in the three-dimensional environment, a joystick, a keyboard's cursor keys, or the mouse can be used. In order to make the navigation easier for

the user, default hotkeys have been defined which move the user to certain points within the virtual chemical plant environment. Table 4.1 summarises the keys on the keyboard, which be used to help navigation around the virtual environment.

Three valves open and close in stages within the virtual world and some keys have been defined in order to operate them. When each valve comes to its fully open position a message box appears and informs the user, as figure 4.17 shows.

Figure 4.17: Message box for the valve mode.

The table 4.2 summarises the hotkeys for each valve's operation.

Hotkey	Operation
Key Q	Open, step by step, the discharge valve A
Key A	Close, step by step, the discharge valve A
Key W	Open, step by step, the discharge valve B
Key S	Close, step by step, the discharge valve B
Key E	Open, step by step, the total discharge valve
Key D	Close, step by step, the total discharge valve

Table 4.2: Hotkey description for valve's operation

The following sections emphasises the necessary steps that the trainees should follow in order to start up both centrifugal pumps.

4.2.3.1.1 Pump A operation

The steps necessary in the starting procedure of a centrifugal pump depend on its type and the service for which it was installed. High and medium head pumps should be started against a closed discharge valve to reduce the starting load on the driver. The starting procedure that should be followed, is presented in the following steps:

?? Move to the total suction valve and open it.

?? Move to suction valve A and open it.

?? Move to the control panel of pump A and press the start button.

?? Slowly open discharge valve A. Both pressure meter A and the total pressure meter should have the same value.

?? Pressing key E slowly opens the total discharge valve. By travelling to the flow meter the user should see that the flow should start to increase.
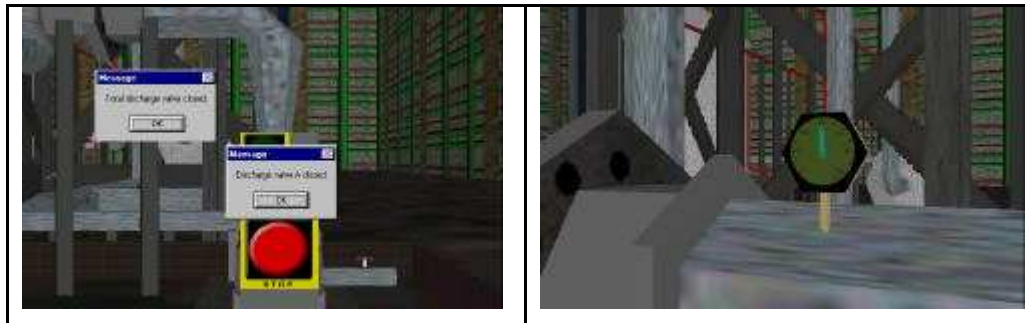
Figure 4.18: Message boxes from the pump training system – The pressure meter indicates that the discharge line is pressurised.

When the users press the start button of the pump's control panel two message boxes appear sequentially, which inform them that all the valves of the discharge pipeline are closed. Having pressed the start button, the pump's motor is running, and the ammeter on the control panel takes its initial value. The users can hear the noise of the motor and they can watch the pressure meter reading in the discharge pipeline, which indicates that the pipeline is pressurised, as shown in figure 4.18. By slowly opening the valve that is placed next to pressure meter, the value of pressure is decreased to its final value at the fully open mode of the discharge valve. If the users try to start up the pump without following the suitable operational procedure the pump training system responds with warning message

boxes, which help them to identify what was going wrong. None of the pumps will start running against a closed suction line.

If the trainees move to the total discharge valve and try to open it, they are going to realise that the flow meter reading is changing. The flow rate of the fluid is proportional to the valve's position.

4.2.3.1.2 Pump B operation while pump A is running

The necessary steps that should be followed in starting the auxiliary centrifugal pump (pump B) are:

?? Move to suction valve B and open it.

?? Move to the control panel of pump B and press the start button. Two pumps are now running in parallel. A message box appears indicating that the valve of the discharge line of pump B is closed, as is shown in figure 4.19.

?? Open slowly discharge valve B. When this valve reaches its fully open position a message box launches as shown in figure 4.20.
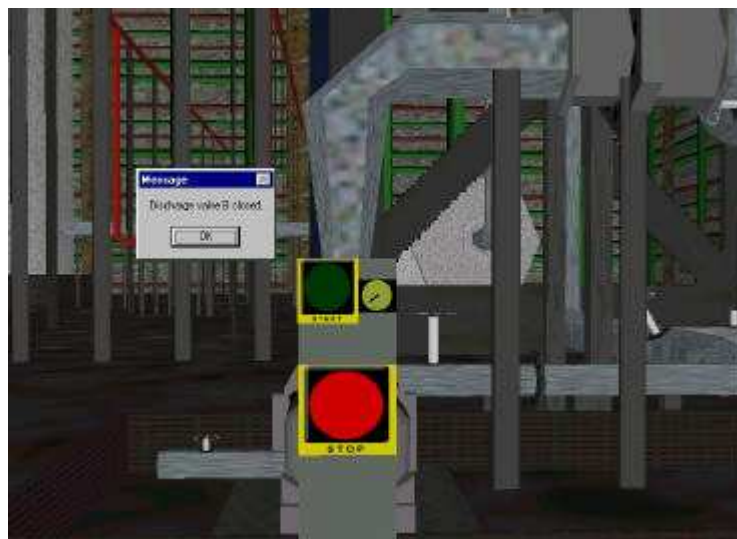
Figure 4.19: Screenshot from pump B start up

When the two pumps are running together the flow rate of fluid that is entering into the heat exchanger is higher. The users can notice this if they compare the values of the flow meter in the two different situations.
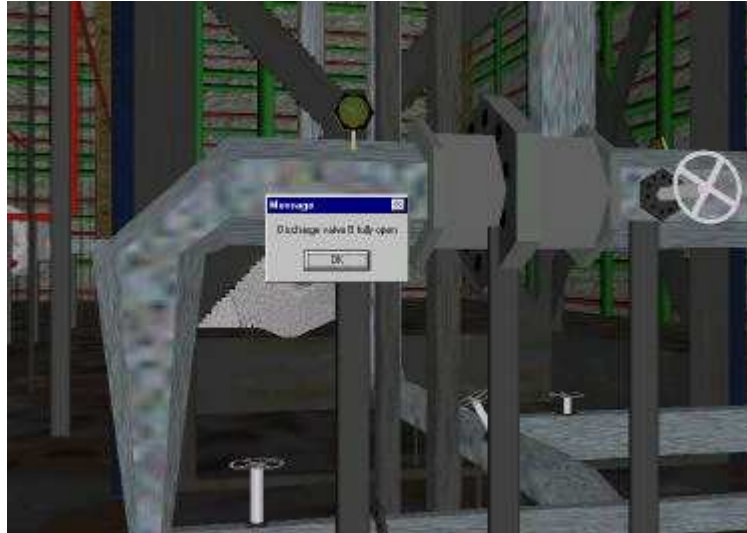
Figure 4.20: Screenshot for fully open mode of discharge valve B

4.3 ICHEME hazard spotting exercise

The Institute of Chemical Engineers in United Kingdom delivers a great number of training packages including courses, books, videos, slides and multimedia training packages. One of their multimedia training package is a hazard spotting computer based training program that shows how to identify common hazards in the handling and processing of chemicals (ICHEME, 1999). The training program is split into three modules, which include fire and explosion hazards, chemical reaction hazards and occupational hygiene hazards. This multimedia training package has an interactive exercise to help trainee spot sources of ignition and occupational hygiene hazards in a pilot chemical plant. It consists of a two-graphical based multimedia exercise which asks for trainee to spot areas in an image from a sample chemical process where hazards arise that are related to occupational hygiene. The sample plant is not specified as an example of good operating practice but it is presented as a useful example of a wide range of hazards. Figure 4.21 shows an image of the sample plant, which is used for the hazard spotting exercise.

In this example chemical plant a forklift truck takes a pallet of powder to the lift on the ground floor. The shrink wrapping enclosing the bags is split and the bags are put into the lift which takes the bags up to the second floor where they are received for the next stage of the process. The bags are taken out of the lift and the powder is charged into a drum by an operator. The powder is weighed out and is

charged into the reactor. Premixed liquid feed is also added and the reactor contents are mixed and heated to initiate the reaction. Cooling is applied, as it is needed for the reaction mixture. After the batch process is completed the suspension is pumped to the centrifuge, which spins to separate the waste liquid from the solid product. The waste liquid is fed to a settling vessel for further treatment and the damp product is scrubbed out by an operator and dumped into the hopper. The contents of the hopper are then charged into a rotary drier. The batch of material is dried under vacuum to roughly 1% by weight moisture content and a steam jacket provides the available heat. Once the batch is dried, it is charged into a flexible intermediate container, which is wheeled over to the milling machine where it is ground down into a fine powder.
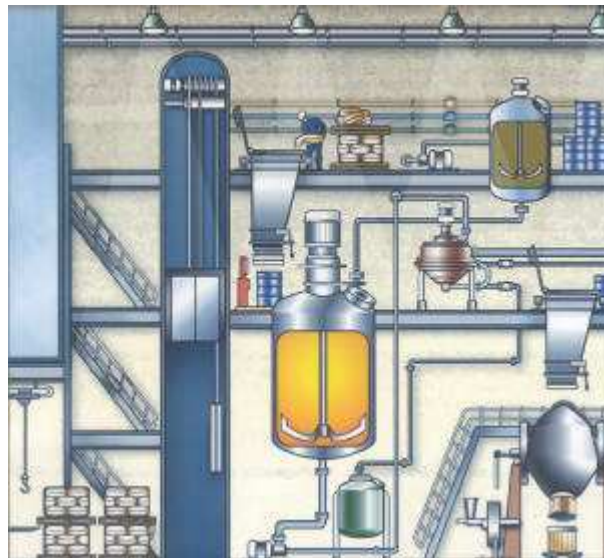
Figure 4.21: The image of the sample plant (after ICHEME, 1999)

4.3.1 Development of the three-dimensional model

The three-dimensional model was constructed in 3D Studio Max by considering carefully the two-dimensional image from the ICHEME multimedia training system. The type and the construction of the objects used to build the virtual chemical environment are discussed and described in this section.

4.3.1.1 Chemical plant building

The chemical plant layout consists of a two-floor building with adequate space for all chemical engineering equipment.

A wire frame view of the plant building is shown in figure 4.22. It consists of various objects, which represent the stairs, different floor levels, sidewalls, roof and lift. A variety of texture maps were produced for each object in order to make it recognisable. The texture maps, which were used for the building, are shown in figure 4.23.
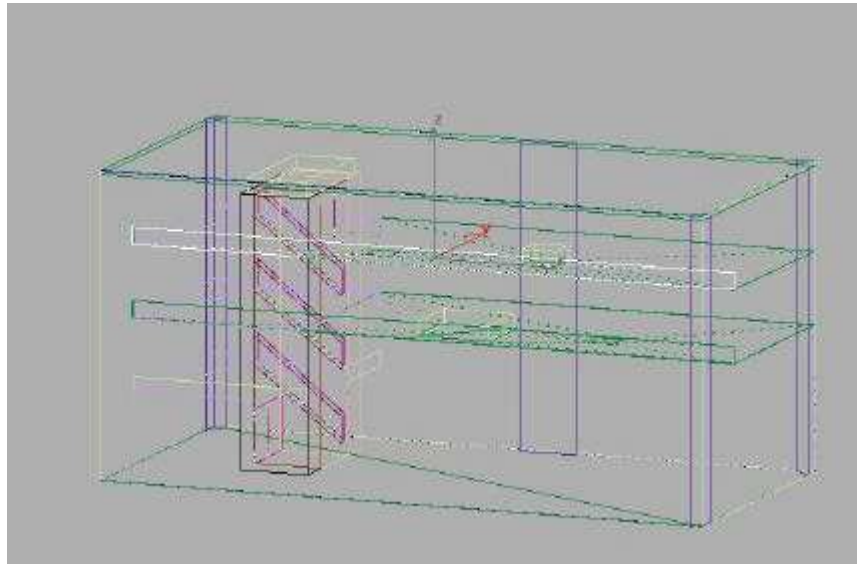
Figure 4.22: Wire frame view of the chemical plant building

Figure 4.23: Texture images for plant building

4.3.1.2 Forklift

The forklift is a common vehicle in industry and it is used for moving pallets around the plant. The construction of this three-dimensional object was complicated because it contained too many polygons to be practical. In order to solve this problem, various texture maps were produced and then applied to different parts of the forklift object with the black colour set as transparent. Figure 4.24 shows a wireframe representation of the forklift object.
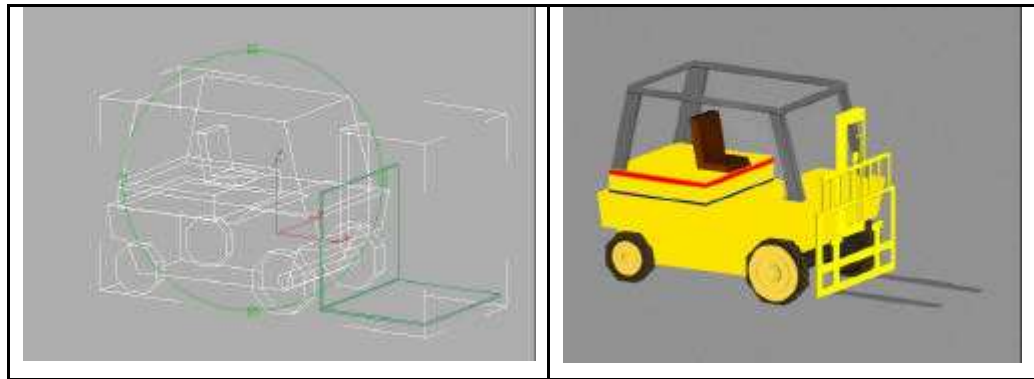
Figure 4.24: Wire frame and perspective view of the forklift object

The texture maps, which are used for the different parts of the forklift object were produced using Adobe's Photoshop software and are shown in figure 4.25.
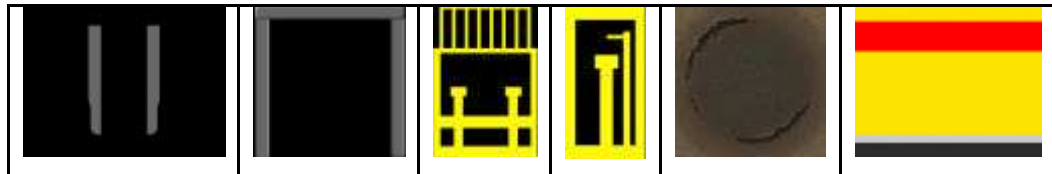
Figure 4.25: Texture maps for the forklift object.

A simple 3D Studio Max box object was made for the pallet and a transparent texture image mapped on it. The figure 4.26 shows the pallet object and the texture map, which was used.
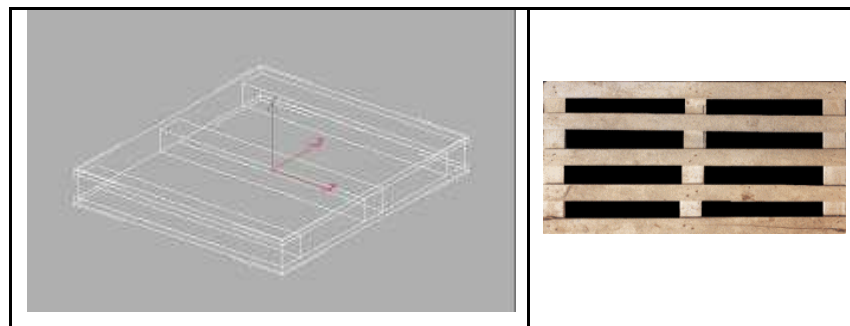
Figure 4.26: A wire frame view of the pallet object and the texture, which was mapped on to it.

4.3.1.3 Operator animation

The construction of an operator who is taking the bags of powder and charges the hopper on the second floor of the plant was done using Character Studio software. Character Studio is a combination of two plug-ins for 3D Studio Max software,

biped and physique, which provide tools for animating three-dimensional characters.

When creating a character the first thing that is developed is the skin as shown in figure 4.27. The skin that was developed for the character was made out of a series of basic shapes each resembling different body parts. It is possible in character studio software to have quite complex meshes for the skin and apply a modifier called physique to control the movement of this mesh. A basic mesh was created, with limited faces and this was used instead of a more detailed body shape. Instead of using the complicated physique modifier the biped was resized to fit the skin and the body parts were simply linked to the biped.
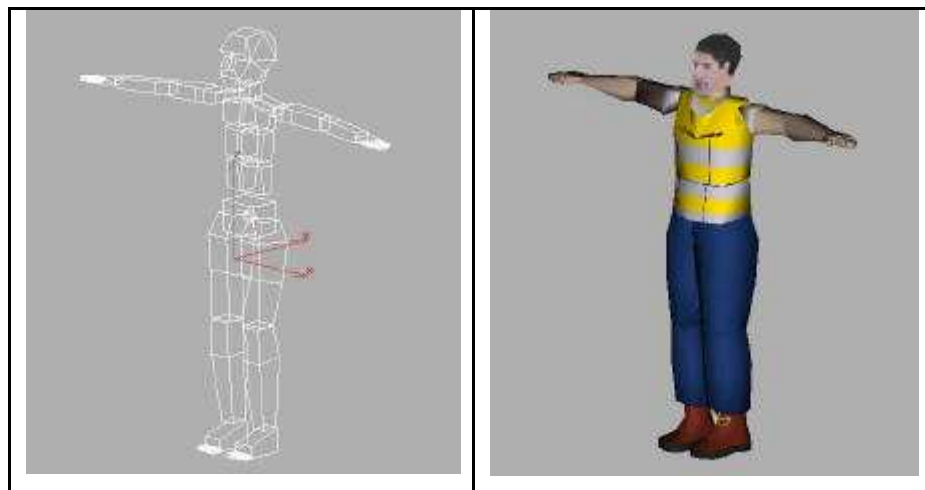
Figure 4.27: Picture of the biped (left) and the character "skin" (right)

The biped can then be animated to perform a realistic movement and if the body parts are linked on correctly they should precisely follow the biped "bones".

4.3.1.3 Barrels

Barrels can be found everywhere in a chemical plant environment. They usually contain heavy oil or various liquid materials and under some circumstances could be leaking generating hazardous situations, which can be difficult to control. The three-dimensional barrel object was made in 3D Studio Max and contains a cylinder, which is mapped by two different texture images. Figure 4.28 shows a wire frame presentation of the barrel object and the texture images, which were used.
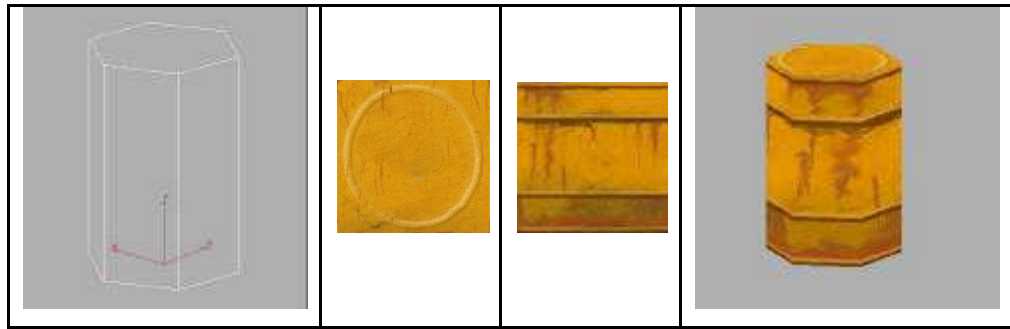
Figure 4.28: Wire frame view and texture images for barrel object

4.3.1.4 Chemical Reactor

Chemical reactors are employed in various industrial processes and come in a variety of designs, which do not always bear any specific relation to the reaction type or the type of operation. A reactor may be defined as any vessel in which the chemical reactions of the process are carried out. The required materials are fed into the reactor and may be mixed, heated, cooled or pressurised in order to bring the desired conditions for chemical reactions. A vertical cylindrical structure with a large height to diameter ratio was constructed in 3D Studio Max software for the reactor object. Different texture images were used for the bolts and nuts, the surface and the motor on the top. The figure 4.28 shows a perspective view from 3D Studio Max of the reactor object.

Figure 4.29: Chemical reaction object

4.3.2 Model development

The converted .agt files from 3D Studio Max were imported in the SAFE-VR software in order to develop the computer-generated environment of the sample

chemical plant environment. The figure 4.30 shows a general view of the virtual hazard spotting exercise in SAFE-VR.
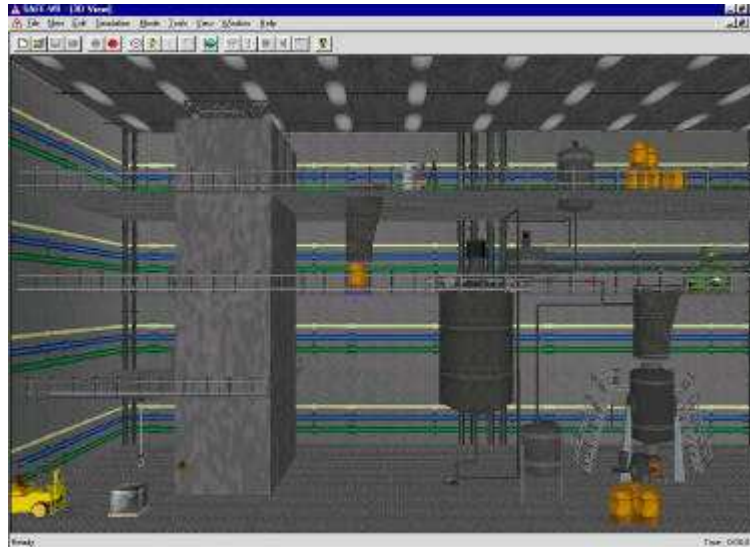
Figure 4.30: General view of the virtual hazard spotting exercise environment

At the beginning of the exercise a welcome message box gives information about the virtual hazard spotting exercise. It informs users how many areas of concern are present within the virtual environment. Figure 4.31 shows this message box.
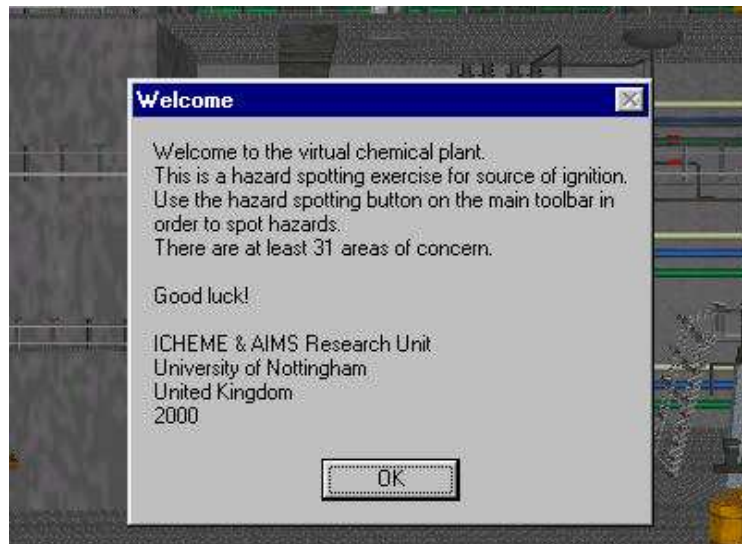
Figure 4.31: Welcome message box from virtual hazard spotting exercise.

When the users approach the stairs a message box automatically appears and asks them if they would like to go up on the next floor, as shown in figure 4.32.

Choosing the affirmative answer the virtual model responds automatically and moves the user to the next floor. At the end of the movement the system informs the users on which floor they are.
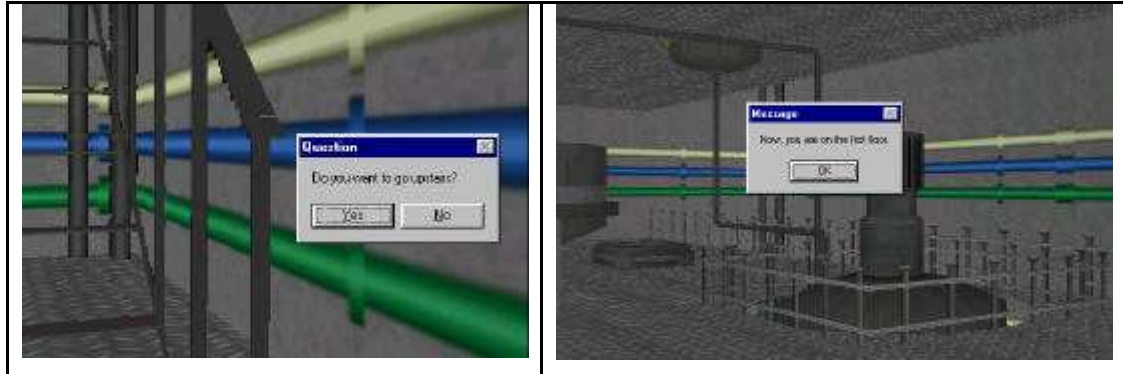
Figure 4.32: Message boxes from the virtual training model

The figure 4.33 shows the ladder logic diagram of the SAFE-VR module, which performs this operation.
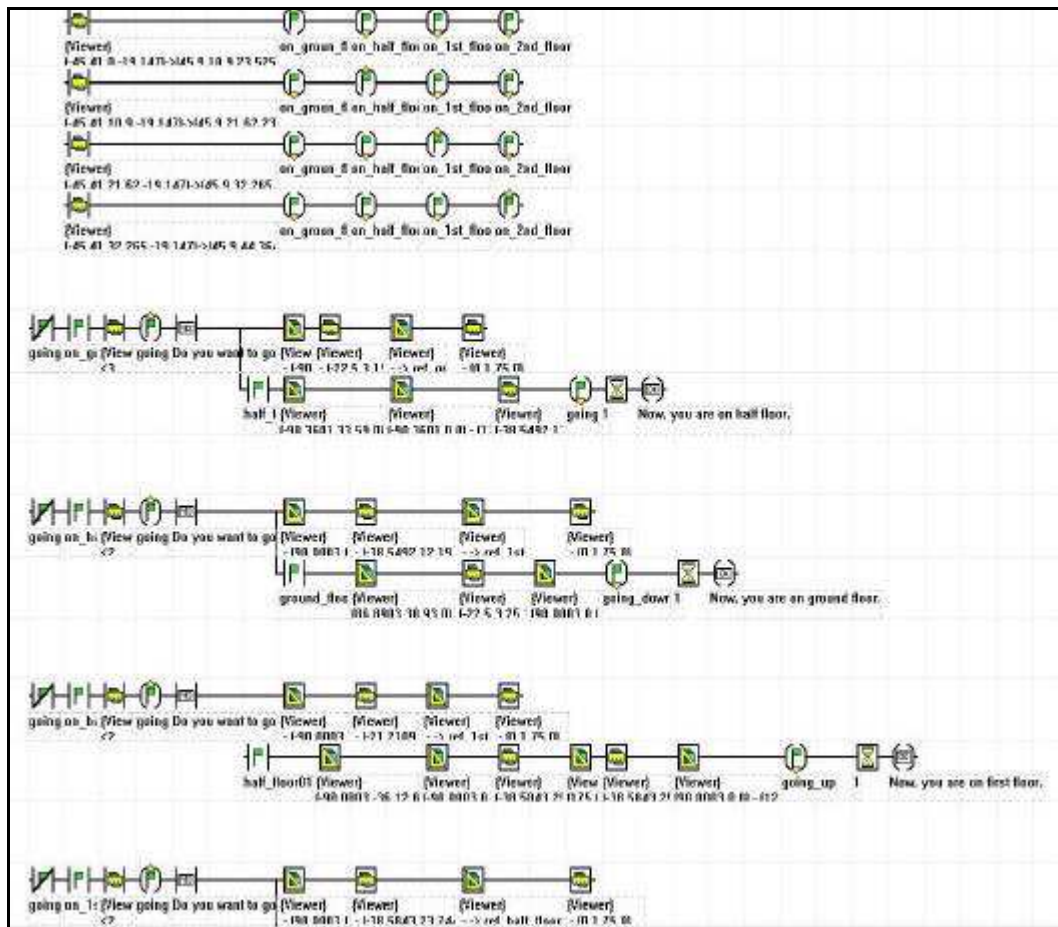
Figure 4.33: The SAFE-VR module for automatic movements

4.3.2.1 Animation

Two animation sequences were produced for the ICHEME hazard spotting virtual model and represent the movements of the forklift and elevator. Both of them were constructed using 3D Studio Max software and they were made to explain the way in which the bags of powder are moved to the second floor.

Figure 4.34: Screenshots from the forklift animation

The first one involves the forklift, which carries the pallet with the bags of powder on to the elevator. By pressing the "Q" key on the keyboard, the forklift animation is activated. Figure 4.34 shows screenshots from this animation.

Figure 4.35: Message box giving instructions for the forklift

When the forklift reaches the lift's doors its animation tops and a message box launches giving instructions to the users as shown in figure 4.35. The user should

press the button next to the doors and when doors open they have to hit the "1" key on their keyboard allowing the forklift's animation to continue.

An operator's animation on the second floor of the plant can be activated by pressing the "M" key on the keyboard. This animation illustrates the movements that a human carries out in order to move a bag of powder from the pallet to the hopper on the second floor. The figure 4.36 shows some screenshots from this animation.
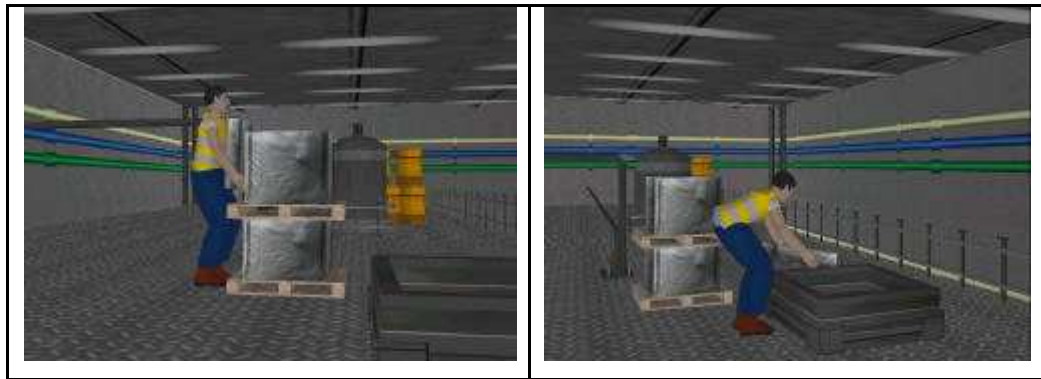
Figure 4.36: Screenshots from operator's animation.

4.3.2.2 Hazards

The virtual hazard spotting exercise is split up into two different parts, which takes place in the same virtual chemical plant environment. The first one asks from users to spot sources of ignition around the virtual environment and the second gives the opportunity to spot occupational hygiene hazards. Users are able to spot hazards by activating the spot button on the SAFE-VR toolbar and double clicking on the objects. If the object, which they choose is associated with a hazard a message box launches giving information, as figure 4.37 shows.

There are 31 different sources of ignition within the virtual plant and 21 areas, which have occupational hygiene hazards. Tables 4.3 and 4.4 summarise the hazard spotting areas for the electrical ignition sources and for the occupational hygiene issues.

Object	Explanation of ignition source
Lights	Lighting can be a source of ignition, unless they are specially designed for flammable atmospheres.
Elevator's motors	Sparks from incorrectly specified or badly maintained motors could result in ignition.
Pump on 2nd floor	The pump's electric motor could spark or there could be mechanical sparks from metal to metal contact.
Vessel's motors	The electric motor could spark or there could be mechanical sparks from metal to metal contact.
Vessel's manhole	Charging material through this manhole could generate static.
Barrels on 2nd floor	Pouring materials from these drums could generate static charges.
Weighting machine	The electric weighing machine could be a source of ignition.
Weighting machine drum	Adding powder to the drum could generate static charge unless proper precautions are taken.
Reactor's motor	The electric motor for the reactor impellers works at a high power and could yield electric sparks or friction heat from its bearing.
Reactor's manhole	Reactor charging of powder could cause a static spark, which could ignite the flammable atmosphere in the reactor.
Centrifuge's motor	The electric motor could spark or the bearings could become hot enough to be a source ignition.
Vessel	Splash filling of this vessel could generate a static spark
Reactor	Agitator blades could scrape the side of the reactor wall and also generate static due to the movement of liquid within the vessel.
Settling vessel	Splash filling of this vessel could generate a static spark.
Pump on ground floor	Electric motors are sources of ignition from electrical sparks or friction from bearings or internal metal to metal contact.
Rotary dryer	The rotary dryer operates at high temperature so the outer or inner surface could act as a source of ignition. Also, static can be generated by the movement of material.
Milling machine	The milling machine applies energy to the dry material. Tramp metal may find its way into the mill or other metal to metal.
Lifting gear	Friction from metal to metal contact on this lifting gear could result in ignition. The motor could also act as an ignition source.
Hook	The hook should be low enough to impact the forklift, causing a mechanical or even thermite sparks (aluminium and rust).
Forklift	The engine of the forklift track could ignite a flammable atmosphere.
Bulk container	Wheeling this flexible intermediate bulk container across a floor could cause the build up of static charge.
Centrifuge	The centrifuge runs at high speed. There could be metal to metal contact or the built up of static charge on the filtered material.
Reactor filling	Reactor filling can generate static charges if the liquid is non-conductive and the pipe is above the reactor contents.
Centrifuge pumping	Pumping the slurry from this centrifuge could generate static.
Hopper on 1st floor	Scrapping material into the hopper could generate static.
Rotary dryer bearing	If not maintained properly, the rotary dryer bearings could generate enough heat to act as a source of ignition.
Filling dryer	Filling the dryer could generate charge.
Hopper on 2nd floor	The pouring action could a generate charge within the hopper and result in a static spark.
Powder	The powder has an MIE of below 50mJ, so if the operator is not earthed he could accumulate enough charge to cause ignition.

Table 4.3: Electrical sources of ignition

Object	Explanation of occupation hygiene hazards
Forklift	Fumes from the forklift's engine could cause a problem. Also, the forklift could puncture the bags causing a spill and also injure personnel directly.
Hook	The atmosphere within the storage area may contain high concentrations of hazardous dusts. Monitoring of airborne concentrations and personnel dose should be carried out.
Pallets	Palleted storage areas could contain unacceptable concentrations of airborne dusts, if the housekeeping is poor or a spill has occurred.
Lift	The lift could contain a different dusts and solvents.
Hopper on 2^{nd} floor	Charging the hopper with powder could create a high concentration of powder in the air. The hazard should be eliminated or controlled.
Barrel on scale	When the powder is charged into the drum, powder could be raised into the air exposing personnel to hazardous concentrations of toxic materials.
Powder	Intermediate storage of bags of powder at this level could lead to housekeeping problems from spills and normal operation. Hazardous concentrations of a flammable powder could be produced.
Reactor's motor	There could be leaks from agitator's seals/glands.
Pump on 2^{nd} floor	Pumps and pump seals can lead hazardous materials.
Vessel	Personnel have to charge flammable and toxic liquid into this vessel exposing them to hazardous concentrations of vapour.
Barrels	These drums could be leaking or left open to generate a hazardous atmosphere that should be controlled.
Reactor's manhole	Charging the reactor could generate flammable dust concentrations.
Centrifuge	Dump material is scraped out of the centrifuge. Personnel could be exposed to hazardous concentrations.
Valve connections	Valve connections and flanges can leak to expose personnel to hazardous atmospheres.
Hopper on 1^{st} floor	The hopper is being charged with damp material. Personnel could be exposed to hazardous concentrations of vapour.
Settling vessel	The settling vessel could be a source of hazardous vapours when the manhole is opened.
Bulk container	Loading the mill with dry material could generate a dust cloud of hazardous material.
Mill	The mill discharges toxic material in to the drum, exposing personnel to further toxic hazards.
Filling dryer	Charging the dryer with damp powder could expose the operator with flammable concentrations of vapour.
Poured out dryer	After the powder is dried, charging of the flexible intermediate bulk container could expose personnel to hazardous concentrations.

Table 4.4: Occupational hygiene hazards

Figure 4.37: Hazard spotting screenshot from the virtual environment

4.3.2.3 System reporting

At the end of each training session SAFE-VR createss a report, which contains the scores of the users converted to a percentage of maximum available scores for that session. It also contains a tree control showing how the score has been derived and giving users the opportunity to see scores for individual hazards. The tree structure also shows where scores have been lost, and displays what the highest scoring answers would have been. Where hazards were present but not spotted, the system can show the hazard clearly, pointing the user towards it, outlining it and fading out the rest of the virtual chemical plant environment as shown in figure 4.38.

Session report

The system highlights a hazard that were unspotted
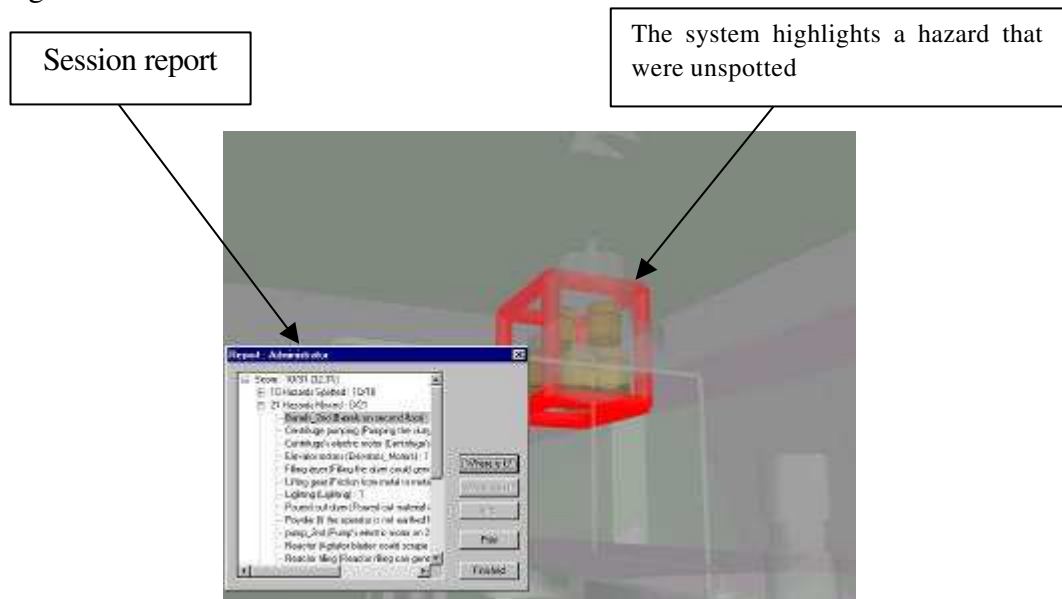
Figure 4.38: Session report from virtual hazard spotting exercise.

4.4 Summary

The virtual pump training system and the virtual hazard spotting exercise represent two simple safety training applications in the chemical engineering field, which are run using the SAFE-VR virtual engine. Both of them are desktop virtual reality systems, which comprise virtual worlds representing two different chemical plants.

The pump training system represents a virtual world, which contains pumps, heat exchangers, vessels, valves, cyclones and other chemical engineering equipment. These objects were constructed using a minimum number of polygons in order to maximise the speed of operation without compromising on realism. When constructing the objects particular attention was given to the general shape, colour, function of object and its location in the chemical plant environment. The main purpose of this training system is the steps that the trainees have to follow in order to safely start two centrifugal pumps without causing any damage to the equipment and to themselves.

The virtual reality hazard spotting exercise is extracted from a multimedia training package, which was commercially delivered by Institution of Chemical Engineers (ICHEME). Since the main purpose of this virtual system is to conduct hazard training, the virtual world contains a number of hazards, which the trainee must identify. The virtual hazard spotting exercise is separated in two different parts, these comprise of the sources of ignition and occupational hygiene hazards. There are 31 different sources of ignition within the virtual plant and 21 areas, which concerns occupational hygiene hazards.

The three-dimensional view of the pilot plant layout in the hazard spotting exercise, allows immersion of users in the virtual world and makes the hazard spotting more effective and more realistic. The two-dimensional static image of the chemical process that is based the original multimedia exercise could not generate the sense of immersion reducing the effectiveness of the safety training system. The trainee's interaction with the virtual chemical engineering equipment

and the existence of plant noise during user's navigation within the computer-generated environment gives the feeling of actually "being there".

Virtual reality training systems can save money and time for training in process industries. However great care has to be taken to ensure that both the visual nature and simulation dynamics accurately reflect the real world to prevent the simulation losing credibility to potentially cynical trainees.

The following two chapters present an integrated simulated chemical plant where the main purpose of their implementation was the realistic simulation of the chemical engineering process that they are describing. In chapter 5 a virtual boiler plant is described which focuses on the dynamic simulation and control of a water tube boiler and highlights issues and problems relating to boiler operation and safety.

Chapter 5

Virtual boiler plant

5.1 Introduction

This chapter presents a virtual boiler plant environment, highlights some of the issues and problems relating to boiler operation and concentrates on issues relating to plant training and safety. This chapter also describes the dynamic simulation of the boiler plant and its implementation in SAFE-VR, and focuses on specific issues related to process operation and control.

5.2 Boilers

The boiler is an essential element in many production sites, because steam power cannot be created unless steam is first generated in a boiler. The majority of plants have to make their own steam so they provide some sort of a closed vessel, place water in it, and heat this vessel until the water is turned into steam. The steam must generally be produced under pressure in order to be used as a heating medium or in some form of work engine for power production. The higher the steam pressure and temperature, the greater efficiency an engine will have in turning the heat of steam into mechanical work energy (Gun and Horton, 1989).

Industrial boilers are used over a wide range of applications, ranging from large power generating units, for which emphasis is placed on maximum efficiency and sophisticated control systems, to small low pressure units for space or process heating, for which the principal aims are simplicity and low cost (Perry, 1984).

Boilers have been used for many years, and some of the early designs showed great ingenuity in the use of then-available materials and fabricating techniques. Trial and error and improved materials and welding have eliminated most of these early designs, but today boilers still encompass a good number of types. One basic classification is based on whether the tubes are filled with water or hot gas, in other words, whether the boiler is of watertube or firetube type.

Firetube boilers constitute the largest share of small to medium sized industrial units. These may be vertical or horizontal, the majority being horizontal, although recent developments in fluidised bed combustion favour the vertical arrangement due to the generous space or freeboard above the fuel bed provided in the furnace. In firetube boilers the flue gas products of combustion flow through the wall of the tubes to the surrounding water. The flue gases are cooled as they flow through the tubes, transferring their heat to the water; therefore, the cooler the flue gas, the greater the amount of heat transferred (Gun and Horton, 1989). A typical firetube boiler is illustrated in figure 5.1.
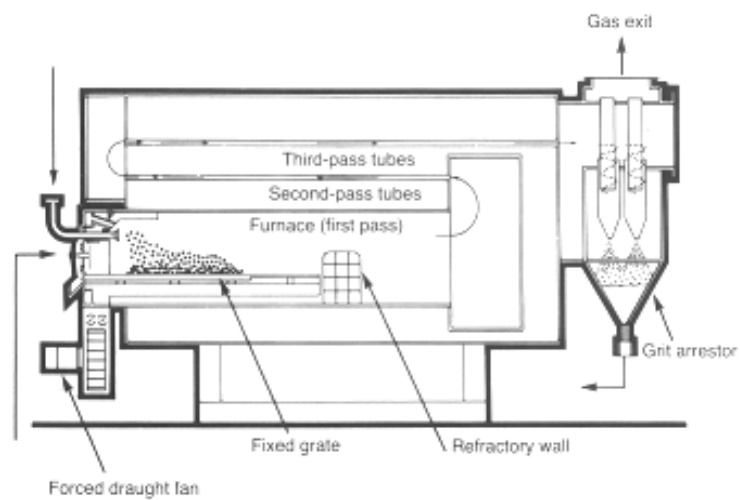
Figure 5.1: Firetube boiler (after Gun and Horton, 1989)

Firetube boilers used today have evolved from the earliest designs of a spherical or cylindrical pressure vessel mounted over the fire with flame and hot gases around the boiler shell. Installing longitudinal tubes in the pressure vessel and passing flue gases through the tubes have improved this obsolete approach. This has increased the heat transfer area and improved the heat transfer coefficient (Swift, 1959).

In watertube boilers the conditions are reversed with the water passing through the tubes and the furnace for the hot gasses is made up of the water tubes. These tubes are usually connected between two or more cylindrical drums. In some boilers the lower drum is replaced with a tube header. The highest drum is called steam drum and is maintained approximately half full of water. The lowest drum is filled with

water completely and is the low point of the boiler. In these boilers fuel is mixed with the correct amount of air and burned in a combustion chamber. The steam collecting at the top is passed back to the banks of the combustion chamber, where additional heating is added to it, "superheating" the steam (Dukelow, 1986). A typical watertube boiler is shown in figure 5.2.
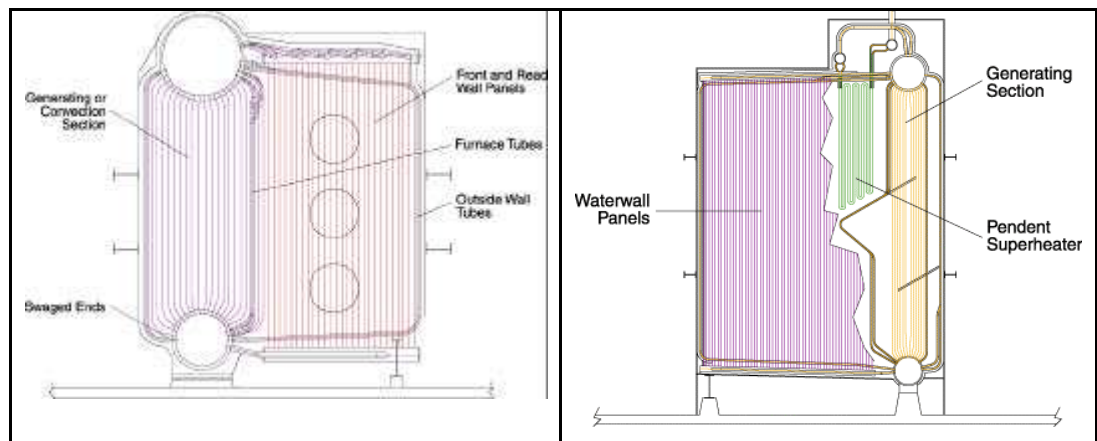
Figure 5.2: Watertube boiler (after Dukelow, 1986)

Because watertube boilers can be easily designed for greater or lesser furnace volume using the same boiler convection-heating surface, watertube boilers are particularly applicable to solid fuel firing. They are also applicable for a full range of sizes and for pressures from 3.5 to 345 bar gauge. The present readily available minimum size of industrial watertube boilers is approximately 9072 to 11340 kg/hr of steam – equivalent to 600 to 750 BoHP (boiler horsepower). Many industrial watertube boilers operate in the 250 to 300 BoHP size range (Swift, 1959 and Gun and Horton, 1989).

5.3 Steam Boiler Systems

A boiler operates using a feedwater system, a steam system, a fuel system and a draft system.

The feedwater system supplies water to the boiler and regulates it automatically to meet the demand of the steam.

The steam system collects and controls the steam produced in the boiler. Steam is directed through piping to the point of use. Throughout the system steam pressure

is regulated using valves and checked with the steam pressure gauges. The steam and feedwater systems share some components.

The fuel system includes all the equipment used to provide fuel to generate the necessary steam. The equipment required in the fuel system depends on the type of fuel used in the system. All fuels are combustible and dangerous if necessary safety standards are not followed. In a fuel oil fired boiler plant, fuel oil leaves the tank through a suction line and duplex strainer and then goes to the fuel oil pump. From the discharge line some fuel is burned and some returned to the tank through a regulating valve.

The draft system regulates the flow of air to and from the burner. For fuel to burn efficiency the right amount of oxygen must be provided. Air must also be provided to direct the flow of air through the furnace to direct the gases of combustion out of the furnace to the breaching (Boiler and Heat Exchange Systems Inc, 2000).

5.4 Safety in Boiler Operation

When water is boiled into steam its volume increase about 1,600 times, producing a force that is almost as explosive as gunpowder. This makes boiler operation a safety critical operation for a chemical plant. Failure to follow well established practices for safe boiler operation can, and likely will, result in catastrophe. There are some common problems that can have catastrophic results for a boiler plant such as fuel explosions, low water condition, poor water treatment, improper warm-up, contaminated feedwater, impact damage to tubes (National Board of Boiler and Pressure Vessel Inspectors, 2000).

One of the most dangerous situations in the operation of a boiler is that of a fuel explosion in the furnace. One of the most likely causes of a fuel explosion is the presence of a fuel mixture with high concentrations of unburned fuel that is called a fuel rich mixture. A fuel rich mixture can occur at any time that insufficient air is supplied for the amount of fuel being burned.

The potential for severe and even catastrophic damage to a boiler as a result of low water conditions is easy to imagine considering that furnaces temperatures exceed 982^0C, yet the strength of steel drops sharply at temperatures above 427^0C. The only thing that allows a boiler to withstand these furnace temperatures is the presence of water in all tubes of the furnace at all times that a fire is present. Low water conditions will melt the steel boiler tubes. Typical industrial boilers are "natural circulation" boilers and do not utilise pumps to circulate water through the tubes. These units rely on the differential density between hot and cold water to provide the circulation. As the water removes heat from the tubes, the water temperature increases and it rises to the boiler steam drum. Eventually, sufficient heat is transferred and steam is generated. Colder water replaces the water that rises, which creates a natural circulation. Normal operating level is generally near the centreline of the steam drum.

The control of the boiler drum level can be difficult and even the best-tuned control systems cannot always prevent a low water condition. The water level in a steam drum is actually a fairly unstable compressible mixture of water and steam bubbles that will shrink and swell with pressure changes and will actually shrink momentarily when more "cold" feedwater is added (Reeves, 1999).

5.5 Plant description

The boiler model created during this project is based on work by Nicholson (1964) on an industrial power station boiler of 45360 kg/h capacity, operating at 45 bar gauge, 454 ^{0}C and supplying steam to process at 16 bar gauge and 7.5 bar gauge. The boiler operates on natural circulation and is controlled to maintain steam pressure and water level using conventional PID controllers in independent loops. A constant fuel-flow/air-flow ratio is maintained for optimum combustion efficiency by trimming initial fan settings.

The flow sheet of the boiler plant, which is used in this project, is shown in figure 5.3.
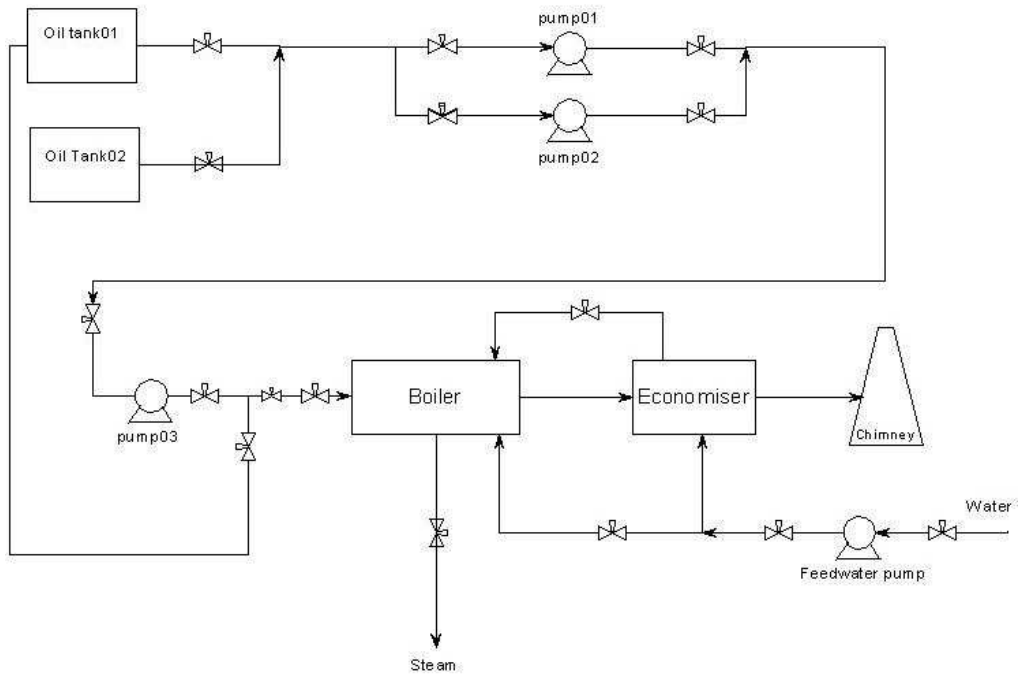
Figure 5.3: Boiler plant's flow sheet

To create a mathematical model of the steam generating process, the boiler is assumed to consist of lumped energy storage elements comprising two rising sections, a single superheater section, steam drum and gas path as shown in figure 5.4.

R_1, R_2	Risers
S	Superheater
E	Economiser
F	Fuel pump
FD, ID	Forced and included draught fan
T_1, T_2	Primary and secondary turbines
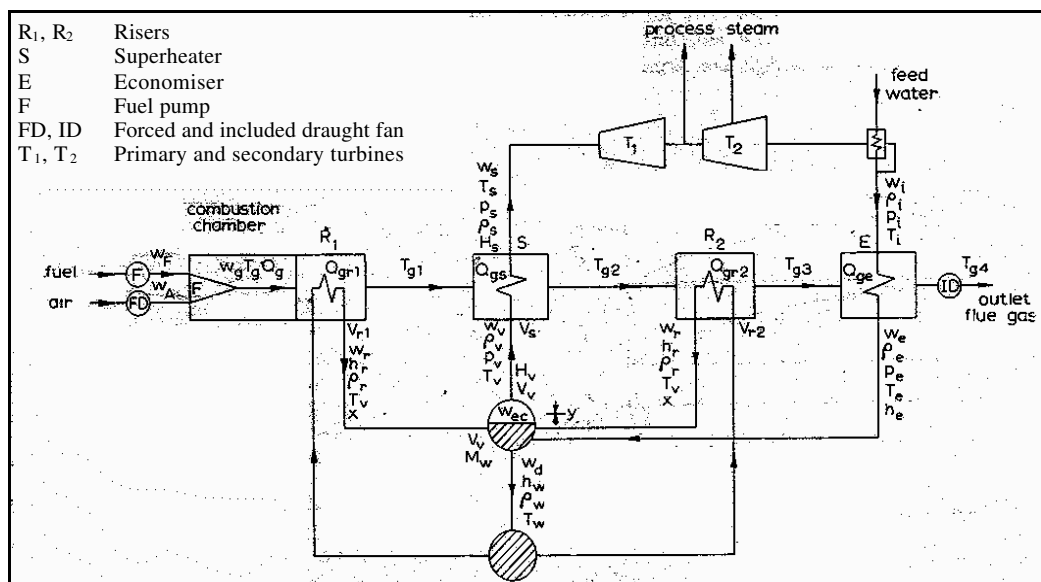
Figure 5.4: Simplified energy-mass-flow diagram (after Davison, 1964)

Dynamic behaviour is described about a steady-state operating level by perturbing the non-linear mass-balance, momentum, heat balance and heat transfer equations associated with each section (Davison, 1966 and Nicholson, 1964).

The system equations are associated with material flows along the gas and water-steam paths interconnected by the heat transmission from gas to tube, from tube to water and steam, and by heat storage. Steam production in the steady state results essentially from boiling in the riser tubes. Evaporation of water in the steam drum will also occur with reduced drum pressure caused by an increasing the steam load, and condensation will occur with increasing pressure (Nicholson, 1964).

Feedwater is supplied below the interface level in the steam drum, and subcooled water enters the risers via the unheated downcomer tubes and water drum. This water is heated to saturation level, and then partial evaporation produces a two-phase steam-water mixture, the reduced density of which maintains natural circulation by convection. Saturated steam separates from the steam-water mixture in the steam drum and passes to the superheater (Davison, 1966 and Nicholson, 1964). With increased steam demand pressure falls, and storage steam in the boiler and steam mains initially fulfils this demand, as far as time lags associated with pressure changes allow.

Operating variables		
Steam density	ρ_s	22.2657 kg/m^3
Superheater outlet pressure	p_s	44.13 bar
Superheater outlet temperature	T_s	454 ^{0}C
Superheater tube-wall temperature	T_{st}	476 ^{0}C
Riser outlet mixture quality	x	1.63%
Riser mass flow rates	w_r	564.2689 kg/s
Steam drum pressure	p_u	45.85 bar
Riser tube-wall temperature	T_{rt}	298 ^{0}C
Drum-downcomer liquid temperature	T_w	254 ^{0}C
Water level displacement	y	0 cm
Outlet mass steam flow	w_s	12.6008 kg/s
Flow of water at economizer	w_e	12.6008 kg/s
Inlet feedwater temperature	T_i	121 ^{0}C
Fuel mass flow	w_f	1.01151 kg/s

Table 5.1: Operating variables

The equations for determination of dynamic boiler behaviour are summarised in Appendix I. The operating variables are listed in table 5.1 and illustrated in figure 5.4.

5.6 Dynamic boiler equations

The equations that describe the dynamic behaviour of the boiler can be reduced to a linearised matrix set of first order differential equations of the form

$$\dot{x}(t) \ ? \ A \ ? \ x(t) \ ? \ B \ ? \ u(t) \tag{5.5.1}$$

where $x(t)$ is a $9?1$ column matrix containing the dependent state variables $?_s$, T_s, T_{st}, x, w_r, p_u, T_{rt}, T_w and y; $u(t)$ is $5?1$ column matrix containing the system unit variables w_s, w_e, sw_e, w_f, T_e; A and B are matrices with constant elements of order $9?9$ and $9?5$, respectively, as summarised in figure 5.5.

Integrating equation (5.5.1) over set time period dT=1sec and assuming $u(t)$ step change only at sample periods, we have:

$$x(k \ ? \ 1) \ ? \ A_{99} \ ? \ x(k) \ ? \ B_{95} \ ? \ u(k) \tag{5.5.2}$$

where

$$A_{99} \ ? \ \exp(\ A \ ? \ ?T\ )$$

$$B_{95} \ ? \ A^{?1}(A_{99} \ ? \ I) \ ? \ B$$

The matrixes A_{99} and B_{95} are shown in figure 5.6.

$$
A =
\begin{pmatrix}
3.395042 & ?\,0.00315463 & 0 & 0 & 0 & 0.0000402537 & 0 & 0 & 0 \\
367.8026 & ?\,3.051455 & 3.030725 & 0 & 0 & ?\,0.00377204 & 0 & 0 & 0 \\
27.43095 & 0.0786945 & ?\,0.0596402 & 0 & 0 & ?\,0.000281321 & 0 & 0 & 0 \\
?\,0.0646776 & ?\,0.0000519827 & ?\,0.0596402 & 0 & 0 & ?\,0.000281321 & 0 & 0 & 0 \\
3851.207 & 17.25898 & 0 & ?\,0.2558487 & ?\,0.00000335212 & 0.00000360429 & 0.000063356996 & 0.0019394473 & 0 \\
22434.67 & 18.03119 & 0 & ?\,35.601 & ?\,0.000104 & ?\,0.4136099 & 90.07017 & 56.89565 & 0 \\
0 & 0 & 0.002339145 & 0 & 0 & 0.000222186 & ?\,0.202623 & 0 & 0 \\
0 & 0 & 0 & ?\,1.272016 & 0.00100585 & 0.00007862347 & 0 & ?\,0.071713 & 0 \\
?\,2.20 & ?\,0.001771046 & 0 & ?\,8.44 & ?\,0.000110586 & 0.00001383153 & 0.001489088 & 0.006018683 & 0
\end{pmatrix}
$$

$$
B =
\begin{pmatrix}
0.010032 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1.5615 & 0 \\
0 & ?\,0.0000051296 & 0 & 0 & 0 \\
5.2020 & ?\,1.5541 & ?\,0.41758 & 8.2755 & 0.039812 \\
0 & 1.7793 & 0 & 0 & 0 \\
0 & 0 & 0 & 2.3259 & 0 \\
0 & ?\,0.024541 & 0 & 0 & 0.0028406 \\
0 & 0.000029417 & 0 & 0 & 0
\end{pmatrix}
$$

Figure 5.5: Matrixes A and B

$$
A_{99} = \begin{bmatrix}
0.0266 & 0.0000096 & 0.000661 & 0.017 & 0.00000056 & 0.00000536 & 0.00187 & 0.00165 & 0 \\
7.25 & 0.0146 & 0.863 & 0.255 & 0.00000641 & 0.0000268 & 0.0173 & 0.0179 & 0 \\
7.91 & 0.0161 & 0.951 & 0.139 & 0.0000046 & 0.0000432 & 0.0153 & 0.0135 & 0 \\
0.00737 & 0.000000979 & 0.00000381 & 0.296 & 0.000000267 & 0.000000308 & 0.0000208 & 0.000306 & 0 \\
2.49 & 0.0203 & 0.00594 & 1560 & 0.00445 & 0.00593 & 1.57 & 6.92 & 0 \\
3100 & 0.225 & 3.36 & 1760 & 0.0562 & 0.51 & 184 & 164 & 0 \\
2.65 & 0.000293 & 0.00927 & 0.56 & 0.0000245 & 0.0045 & 0.458 & 0.0763 & 0 \\
1.58 & 0.00126 & 0.000249 & 13.6 & 0.000286 & 0.000173 & 0.0421 & 0.77 & 0 \\
11 & 0.00885 & 0 & 42.2 & 0.000555 & 0.000069 & 0.00745 & 0.0301 & 1
\end{bmatrix}
$$

$$
B_{95} = \begin{bmatrix}
0.0039 & 0.0000543 & 0.000000595 & 0.00894 & 0.0000131 \\
0.596 & 0.00117 & 0.0000102 & 6.28 & 0.000213 \\
0.379 & 0.000443 & 0.00000486 & 7.47 & 0.000107 \\
0.000407 & 0.0000386 & 0.00000119 & 0.000404 & 0.00000296 \\
15.6 & 1.77 & 0.156 & 3.79 & 0.147 \\
183 & 5.99 & 0.063 & 1450 & 1.37 \\
0.0805 & 0.0011 & 0.0000186 & 7.82 & 0.00043 \\
0.0245 & 0.108 & 0.000609 & 0.226 & 0.0125 \\
0 & 0.000147 & 0 & 0 & 0
\end{bmatrix}
$$

Figure 5.6: Matrixes A_{99} and B_{95} for 1 second sample period

For practically all the linear dynamics and control studies, it is useful to look at the changes of the variable away from steady state values instead of the absolute variables themselves. Since the total variables x are functions of time, their departures from steady state values x_0 will also be functions of these. These departures from steady state are called perturbation variables. The perturbation in x and u is defined as

$$x^* ? x ? x_0$$

$$u^* ? u ? u_0$$

The equation (2) that describes the linear system can now be expressed in terms of these perturbation variables.

$$x ? A_{99} ?x^* ? B_{95} ?u^*$$

When this is done, two very useful results occur:

1. The constant terms in the ordinary differential equation drop out
2. The initial conditions for the perturbation variables are equal to zero if the starting point is the steady state operating condition around which the equation have been linearised (Luyben, 1997).

So, once per sample period d?=1 second we have the circulation that is shown in figure 5.7.

```
┌──────────────┐                              u*
│  Simulator   │──────────────────────────────────┐
│   (x, u)     │                                   │
└──────────────┘                                   │
       ▲         Once per 1 second                 ▼
       │                              ┌──────────────────────┐
       │      x*                      │  State Space Model    │
       └──────────────────────────────│     (x*, u*)          │
                                       └──────────────────────┘
```
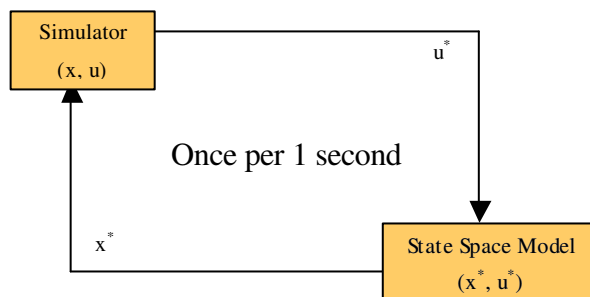
Figure 5.7: Schematic presentation of the mathematical model

The responses of the dependent variables for step inputs of steam, fuel and feedwater flow rates are shown in the diagrams in figures 5.7, 5.8 and 5.9. The x-axis of the diagrams represents the time in seconds.
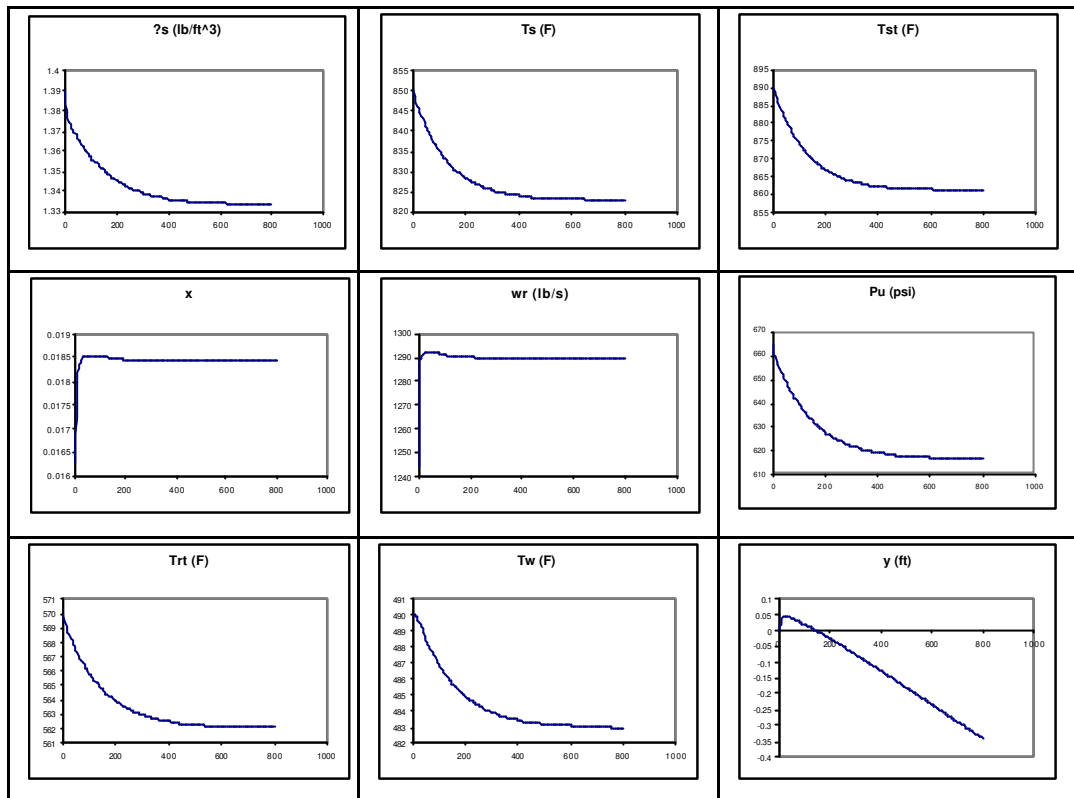
Figure 5.7: Responses of dependent variables for step increase of steam export

flow
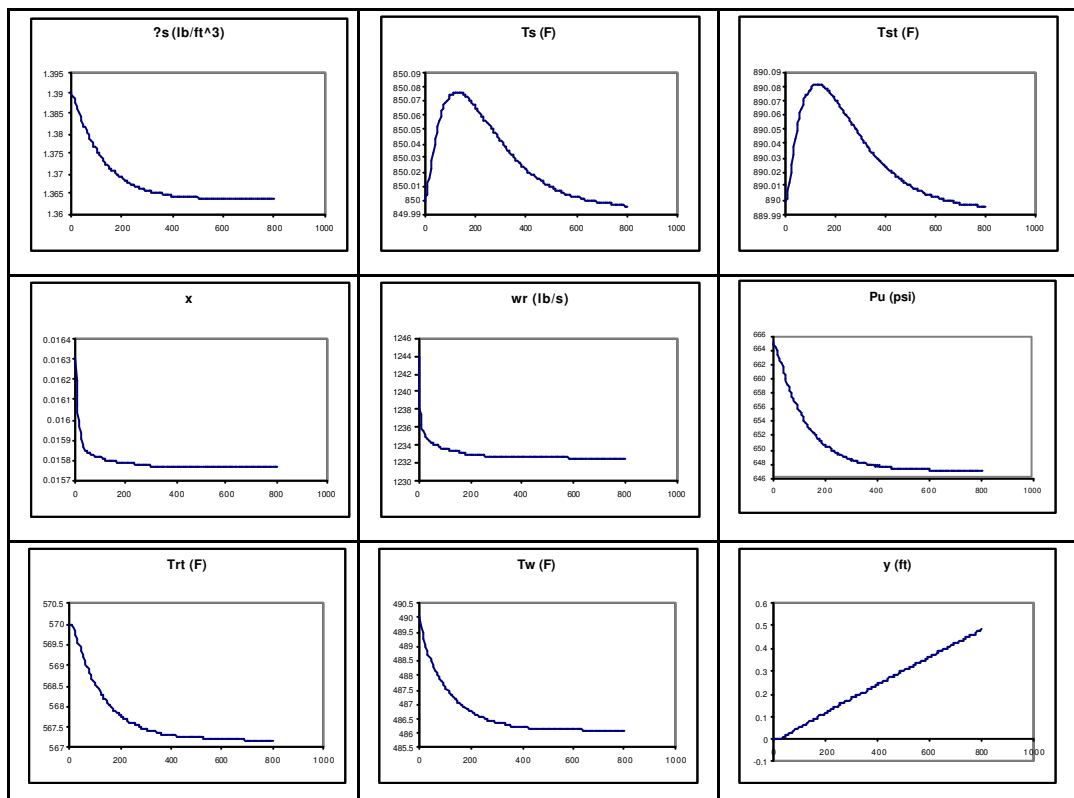
Figure 5.8: Responses of dependent variables for step increase of feed water flow
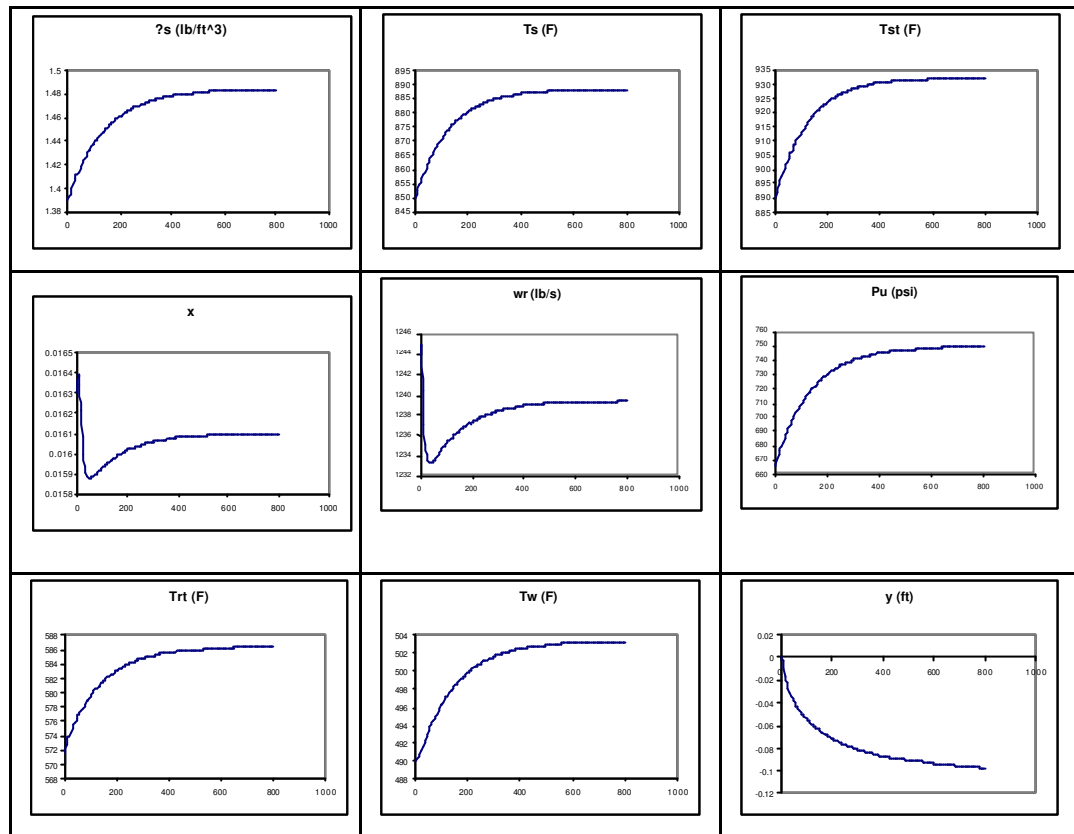
Figure 5.9: Responses of dependent variables for step increase of fuel flow

The responses are mostly of a simple form and may be approximated using single time constants, but the response of the drum level to steam change is of expected non-minimum phase form with water level rising initially and then decreasing uniformly. These illustrate qualitatively the effects of bubble formation and evaporation format effects in the riser tubes

5.7 Drum level control system

The control of water level in the boiler's steam drum is a major function in the steam generation process. Maintaining the correct water level in the drum is critical for many reasons. A water level that is too high causes flooding of steam purification equipment; resulting in the carry over of water and impurities into the steam system. A water level that is too low results in a reduction in efficiency of treatment and recirculation function. It can even result in tube failure due to overheating from lack of cooling water on boiling surfaces. Normally drum level is expected to be held within 2 to 5 cm of the set point with some tolerance for temporary load changes (ABB, 1999 and Dukelow, 1986).

Under boiling conditions, steam supporting field products such as bubbles exist below the steam/water level interface. These bubbles have volume and displace water to create a misrepresentation of the true water level in the drum. Another effect upon drum level is pressure in the drum. Because steam bubbles compress under pressure (if drum pressure changes due to load demands), the steam bubbles expand or contract due to these pressure changes. A higher steam demand will cause the drum pressure to drop, and the steam bubbles to expand to give the appearance of a water level higher than it truly is. This fictitious higher water level causes the feedwater input to be shut down at a time when more water is really required. A surge in water level as a result of drum pressure decreasing is called "swell". A water level decrease due to drum pressure increase is called "shrink" (ABB, 1999 and Dukelow, 1986).

5.8 Proportional-Integral-Derivative (PID) Control

Controllers are designed to eliminate the need for continuous operator attention. They are used to automatically adjust some variable to hold the measurement (or process variable) at the set point.
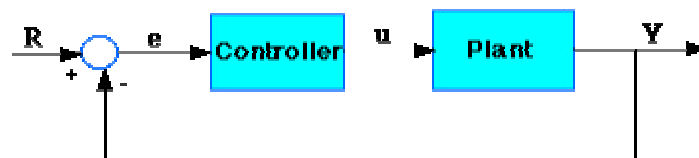
Plant: A system to be controlled

Controller: Provides the excitation for the plant;

Designed to control the overall system behaviour

Figure 5.10: PID controller schematic presentation (after Messner and Tilbury, 1996)

The transfer function of the PID controller is given by:

$$K_p \; ? \; \frac{K_I}{s} \; ? \; K_D \; ?s \; ? \; \frac{K_D \; ?s^2 \; ? \; K_p \; ?s \; ? \; K_I}{s} \tag{5.7.1}$$

K_p = Proportional gain

K_I = Integral gain

K_d = Derivative gain

The variable (e) represents the tracking error, the difference between the desired input value (R) and the actual output (Y). This error signal (e) will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal. The signal (u) just past the controller is now equal to the proportional gain (Kp) multiplied by the magnitude of the error plus the integral gain (Ki) multiplied by the integral of the error plus the derivative gain (Kd) multiplied by the derivative of the error.

$$u ? K_p ?e ? K_I ??edt ? K_D ?\frac{de}{dt} \qquad (5.7.2)$$

This signal (u) will be sent to the plant, and the new output (Y) will be obtained. This new output (Y) will be sent back to the sensor again to find the new error signal (e). The controller takes this new error signal and computes its derivative and its integral again. This process then repeats until the error is eliminated (Messner and Tilbury; 1996, ExperTune, 2000 and Luyben, 1997).

5.9 Development of the three-dimensional model

This section describes and discusses the type and the construction of the objects used to build the virtual boiler plant environment. All the objects were created using the 3D Studio Max modelling program. The textures, which are used, for mapping the three-dimensional objects were constructed using Adobe's Photoshop and Macromedia's Fireworks software packages.

The boiler plant model was consisted by the watertube boiler, three centrifugal pumps, two oil tanks, economiser, chimney, control and gate valves, pipes of different size and the plant's control room.

5.9.1 Watertube boiler object

The watertube boiler is consisted of two drums, a combustion chamber, superheater and riser sections. The superheater and riser section are inside in a

large dimension box object, which represent the main part of the boiler. The highest drum is the steam drum and is maintained approximately half full of water. The lowest drum is filled with water completely and is the low point of the boiler. Figure 5.11 shows a screenshot from the three-dimensional watertube boiler object.

Figure 5.11: A rendered view of the three-dimensional watertube boiler

The textures, which were used for the water and steam drum, were similar, they were trying to indicate the condition and the age of the boiler. The combustion chamber of the boiler was constructed using different box objects, which were mapped with textures shown in figure 5.12.

Figure 5.12: Watertube boiler texture images

5.9.2 Control valves

Control valves are installed in a variety of applications in chemical plants to perform stream control functions. The function of the great mass of valves in the process industries is preliminary a blocking operation, requiring valves in a completely open or closed position. The majority of control valves generally operate continuously in an automatic mode with a sensor controlling the valve position through a controller, transmission system and valve operator (Lipton and

Lynch, 1994). Figure 5.13 shows a three-dimensional control valve, which was constructed using 3D Studio Max.
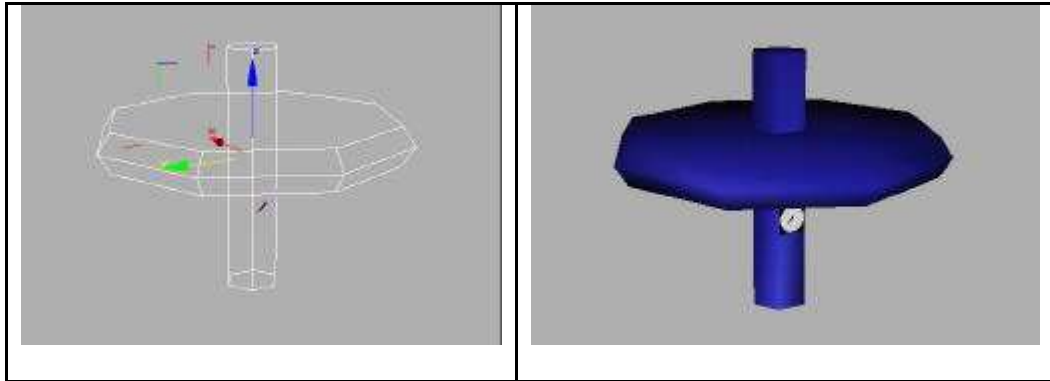
Figure 5.13: Wireframe and rendered presentations of the control valve object

Because the number of control valves in a chemical plant environment such as this, is extremely high, it was necessary to keep the number of polygons of this object as low as possible. No textures were needed for this object and many instances of it were loaded into the virtual boiler plant.

5.9.3 Electrical box

Electrical boxes are obvious and common objects through which the mains power is supplied to the boiler plant. This object is constructed as a simple box using 3D Studio Max with purpose created texture images mapped onto front surface. The texture map for the electrical box is shown in figure 5.14.

Figure 5.14: Electrical box texture image

5.9.4 Control room

The control room of the boiler plant is the place from where the employees can operate the boiler adjusting the fuel or water flow and determine the level of the steam export flow. They should be also capable of examining the condition of chemical plant equipment and obtaining valuable measurements from all the pipelines. In order to make this possible, two different control panels and an interactive flowsheet were created in the plant's control room.

Figure 5.15 illustrates the pumps control panel where there are many switches for starting up pumps and opening or closes valves. There are also indicators for the fuel filters conditions, which are placed at the beginning of the fuel pipeline.
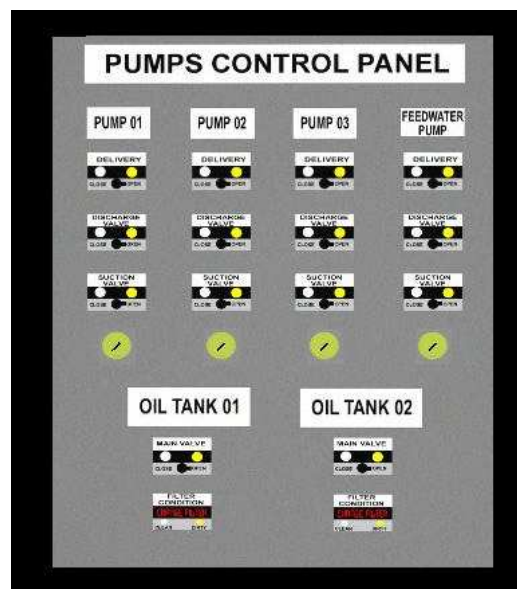
Figure 5.15: Pump's control panel

The textures that are used for the open and closed stages of a valve on the pumps control panel are shown in figure 5.16. These textures are applied on the front face of simple boxes, which are placed on the pump's control panel. Two different objects were built for the open and closed stages of each valve, mapping them with one of the following textures. Two indicators are also placed on the pump's control panel, which help to identify the fuel filter's conditions. Different textures

have been applied to define different modes for these indicators. These textures are presented in figure 5.16.
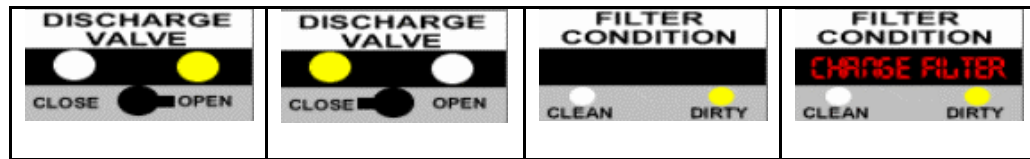
Figure 5.16: Textures for pump's control panel

The design of the boiler's plant control panel was complicated because a variety of indicators and controller should have been imported. Figure 5.17 shows the three-dimensional object, which was constructed in 3D Studio Max for the boiler's control panel.

Figure 5.17: Perspective view of boiler's control panel

The construction of the different types of controller was based on a variety of photos from the literature and these are illustrated in figure 5.18. The bars on the controller's plate are animated and were built in 3D Studio Max by rescaling small three-dimensional box objects.
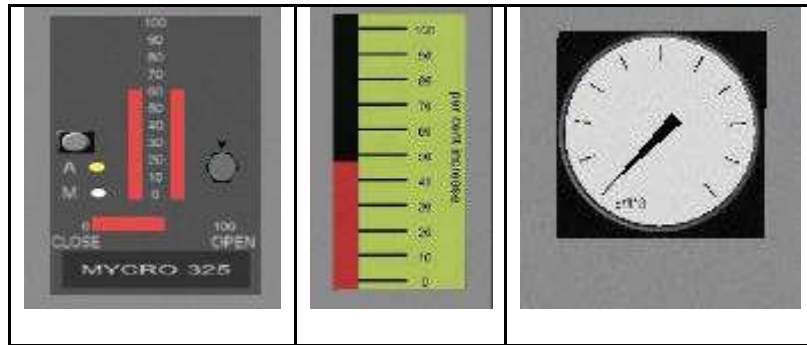
Figure 5.18: Different types of measurement instruments on the boiler's panel

Two different textures were applied on the plate of the first controller indicating the automatic and manual mode. These and other textures used in various instruments on the boiler's control panel are presented in figure 5.19.
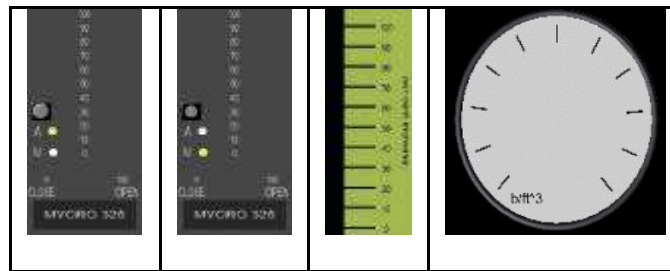
Figure 5.19: Instruments texture images on boiler's control panel

In order to have a general view of plant's condition and see at a glance, which valves or pumps are on, it was decided to construct an interactive flowsheet panel. This flowsheet represents the actual condition of all equipment that constitutes the boiler plant. A view of the three-dimensional panel object is shown in figure 5.20.
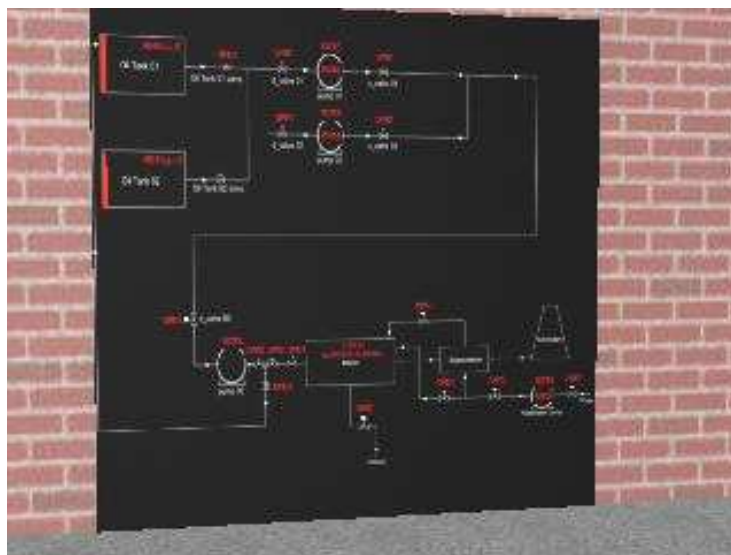
Figure 5.20: A rendered view of the flowsheet panel

On the flowsheet panel's faceplate, there are plenty of indicators that display the state of each item of chemical equipment. These indicators turn on or off depending on the offline or online state of valves and pumps. A animated bar indicator on oil tank's position displays its fuel capacity. All these three dimensional objects were constructed in 3D Studio Max and different texture images were used for offline and online condition.

5.10 The virtual reality model

This model involved the development of a very large and detailed virtual reality model of a boiler plant. Data for the main items of equipment in the plant was imported from AutoCAD designs, the three-dimensional model was then built using 3D Studio Max and the virtual model is running within the SAFE-VR application tool. Figures 5.21 and 5.22 shows general views of the completed virtual boiler plant model.

The real time dynamic simulation of the boiler constitutes one of the most important features of this virtual reality model making training more relevant and realistic. The simulated process translates into a realistic dress rehearsal where the trainees can get as much practice as they need. The complicated chemical process can become second nature to trainees and mistakes are opportunities to learn rather than reasons for reprimands.

The trainees can move around the plant concurrently with the plant simulation that is running independently. As they walk around the plant, hearing the boiler noise, watching or controlling valves, pressure or flow meters, pumps, pipe work, filters, heat transfer devices, storage tanks, vessels and any kind of equipment related to a chemical process. Approaching any pump the trainees are able to hear the sound of its motor. It is necessary for trainees to notice that a pump noise is different when a pump hazard is present. Also, users can test their ability to identify leaks from pipelines, barrels and other vessels that contains toxic or hazardous chemical materials, and to check the performance and condition of boilers, pumps and mechanical equipment which is located in different places. Being able to navigate around a complex chemical plant, such as the boiler plant brings many advantages to the design and the control process.

Figure 5.21: General view of the virtual boiler plant

Figure 5.22: Panoramic view of the virtual boiler plant

A help system built into the model provides additional information about each of the objects present. The help system is implemented in separate windows within the Microsoft Windows environment and includes both text and scanned photographs connected in a hypertext format. Users can activate the help system by clicking on any object with the mouse.

Hotkey	Location
Num1	PC1
Num2	PC2
Num3	PC3
Num4	PC4
Num5	pump03
Num6	feedwater pump
Num7	Pump's control panel
Num8	Boiler plant flow sheet
Num9	Boiler's control panel
Num0	pump01
J	Fuel flow control valve
K	Feed water control valve we
L	Steam export control valve
[	suction valve04
]	discharge valve 04

;	discharge valve03
'	suction valve 03
#	discharge valve01
,	discharge valve02
.	suction valve01
/	suction valve02

Table 5.2: Navigation hotkeys for the boiler plant

To move around in the three-dimensional environment, a joystick can be used, the keyboard's cursor keys, or the mouse. In order to make the navigation easier for the user, default hotkeys have been defined which move the user to certain points within the virtual boiler plant environment. By pressing "H" key on keyboard, a hypertext format page launches which provides available information for navigation around the virtual environment as shown in figure 5.23. Table 5.2 shows the keys used for navigation around the virtual environment.
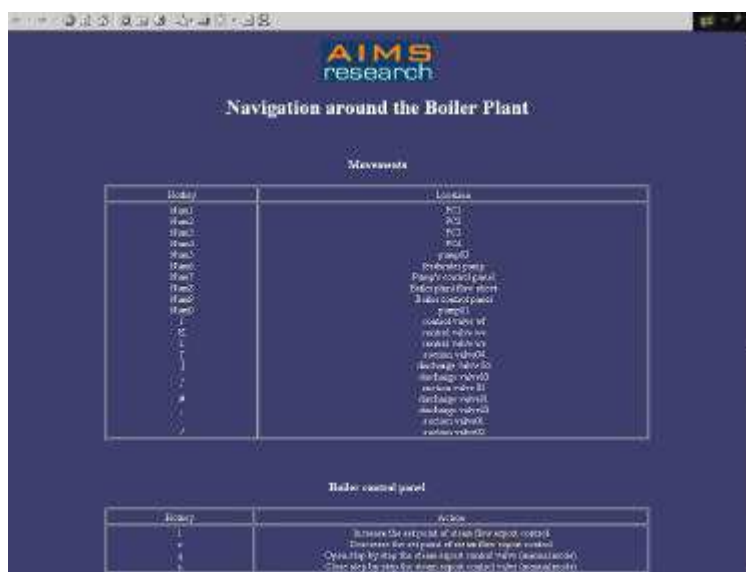
Figure 5.23: The navigation help page for the virtual environment

5.10.1 Process

One of the most obvious benefits on this virtual model is the way it allows easy access to very complex data. Traditionally, a large number of different drawings and diagrams would be needed to describe a chemical plant and an associated process.
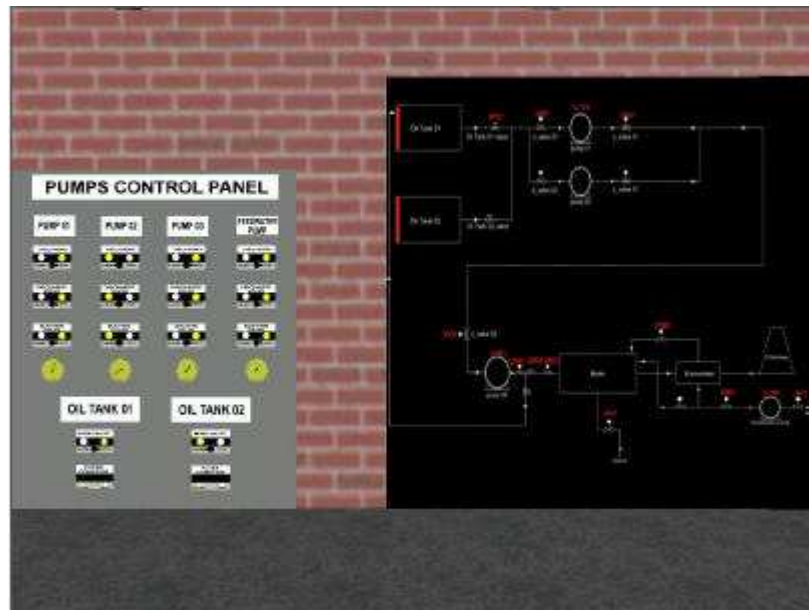
Figure 5.24: The dynamic flow sheet and the pumps control panel

The detailed panels and the interactive flow sheet display of the plant are located in the control room providing information on the status of the equipment, as shown in figure 5.24. The flow sheet responds quickly, showing indicators representing each valve-pump action or hazardous occurrences in every aspect of the boiler plant. This means that if the trainee starts up a pump or manipulates a valve, an indicator is going to appear on the flow sheet panel, corresponding to the user's action. In a hazardous situation the flow sheet panel responds automatically, flashing an indicator over any equipment, which has a problem. For example, if the boiler water level is extremely low, a sign appears on the boiler draw of the flow sheet indicating an emergency situation for the plant. As well as the boiler's condition, the dynamic flow sheet display gives information about the oil tanks capacity. The oil tanks are located outside the enclosed building.

Inside the boiler's plant control room are located vital instruments for watching and checking the performance, condition and operation of equipment involved in the steam generation process. Figure 5.25 shows the message boxes that give information about the operating condition of the water tube boiler. Users can have at any time the value of any variable, which controls the boiler operation.
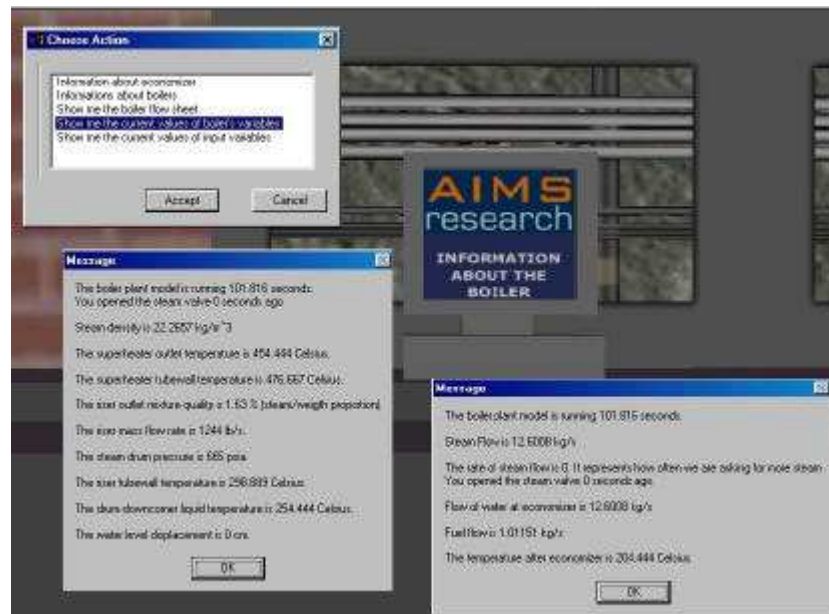
Figure 5.25: Information about the virtual watertube boiler

Using the dynamic graph that is displayed on a monitor inside the control room the user can easily watch the different the values of many plant variables ensuring proper plant operation. Having the possibility to choose the time sample for the dynamic graph, the user is able to follow each variable for a long period during the boiler's operation. Figure 5.26 shows the message boxes, which appear by clicking the monitor. The first message box allows users to choose the sample time for the graph and the second one allows them to choose the variable to monitor.
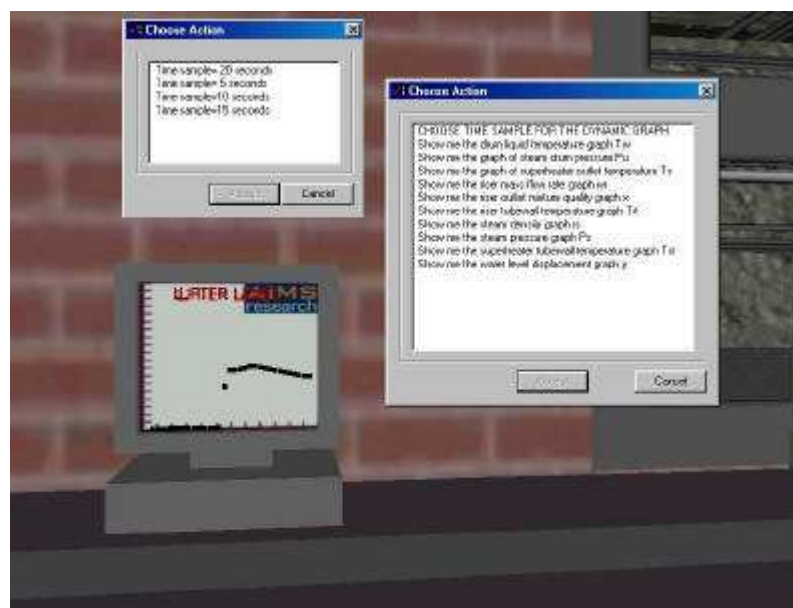
Figure 5.26: The dynamic graph and its control option

There are some hotkeys for the dynamic graph's operation, which are summarised, in table 5.3.

Hotkeys	Action
0	Dynamic graph updated
P	Dynamic graph not updated
T	Displays the graph's time sample

Table 5.3: Hotkeys for dynamic graph's operation

There are three other monitors that give the user of time information about the boiler plant. Details of the types of boilers and knowledge about pump dynamics are provided to help the user to gain a deep understanding of what's happening in this chemical process.

Figure 5.27: Boiler control panel. Prompt for automatic control

Another innovative feature of this virtual reality model is the implementation and existence of two PID controllers on the boiler's control panel as shown in figure 5.27. Both of them control vital variables for the correct operation of the boiler.

The first PID controller adjusts the water level of the steam drum controlling the feed water control valve. It adjusts the water level displacement in the desired value, which is determined by the set point on the controller faceplate. Figure 5.28 explains what the buttons and the bars represent on the faceplate of the controller.
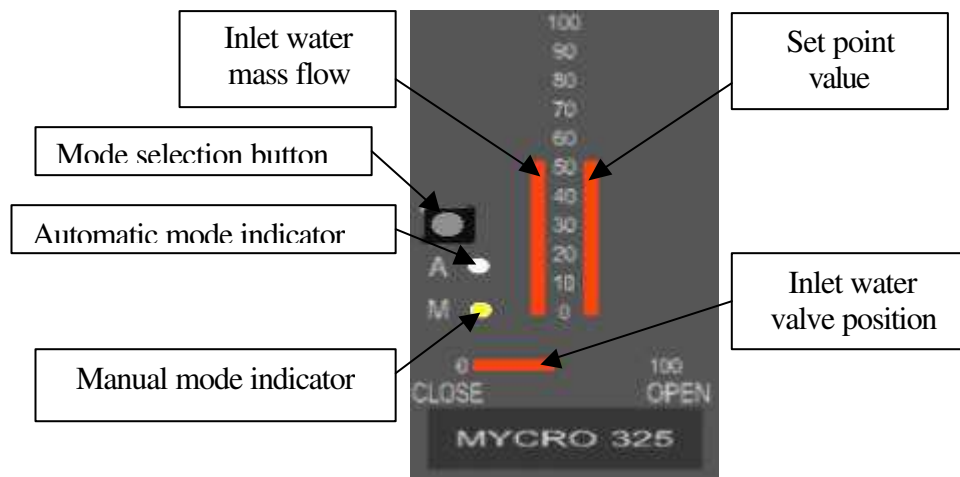
Figure 5.28: Water level PID controller

The left vertical bar represents the mass flow of inlet water in the boiler. The horizontal bar shows how far the valve that controls the water inlet flow is opened. However the right vertical bar represents the set point that the user wants for the water level. Finally, there is a button on the faceplate of the controller, which switches the mode from automatic to manual. When the mode is manual the user is able to open and close the valve manually but this is not allowed in the automatic mode. In the automatic mode the user can only control the variable's set point. So, by turning the water level controller of the steam drum to automatic mode, the system responds by dynamically controlling, proportionately, the feed water flow and trying to set it near to the desired value. As a result the operator does not need to keep watching the instrument, as the steam drum water level is constantly trying to stabilise this in the appropriate position for safe operation. The control of boiler's water level is the most important factor in boiler plant operation. If the water level drops down below the minimum required volume, the hazardous potential for the plant will rise dramatically and explosion hazards become more visible. The other PID controls the steam pressure of the steam drum joint to fuel flow. The algorithms and the operation of these controllers are similar.

The PID control algorithm is built as a state space model simulation, similar to the boiler model, it uses the velocity form of control equation, which provides bumpless auto/manual transfer and facilitates the manual manipulation of control valve positions. This is a standard technique on real controllers and also provides an excellent basis for virtual reality implementation. Section 5.9.1.1 will discuss the representation of the algorithm, which is used for the PID controller implementation.

There are, also, on the boiler's control panel, all the essential instruments that display the values of the nine different variables of the boiler. For instance, there are different meter types for steam density, temperatures, flows, level displacement and pressures. A number of hotkey have been assigned to different controller functions, which are placed on the boiler's control panel faceplate. Table 5.4 summarises some of these.

Hotkey	Operation
1	Increase the set point of steam flow export control
z	Decrease the set point of steam flow export control
q	Open step by step the steam export control valve (manual mode)
a	Close step by step the steam export control valve (manual mode)
2	Increase the set point of fuel flow controller
x	Decrease the set point of fuel flow controller
w	Open step by step the fuel flow control valve (manual mode)
s	Close step by step the fuel flow control valve (manual mode)

Table 5.4: Hotkeys for boiler's control panel operation

Figure 5.29: The ladder logic diagram in SAFE-VR for the dynamic boiler

operation

Figure 5.29 shows the SAFE-VR simulation module, which is controlling the dynamic operation of the boiler. The ladder logic diagram is running from left to right continuously, calculating the dependent variables of the mathematical model in step changes of operating variables.

5.10.1.1 PID Controller Implementation

For controller (I%) the tuning parameters are:

K(I%) – proportional gain factor

I(I%) – internal factor

R(I%) – derivative action time

The controller sample period is MR(I%), which has the same time units as I(I%)

and R(I%).

AM(I%) is a flag set to 0 for manual mode (allowing the control valve to be manipulated manually) and set to 1 for automatic mode (where the three term control equation manipulates the valve).

MV(I%) is the most recently updated value of the measured variable under control.

SP(I%) holds the set point value (which is set manually through the controller faceplate)

A suitable coding for the controller operation is shown in figure 5.30:

```
IF AM(I%)=0 THEN
CO(I%) = 0
E1(I%) = 0
DE1(I%) = 0
ELSE
E = SP(I%)-MV(I%)
        DE = E-E1(I%)
        D2E = DE-DE1(I%)
        CO(I%) = K(I%)·(MR·E/I(I%)+R(I%)·D2E/MR)
        E1(I%) = E
        DE1(I%) = DE
ENDIF
```

Figure 5.30: PID algorithm

Obviously E1(I%) and DE1(I%) must be stored between cycles (and also initially to zero at the programme start up).

Figure 5.30 shows the SAFE-VR simulation module, which is holding the algorithm for both PID controllers. The ladder logic diagram is running from left to right continuously, as the virtual boiler model is running.

The graphs in figures 5.32 and 5.33 show the responses of both controllers after a steam export increases. As can be seen from the graphs the controllers are able to stabilise the process variables, which is important for proper operation.
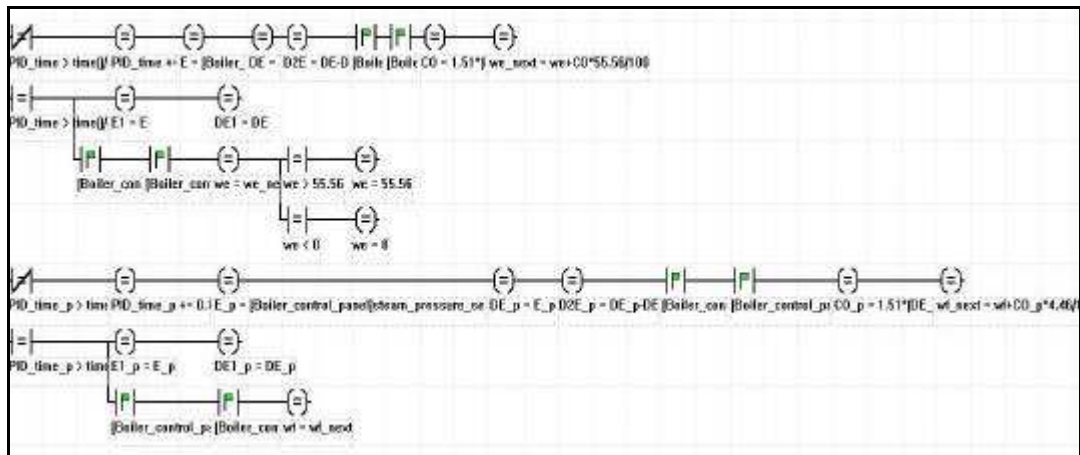
Figure 5.31: The ladder logic diagram in SAFE-VR for the PID controller algorithm
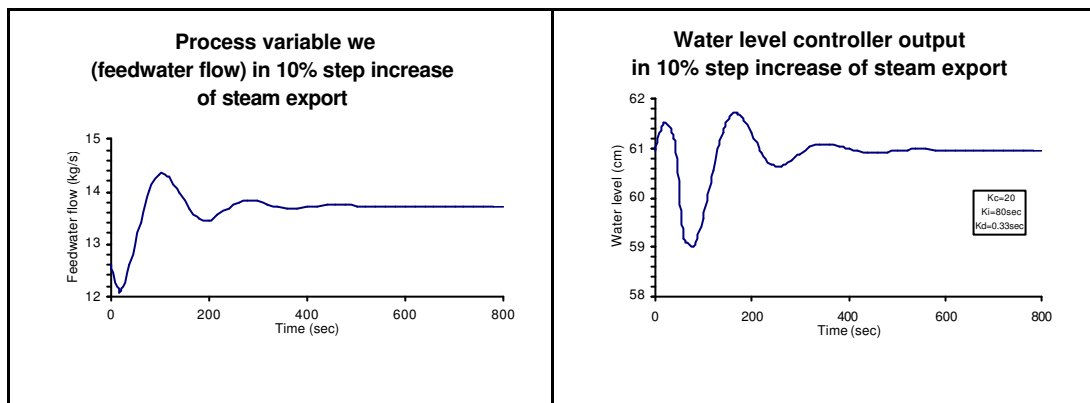
Figure 5.32: Water level controller output in step changes of steam export flow
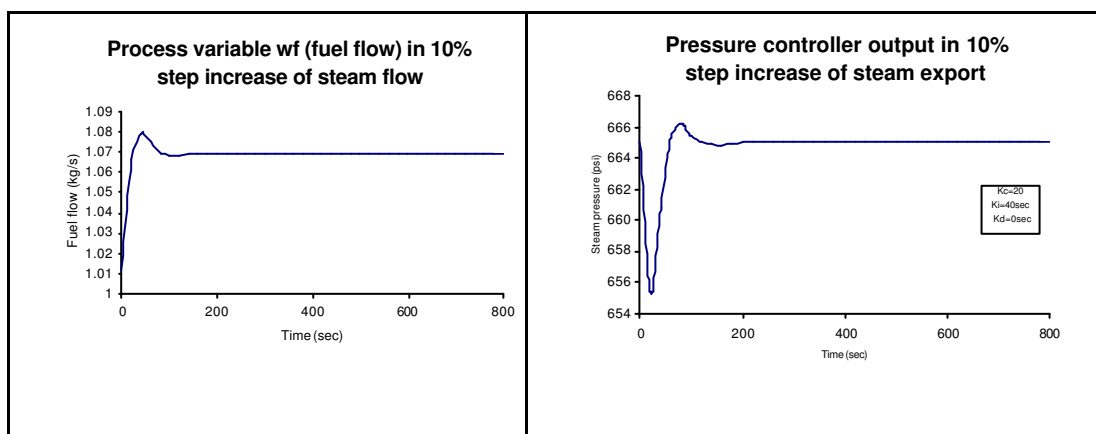
Figure 5.33: Pressure controller output in step changes of steam export flow

5.10.2 Hazard spotting

Health, safety and training are the other areas where the virtual boiler plant provides significant advantages and benefits.

At the beginning of each training session, the users need to decide what personal protective clothing and equipment must be worn in order to navigate safely around the chemical plant. As figure 5.34 illustrates, the users can make a choice between safety boots, overalls, goggles, hard hat, ear protectors, gloves and bibs. These safety aspects improve the safety awareness of the trainee and make plant operation training safer and more efficient.
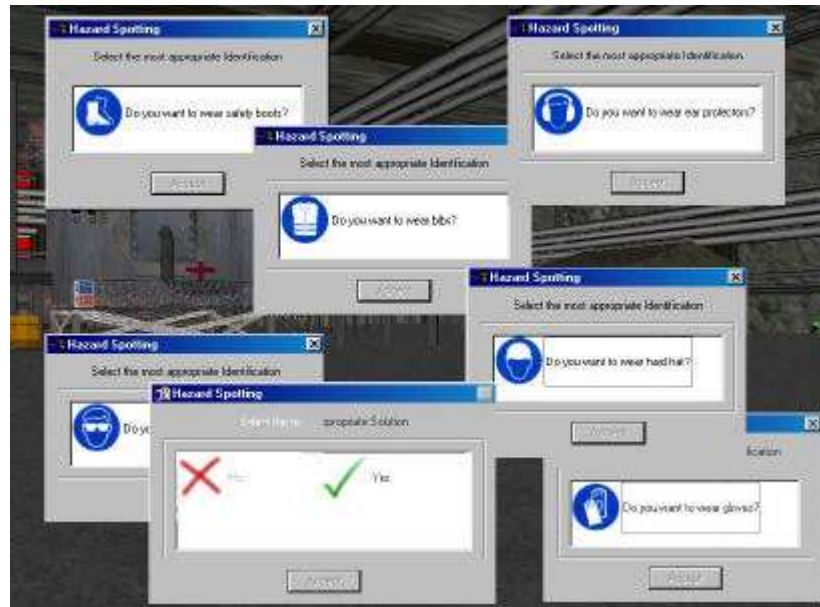
Figure 5.34: Prompts for personal protective equipment

The user is also able to check issues such as fuel leakages and barrels of toxic materials that are sources of hazards with a potential for causing an accident in the plant. Figure 5.35 shows the message boxes that are displayed when the users spot a hazard in the virtual boiler plant. The first message box asks for them to select the most appropriate hazard identification and the second one to choose the most appropriate solution.

Figure 5.35: Hazard spotting in virtual boiler plant

In the event of a chemical equipment failure, the user should perform certain tasks in order to avoid catastrophic consequences for the plant and then should go to the place that the certain equipment is located trying to find out what is wrong.
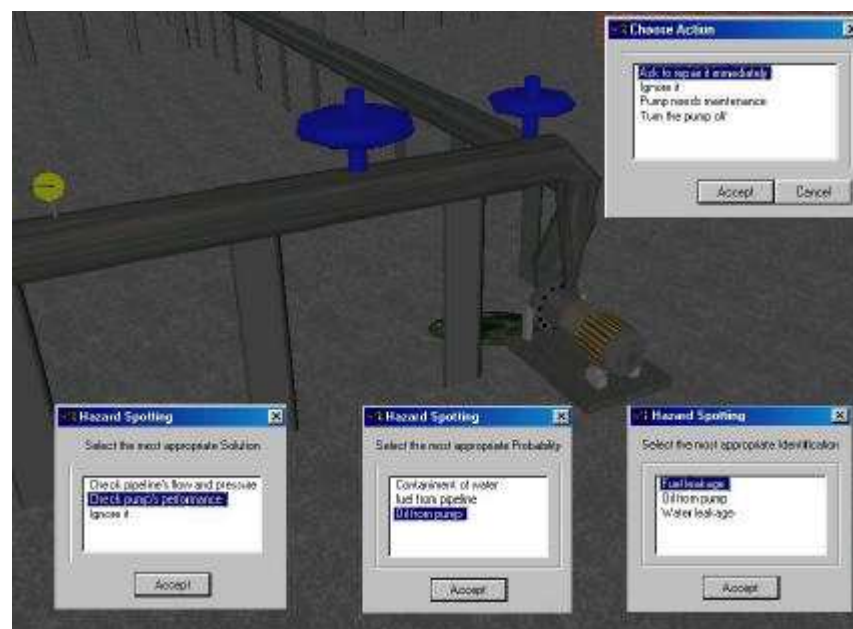
Figure 5.36: Fuel pump system failure to deliver

Figure 5.36 shows the message boxes that are displayed when a pump fails to deliver a large enough volume of fuel. As it is shown in the image, the trainee

should first identify the hazard, the problem of the bad pump's performance and then should choose the most appropriate solution from a list.

Each entry in the hazard's multiple-choice list has a score associated with it. At the end of the session these scores are totalled, converted to a percentage of maximum available scores for that session, and then presented to the user. In addition to the total score, the session report also contains a tree, showing how the score has been derived. Users can see scores for individual hazards, and where scores have been lost can see what the highest scoring answers would have been. Where hazards were present but not spotted, the system can show the hazard clearly, pointing the user towards it, outlining it and fading out the rest of the world.

5.11 Summary

The virtual boiler plant safety training system is characterised by a number of features each of which contributes to the sense of "reality" in the experience. Having consider all these features, it is quite easily to understand that the virtual boiler plant training system is a powerful engineering tool that anyone can learn to operate it or to train oneself to prevent hazardous situation in half an hour.

First of all, the view of the chemical plant layout is three-dimensional providing the user with a view of the virtual world that matches their physical position and direction of view within the world, allowing the immersion of the user in the virtual world. The virtual environment of the chemical plant is dynamic, making training and navigation similar realism, as it would be in the actual world. The plant noise and the pump's motor sounds in combination with the attenuation distance from the three-dimensional objects make the virtual model more realistic. The steam generation process in the boiler responds dynamically in any changes of fuel or feedwater fuel. This dynamic simulation of the steam generation process provides a realistic system view to operators and prepare them for critical or dangerous situations which otherwise would be very difficult or impossible to create. Users can monitor all these features, by looking at the extensive panels in the control room. For example, turning switches on the control panels, the user can see valves opening or closing and pumps starting to run. The instruments,

which are inside the control room are so interactive and realistic that the user's immersion becomes more effective in the virtual environment.

One of the significant advantages of this virtual training environment over a real one is its enormous flexibility. The virtual environment can be used as a basis for training in any number of different scenarios so that trainees can learn to cope with many different situations, some of which are impossible to prepare for in any other way. Another advantage of the virtual boiler plant is that trainees learn by actively performing actions. This has a significant effect on their ability to retain what they learn, and is clearly superior to passive techniques such as video or books, for training where spatial understanding is important.

Thus, in exploring a virtual world of a chemical plant environment, the user must perform a number of tasks, including navigation, operating different types of equipment, checking meters and responding in any hazardous situation without having shutting down any operating process of the real plant. An industry has the possibility to train workers and engineers using virtual reality before the plant is built. Furthermore, they are able to visit areas of the plant, which would have been very difficult to access in reality.

Chapter 6

Virtual packed column

6.1 Introduction

This chapter describes a virtual world based on an undergraduate laboratory experiment for the Chemical Engineering degree course at the University of Nottingham. It concerns two packed columns, which are used to absorb ammonia from an air stream. It describes the dynamic mathematical model, the simulation and the virtual reality implementation of this gas absorption experiment. This chapter also discuses issues related to laboratory safety and explains the functionality of the current virtual reality experiment.

6.2 Laboratory safety

University laboratories present a unique challenge to health and safety personnel due to the many types of hazards that are present. Laboratory safety is extremely important, particularly in those laboratories where students first develop practices and habits that they may carry with them throughout their careers. Because this importance is widely agreed upon, all undergraduate chemistry and unit operations labs include some amount of safety training, encompassing at a minimum a long list of safety rules. These rules are often handed out on the first day of laboratory work, along with the course grading policy, exam schedule, and instructor's e-mail and office location (Jenkate *et al*, 2001)

In spite of these precautions, however, accidents are possible to occur. Two major causes for these possible safety violations are forgetfulness and complacency, the latter of which can be considered as forgetfulness of the importance and significance of the rules, as opposed to forgetfulness of the rules themselves. The bottom line is that safe practices are not retained in students' memory as well as they would like (Bell and Fogler, 1999).

Those persons who have ever been involved in an accident, however, tend to remember their experience much longer and more vividly than any set of written

rules. As a result, they tend to follow safe practice guidelines much more rigorously, in order to ensure that such experiences never happen again. If all students could be involved in laboratory accidents, then they would all follow safer laboratory practices in the future. Virtual reality is able to deliver highly realistic experiences through the medium of enhanced computer simulations. The ultimate goal of virtual reality is to produce simulations so realistic and believable that users cannot discern them from reality. Virtual reality simulations are enhanced through high-speed interactive immersive three-dimensional computer graphics (Bell and Fogler, 1999).

6.3 Packed columns

The flow of fluids through beds composed of stationary granular particles is a frequent occurrence in the chemical industry and therefore expressions are needed to predict pressure drop across beds due to the resistance caused by the presence of particles. Packed columns are used for distillation, gas absorption, and liquid-liquid extraction but are commonly employed to carry out absorption and scrubbing operations. They provide a medium in which counter-current two phase flow occurs, and in which a relatively large gas-fluid interface per unit volume of column volume exists. The gas liquid contact in a packed column is continuous, not stage-wise as in a plate column (Coulson and Richardson, 1999). A schematic diagram showing the main components of a packed absorption column is given in figure 6.1.
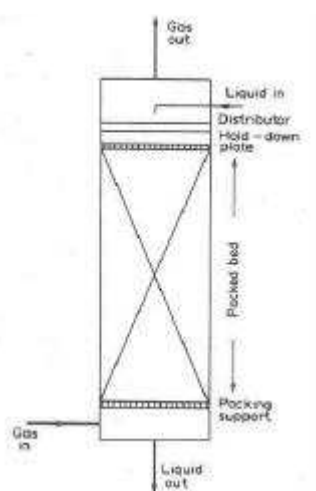
Figure 6.1: Schematic diagram of a packed absorption column (after, Coulson and Richardson, 1999)

The principal requirements of the packing material are to provide a large surface area with low resistance to gas flow, and to promote uniform liquid distribution on the packing surface and vapour gas flow across the column cross section. Many types and shapes of packing have been developed which can be divided into two broad categories:

?? Packings with a regular geometry such as stacked rings, grids and proprietary structured packings

?? Random packings, as it is used in both column of the simulated experiment, such as rings, saddles and proprietary shapes, these are dumped into the column and take up a random arrangement (Coulson and Richardson, 1999).
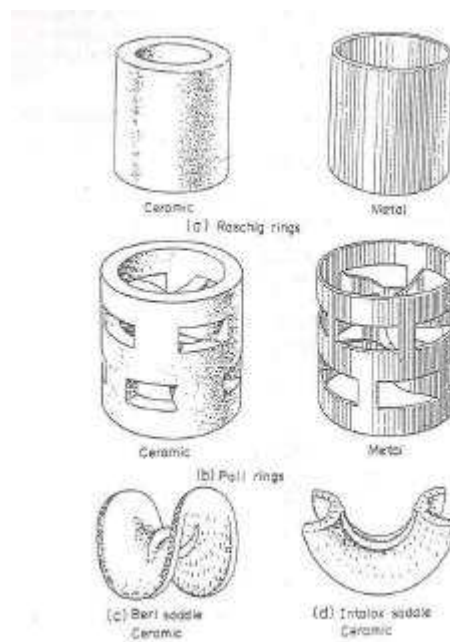
Figure 6.2: Types of packing (after Coulson and Richardson, 1999)

The principal types of packing are shown in figure 6.2. The gas absorption packed columns of this experiment have raschig rings made of glass and ceramic respectively. Raschig rings are one of the oldest specially manufactured types of random packing and are still in general use in the process industries. They are cheaper per unit volume than Pall rings and they are available in a variety of materials.

6.4 Laboratory rig

The pilot plant consists of two packed columns, which share the same ammonia; air and sulphuric acid (0.5M) supply and connected to the same air through a kerosene manometer. The flow sheet of this process is shown in the figure 6.3. and some photos of the laboratory rig are shown in figures 6.4 and 6.5.
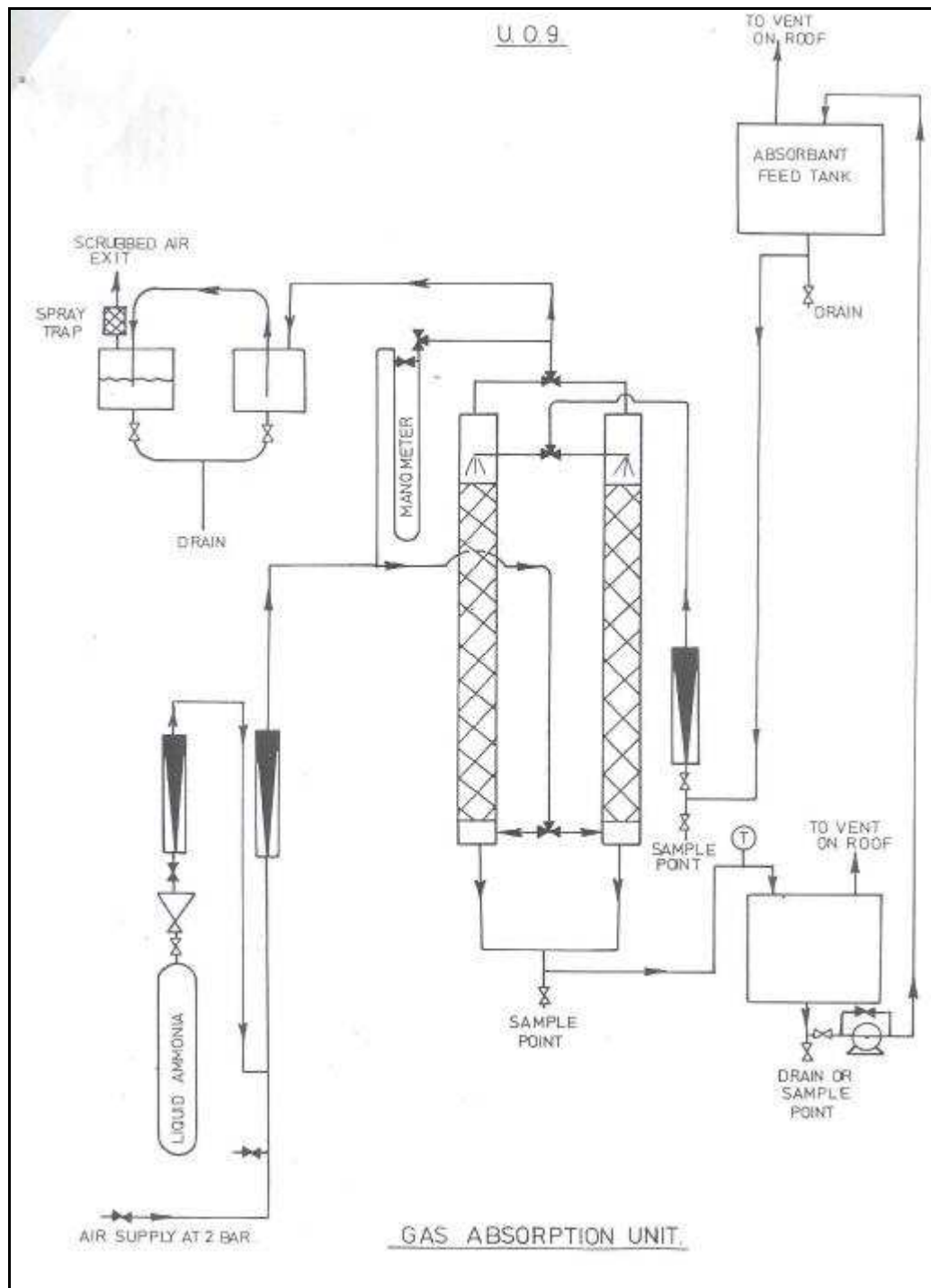
Figure 6.3: The flow sheet of the gas absorption unit

Figure 6.4: Photo from the laboratory rig
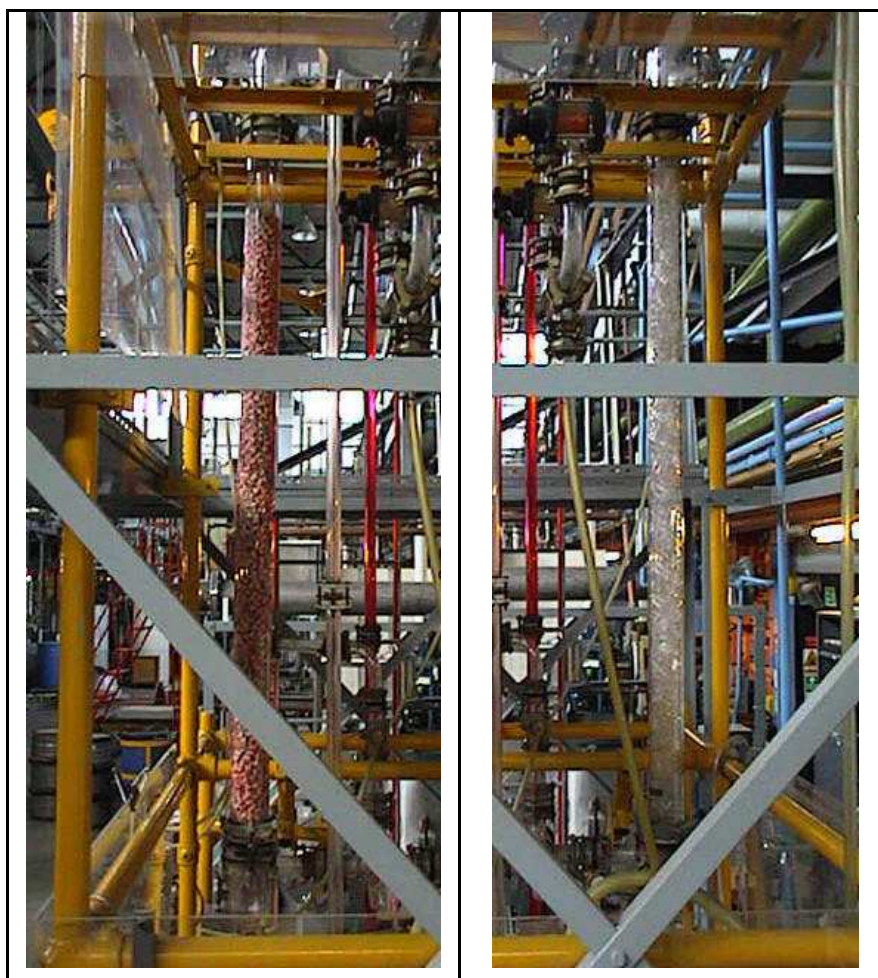
Figure 6.5: Photos from ceramic and glass raschig rig columns

The operation between the two columns is switched by changing four valves on the plant. Dilute sulphuric acid flows down each column from the tank above and is metered. Ammonia is supplied at 1 bar and is metered as it leaves the liquid cylinder. Air is supplied at 2 bar pressure and mixed with ammonia before it reaches the columns. A rotameter measures the flow of combined air and ammonia, which enters the column at the bottom and exits at the top. Calibration charts for the two rotameters are provided and they can found in figures 6.6 and 6.7. A sampling point is provided at the top of each column, so that ammonia concentration in the gas outlet can be measured. Any ammonia present is then scrubbed to make sure that only air is released into the atmosphere. An indicator is used, so as to detect excess ammonia in the outlet stream.

Voidage for each column has been estimated using the volume of packing and the volume of column bed. The values of voidage for each column are similar to those provided by the published literature for ceramic and glass raschig rings column (Coulson and Richarson, 1998). Table 6.1 provides some physical data for both columns.

Column	A	B
Height of packing, Z	1.5 m	1.5 m
Diameter of packed section	76 mm	76 mm
Volume of column bed	$0.00681 \, m^3$	$0.00681 \, m^3$
Packing material	Glass raschig rings	Ceramic raschig rings
Diameter of packing material	16mm OD, 12mm ID	11.45mm OD, 6.45mm ID
Length of packing material	22 mm	13.5 mm
Number of packing pieces	964	2672
Surface area of packing	$2.108 \, m^2$	$2.108 \, m^2$
Volume of packing	$0.00187 \, m^3$	$0.00254 \, m^3$
Specific surface area of packing S	$1130 \, m^2/m^3$	$948 \, m^2/m^3$
Voidage, e	0.73	0.63

Table 6.1: Physical data for both columns
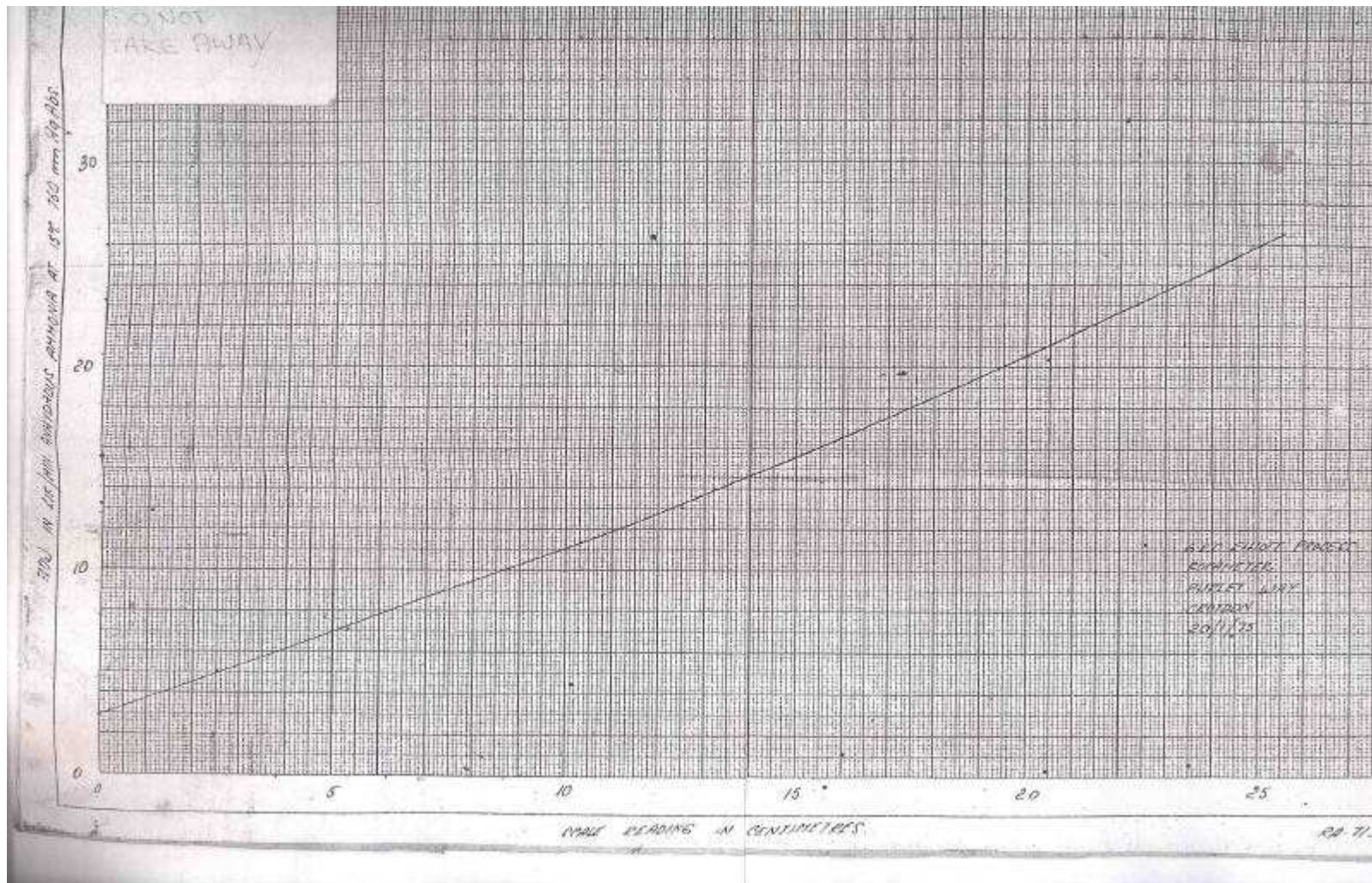
Figure 6.6: Ammonia rotameter calibration chart
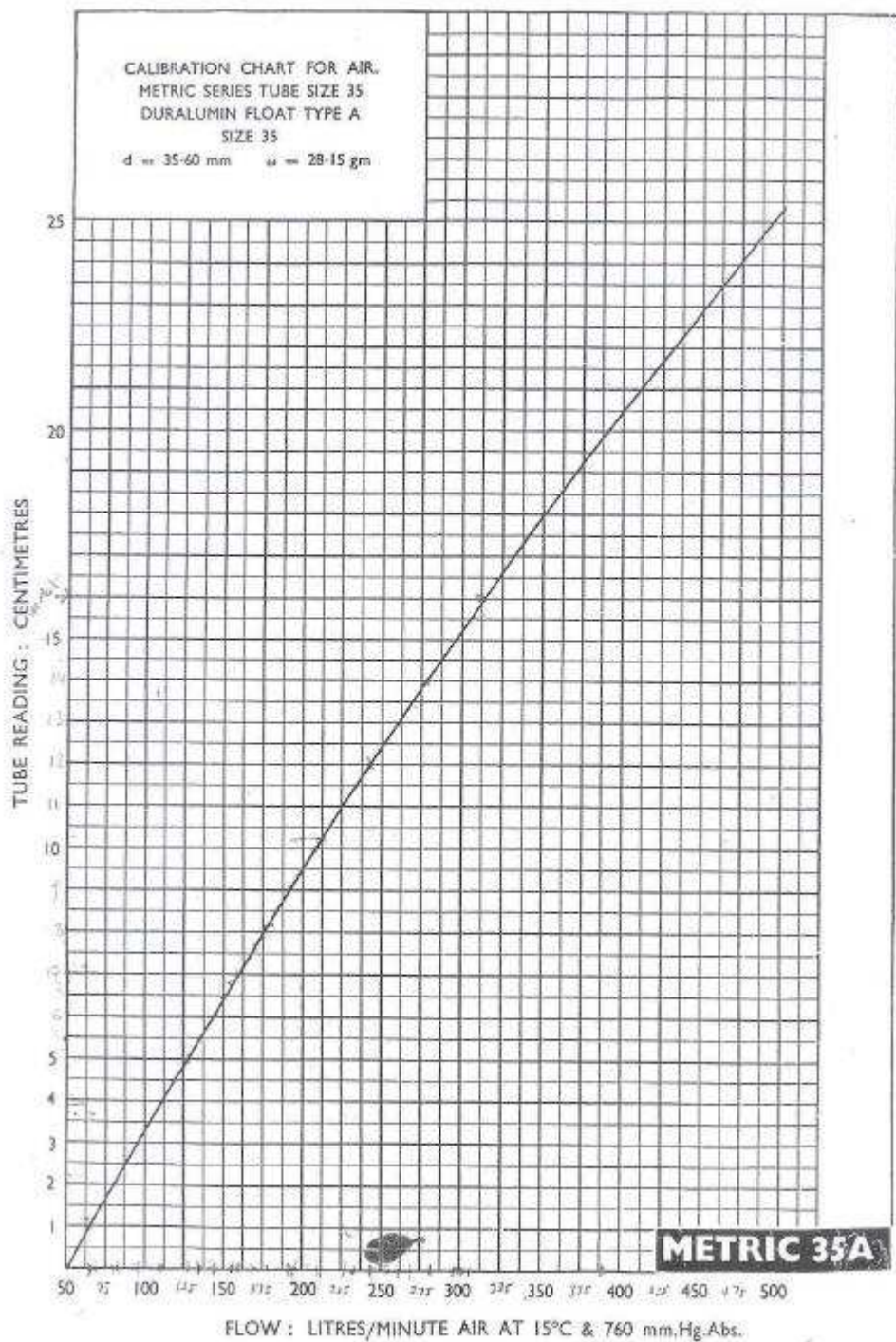
Figure 6.7: Air rotameter calibration chart

6.5 Flooding and loading points

The hydraulics and dynamics of a packed column are represented by its loading and flooding points. These are determined from a number of experimental runs at various liquid and gas flowrates. The loading and flooding conditions are characterised by sudden increases in pressure drop across the column, when plotted against gas flow on the log-log scale. Below the loading point, liquid present in the column is minimal and pressure drop is mainly due to gas flowing up the relatively empty column. At the loading point liquid starts to build up in spaces between the packing, which increase the resistance to gas flow and causes an increase in pressure drop. When the flooding point is reached, these spaces are completely filled up with liquid. The gas now has to bubble its way through the column and this is associated with a large pressure drop.

For each column the first series of experimental runs involve determining pressure drop as a function of gas flow using a different number of liquid flowrates for both columns. In each case pressure drop is measured using the kerosene manometer. During each run, the column is allowed to reach a steady state for 5 minutes under required conditions before any measurements are taken. All experimental runs are carried out at the room temperature (approximately $20^{o}C$ and pressure 1 atm).

Figures 6.8, 6.9, 6.10, 6.11 and 6.12 summarise pressure drop $?P$ across the column in cm Kerosene at different gas and liquid flowrates for column A and B respectively. Around flooding, each column is filled to the top of its packing with liquid and at higher flowrates, liquid continues to accumulate above the packing and as a result gas bubbles begin to appear and become more vigorous. In general, column A (glass raschig rings) has a lower pressure drop that column B (ceramic raschig rings) for the same conditions, this may happen because the voidage in column A is larger than that of column B, allowing an easier passage of gas.

Liquid flow rate 20 l/h		
Rotameter Reading	Air Flow (lt/min)	? P (cm Kerosene)
1	65.62	0.8
2	81.25	1.2
3	96.87	1.6
4	112.5	2.4
5.4	134.37	3.2
7	159.37	4.6
8.5	182.81	6.2
10	206.25	8.2
11	221.87	9.6
12	237.50	11.2
13	253.12	13.2
14	268.75	15.8
14.5	276.56	17.2
15	284.37	18.6
15.5	292.19	20.2
16	300.00	21.2

Liquid flow rate 50 l/h		
Rotameter Reading	Air Flow	? P (cm Kerosene)
1.1	67.19	1.2
2.1	82.81	1.6
3.1	98.44	2.4
4.1	114.06	3.0
5.1	129.69	3.8
6.1	145.31	5.0
7.1	160.94	6.0
8	175.00	7.0
9	190.62	8.6
10	206.25	10.2
11	221.87	12.6
12	237.50	14.6
13	253.12	18.0
13.5	260.94	20.4
14.1	270.31	23.8
14.6	278.12	26.4
15.2	287.50	30.2
15.5	292.19	31.6
16.1	301.56	34.8

Figure 6.8: Pressure drop across column A (glass raschig rings) at various air flowrates and liquid flowrates 20lt/h and 50 lt/h

Liquid flow rate 80 l/h		
Rotameter Reading	Air Flow (lt/min)	? P (cm Kerosene)
1	65.62	1.2
2	81.25	1.8
3.1	98.44	2.6
4	112.50	3.4
5.3	132.81	4.8
6.1	145.31	5.6
7	159.37	7.2
7.8	171.87	8.4
8.2	178.12	9.0
8.9	189.06	10.6
9.4	196.87	11.6
9.8	203.12	13.0
10.3	210.94	14.4
10.8	218.75	16.2
11.4	228.12	19.0
12	237.50	22.0
14.2	271.87	36.2
15.2	287.50	49.2

Liquid flow rate 112 l/h		
Rotameter Reading	Air Flow	? P (cm Kerosene)
1	65.62	1.4
2.1	82.81	2.1
3.1	98.44	3.0
4.1	114.06	4.2
4.9	126.56	5.0
6	143.75	6.6
6.9	157.81	8.4
8	175.00	11.2
8.7	185.94	13.0
9.4	196.87	16.0
10.1	207.81	18.8
10.6	215.62	21.2
11.4	228.12	25.4
12.3	242.19	33.4

Figure 6.9: Pressure drop across column A (glass raschig rings) at various air flowrates and liquid flowrates 80 lt/h and 112 lt/h

Liquid flow rate 136 l/h		
Rotameter Reading	Air Flow	?P (cm Kerosene)
1.2	68.75	1.8
2	81.25	2.4
3	96.87	3.4
4.3	117.19	5.0
5	128.12	6.2
6.7	154.69	9.8
7.4	165.25	11.8
8	175.00	14.6
8.7	185.94	17.8
9.3	195.31	21.0
10.4	212.50	27.2

Liquid flow rate 160 l/h		
Rotameter Reading	Air Flow (lt/min)	?P (cm Kerosene)
0.8	62.50	1.4
1.8	78.13	2.4
3	96.88	3.8
3.9	110.94	5.2
4.5	120.31	6.2
5.1	129.69	7.6
5.6	137.50	8.8
6	143.75	10.0
6.6	153.13	12.6
7.3	164.06	15.2
8	175.00	17.6
8.6	184.38	20.4
9	190.63	25.6
9.7	201.56	30.0
10.9	220.31	40.8
11.6	231.25	62.2

Figure 6.10: Pressure drop across column A (glass raschig rings) at various air flowrates and liquid flowrates 136 lt/h and 160 lt/h

Liquid flow rate 20 l/h		
Rotameter Reading (cm)	Flow of air	? P (cm Kerosene)
0.5	57.81	1.8
1.5	73.44	3.4
2.5	89.06	4.8
3.5	104.69	6.0
4.5	120.31	8.2
5.5	135.94	10.6
6.5	151.56	13.6
7.5	167.19	16.4
8.6	184.38	20.2
9.6	200.00	25.6
10.6	215.63	31.6
11.6	231.25	42.4
12.6	246.88	49.8
13.5	260.94	60.4

Liquid flow rate 50 l/h		
Rotameter Reading (cm)	Flow of air	? P (cm Kerosene)
0.4	56.25	2.6
1.4	71.88	4.2
2.4	87.50	6.4
3.3	101.56	8.8
4.2	115.63	11.0
5.2	131.25	15.4
6.4	150.00	21.2
6.8	156.25	25.2
8.0	175.00	34.2
8.5	182.81	41.6
10.1	207.81	56.0

Figure 6.11 Pressure drop across column B (ceramic raschig rings) at various air flowrates and liquid flowrates 20lt/h and 50 lt/h

Liquid flow rate 60 l/h		
Rotameter Reading	Air Flow	?P (cm Kerosene)
1.2	68.75	46
2.3	85.94	80
3.4	103.13	112
4.3	117.19	162
5.3	132.81	218
6.5	151.56	308
7.4	165.63	314
6	143.75	320
6.7	154.69	422

Liquid flow rate 80 l/h		
Rotameter Reading	Air Flow (lt/min)	?P (cm Kerosene)
1	65.63	56
2	81.25	90
3.3	101.56	160
4.2	115.63	250
5.2	131.25	372
6	143.75	516

Liquid flow rate 100 l/h		
Rotameter Reading	Air Flow	?P (cm Kerosene)
0.4	56.25	54
1	65.63	72
1.6	75.00	96
2.1	82.81	130
2.8	93.75	206
3.3	101.56	270
3.6	106.25	302

Liquid flow rate 120 l/h		
Rotameter Reading	Air Flow (lt/min)	?P (cm Kerosene)
0.2	53.13	60
0.8	62.50	98
1.4	71.88	124
1.9	79.69	176
2.4	87.50	280
3.1	98.44	360

Figure 6.12: Pressure drop across column B (ceramic raschig rings) at various air flowrates and liquid flowrates 60, 80, 100 and 120 lt/h

The data for pressure drop against gas flowrates are plotted in a log-log paper for each column as shown in figures 6.13 and 6.14. This type of graph is used to detect any trends, which may help to identify the loading and flooding points for each column. As predicted in the literature, the loading and flooding points are associated with changes in the gradient and the gradient should changed by at least a factor of two at the loading points and the graph should be also vertical at the flooding points. This is not observed with experimental data because there are still some void spaces not filled with liquid even at high gas flowrates and as a result the gas can still make its way through the column, without being subjected to an excessive pressure drop.

The loading points for column A are seen around 1.8×10^{-3} and 2.7×10^{-3} m³/s of gas flowrate, and around 2.8×10^{-3} and 4.3×10^{-3} m³/s of gas flowrates for column B. Pressure drop ΔP at the loading points are 5-5.6 cm of Kerosene for column A and 13.2-16 cm of Kerosene for column B.

There is no completely generalised expression for calculating the onset of loading and flooding conditions. A useful graphical correlation for flooding rates was first presented by Sherwood for random-dumped packing in which (Coulson and Richarson, 1998 and Perry *et al*, 1984) :

$$\frac{u_G^2 S(1-\epsilon)}{g\epsilon^3} \frac{\rho_G}{\rho_L} \left(\frac{\mu_L}{\mu_w} \right)^{0.2} \quad \text{is plotted against} \quad \frac{L'}{G'} \sqrt{\frac{\rho_G}{\rho_L}}$$

where

u_G is the superficial velocity of the gas in m/s,

S is the surface area of packing per unit volume of bed in m²/m³,

ρ is the density in kg/m³,

g is the acceleration due to gravity,

L' is the mass rate of flow per unit of the liquid in kg/m²s,

G' is the mass rate of flow per unit of gas in kg/m²s,

μ is the viscosity in Ns,

e   is the voidage

Suffix G, L and W refers to gas, liquid and water respectively

Figure 6.13: Pressure drop against gas flow rate for various liquid flow rates, for Column A (ceramic raschig rings)

206
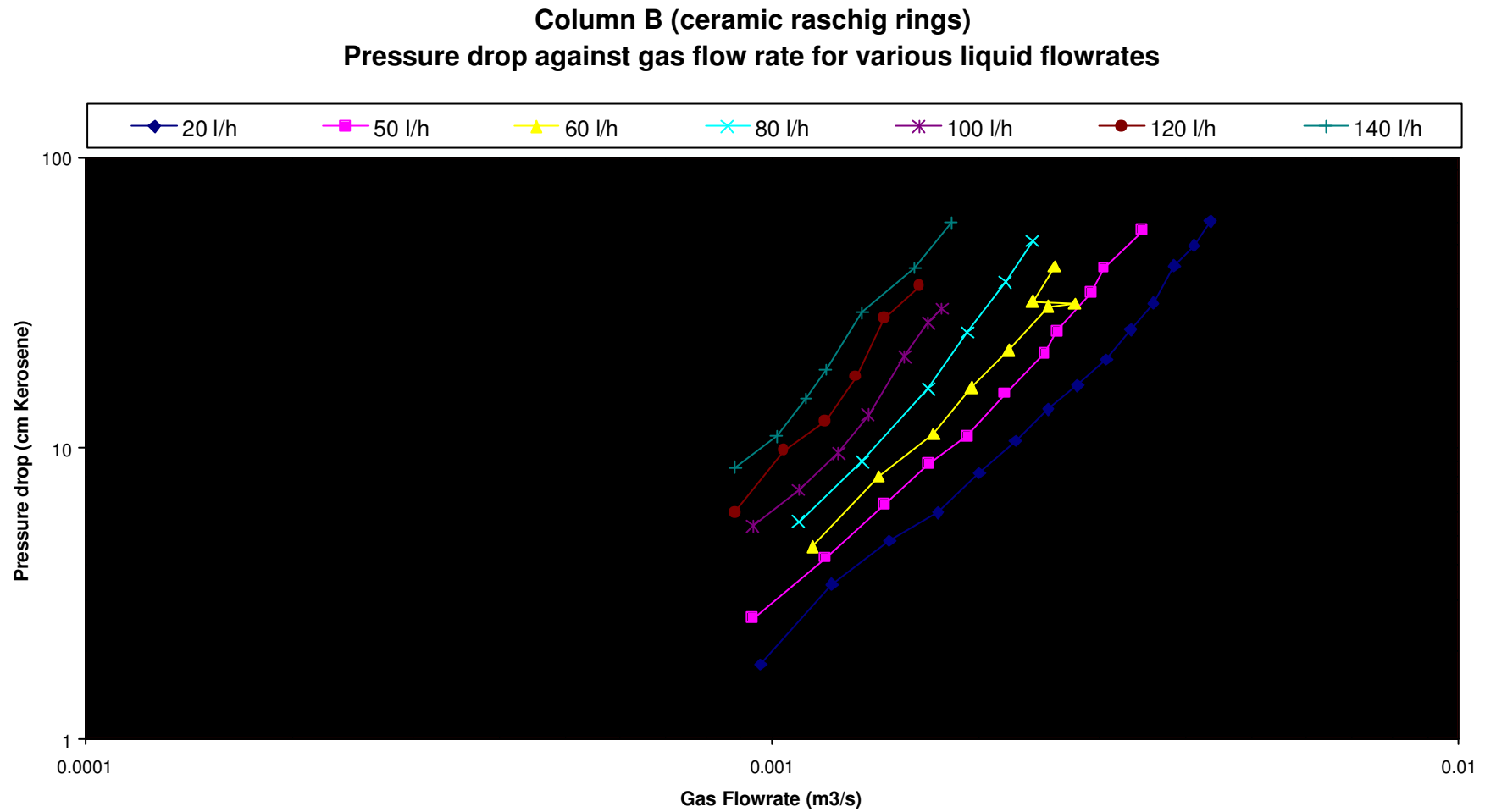
Figure 6.14: Pressure drop against gas flow rate for various liquid flow rates, for Column B(ceramic raschig rings)

The superficial velocity of the gas u_G is the velocity of the gas calculated over the whole cross-section of the packed bed and is given

$$u_G \ ? \ \frac{\text{volumetric flow } (m^3/s)}{\text{column cross - sectional area } (m^2)} \qquad (6.5.1)$$

where

column cross-sectional area$=\frac{1}{4} ?? \ ? D^2$

and D is the diameter of packed section

The generalised correlation graph of Sherwood for flooding rates in packed towers is presented in figure 6.15
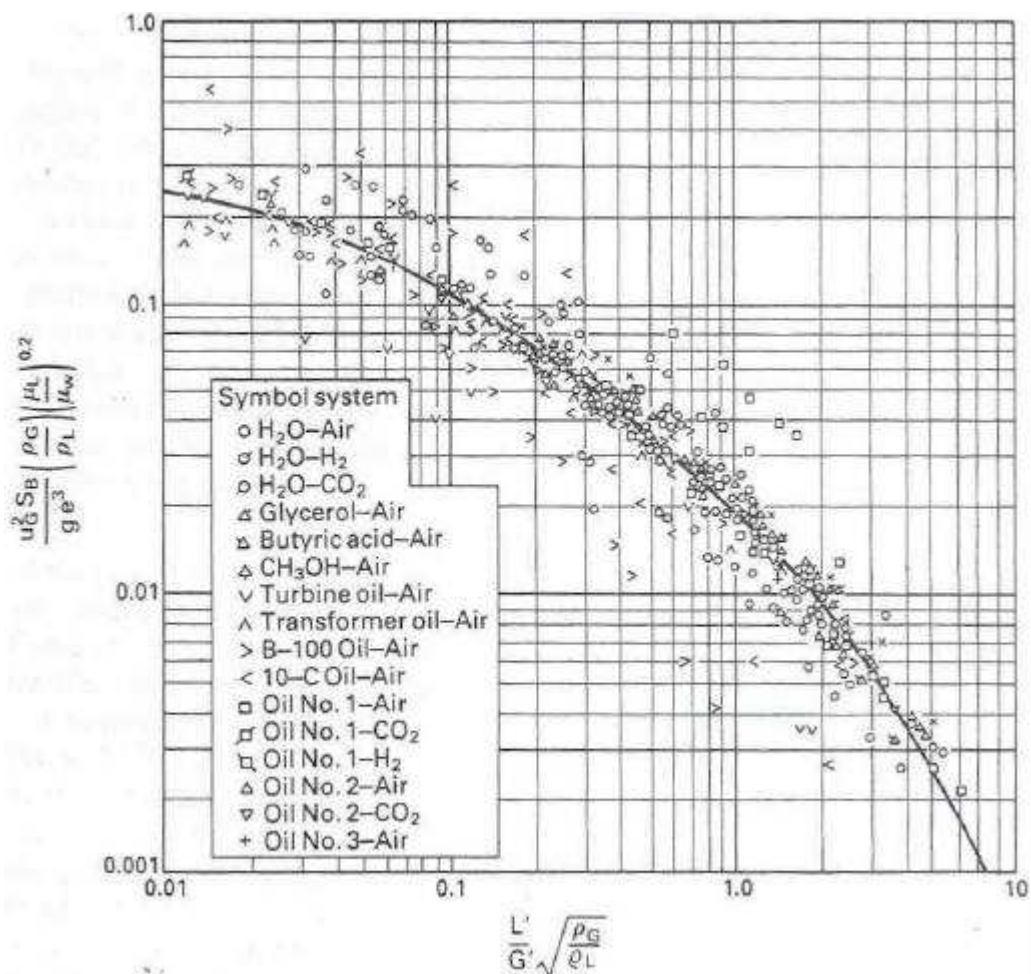
Figure 6.15: Generalised correlation for flooding rates in packed towers (after Coulson and Richardson, 1998)

The area inside the curve represents possible operating conditions. The ratios ρ_G / ρ_L and ρ_G / ρ_L have been introduced so that the relationship can be applied for a wide range of liquids and gases.

Data obtained at various gas and liquid flowrates as shown in tables 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8 and 6.9 and then are plotted on the same axes as the Sherwood correlation curve as shown in figures 6.16 and 6.17. Points above flooding, below flooding and at flooding are indicated using different colours in the graphs. As the graphs shows flooding points for ceramic raschig ring column are scattered slightly below the Sherwood correlation curve and those of glass raschig rings column are found slightly to the right on the correlation curve.

Liquid Flowrate (l/h)	Rotameter reading in cm	Gas Flowrate (m^3/s)	G'	x	y
20	13	0.004291992	0.00515	0.037461	0.085307
50	12	0.004027054	0.004832	0.099815	0.0751
80	10.3	0.00357666	0.004292	0.179814	0.059241
112	9.4	0.003338216	0.004006	0.269721	0.051605
136	8	0.002967303	0.003561	0.368458	0.040775
160	7.3	0.002734375	0.003281	0.470407	0.034624

Table 6.2: Sherwood correlation plot data for Column A - At flooding

Liquid Flowrate (l/h)	Rotameter reading in cm	Gas Flowrate (m^3/s)	G'	x	y
20	7.0	0.002702365	0.003242839	0.059497323	0.033818399
50	5.1	0.002198984	0.00263878	0.182792981	0.022392825
80	6.1	0.002463921	0.002956706	0.261020515	0.028113738
112	4.9	0.002145996	0.002575195	0.41956631	0.021326655
136	4.3	0.001987033	0.00238444	0.550231247	0.018284169
160	3.9	0.001881058	0.00225727	0.683800224	0.016385866

Table 6.3: Sherwood correlation plot data for Column A - At loading

Liquid Flowrate(l/h)	Rotameter reading in cm	Gas Flowrate (m³/s)	G'	x	Y
20	1	0.001112739	0.001335286	0.1444935	0.005733915
	2	0.001377677	0.001653212	0.116706288	0.008789403
	3	0.001642614	0.001971137	0.097882693	0.012494995
	4	0.001907552	0.002289063	0.084287875	0.01685069
	5.4	0.002278465	0.002734158	0.070566593	0.024040838
	7	0.002702365	0.003242839	0.059497323	0.033818399
	8.5	0.003099772	0.003719727	0.051869461	0.044496354
	10	0.003497179	0.004196615	0.045975204	0.056637042
	11	0.003762117	0.00451454	0.042737514	0.065543464
	12	0.004027054	0.004832465	0.039925835	0.07509999
50	1.1	0.001119792	0.00134375	0.358958536	0.005806833
	2.1	0.001380208	0.00165625	0.291230511	0.008821738
	3.1	0.001640625	0.00196875	0.245003446	0.012464749
	4.1	0.001901042	0.00228125	0.21144133	0.016735865
	5.1	0.002161458	0.00259375	0.185966471	0.021635086
	6.1	0.002421875	0.00290625	0.165970076	0.027162412
	7.1	0.002682292	0.00321875	0.149856476	0.033317844
	8	0.002916667	0.0035	0.137814438	0.039394762
	9	0.003177083	0.0038125	0.126518173	0.046743594
	10	0.0034375	0.004125	0.116933463	0.054720531
	11	0.003697917	0.0044375	0.108698712	0.063325573
80	1	0.00109375	0.0013125	0.588008269	0.005539888
	2	0.001354167	0.001625	0.474929756	0.008491983
	3.1	0.001640625	0.00196875	0.392005513	0.012464749
	4	0.001875	0.00225	0.343004824	0.016280488
	5.3	0.002213542	0.00265625	0.290545262	0.022690303
	6.1	0.002421875	0.00290625	0.265552122	0.027162412
	7	0.00265625	0.0031875	0.242121052	0.032674036
	7.8	0.002864583	0.0034375	0.224512248	0.038000369
	8.2	0.00296875	0.0035625	0.216634626	0.04081428
	8.9	0.003151042	0.00378125	0.204102044	0.045980446
	9.4	0.00328125	0.0039375	0.196002756	0.049858996
	9.8	0.003385417	0.0040625	0.189971902	0.053074895
	10.3	0.003515625	0.00421875	0.182935906	0.057236092
112	1	0.00109375	0.0013125	0.823211577	0.005539888
	2.1	0.001380208	0.00165625	0.652356344	0.008821738
	3.1	0.001640625	0.00196875	0.548807718	0.012464749
	4.1	0.001901042	0.00228125	0.473628579	0.016735865
	4.9	0.002109375	0.00253125	0.426850447	0.020604993
	6	0.002395833	0.002875	0.375813981	0.026581415
	6.9	0.002630208	0.00315625	0.342325606	0.032036509
	8	0.002916667	0.0035	0.308704341	0.039394762
	8.7	0.003098958	0.00371875	0.290545262	0.044472993
136	1.2	0.001145833	0.001375	0.954177055	0.006080059
	2	0.001354167	0.001625	0.807380585	0.008491983
	3	0.001614583	0.0019375	0.67715791	0.012072183
	4.3	0.001953125	0.00234375	0.559783872	0.017665461
	5	0.002135417	0.0025625	0.511997444	0.021116899
	6.7	0.002578125	0.00309375	0.424078691	0.030780299
	7.4	0.002760417	0.0033125	0.396073495	0.035286954
160	0.8	0.001041667	0.00125	1.234817365	0.005024842
	1.8	0.001302083	0.0015625	0.987853892	0.007851316
	3	0.001614583	0.0019375	0.796656365	0.012072183
	3.9	0.001848958	0.00221875	0.695671755	0.015831393
	4.5	0.002005208	0.00240625	0.641463566	0.018620181
	5.1	0.002161458	0.00259375	0.595092706	0.021635086
	5.6	0.002291667	0.00275	0.561280621	0.024320236
	6	0.002395833	0.002875	0.536877115	0.026581415
	6.6	0.002552083	0.0030625	0.504007088	0.030161615

Table 6.4: Sherwood correlation plot data for Column A - Below flooding

Liquid Flowrate (l/h)	Rotameter reading in cm	Gas Flowrate (m³/s)	G'	x	y
20	14	0.00455693	0.005468316	0.035283296	0.096163353
	14.5	0.004689399	0.005627279	0.034286593	0.101835509
	15	0.004821868	0.005786241	0.033344654	0.10767019
	15.5	0.004954337	0.005945204	0.032453085	0.113667398
	16	0.005086806	0.006104167	0.031607953	0.119827131
50	13	0.004291992	0.005150391	0.093653194	0.08530662
	13.5	0.004424461	0.005309353	0.090849206	0.090653723
	14.1	0.004583424	0.005500109	0.087698367	0.097284782
	14.6	0.004715893	0.005659071	0.08523493	0.102989443
	15.2	0.004874855	0.005849826	0.08245553	0.11004957
	15.5	0.004954337	0.005945204	0.081132714	0.113667398
	16.1	0.005113299	0.006135959	0.078610453	0.121078581
80	10.8	0.003645833	0.004375	0.176402481	0.061554316
	11.4	0.003802083	0.0045625	0.169153064	0.066943459
	14.2	0.004609918	0.005531901	0.139510965	0.098412712
	15.2	0.004874855	0.005849826	0.131928847	0.11004957
112	10.1	0.003463542	0.00415625	0.259961551	0.05555277
	10.6	0.00359375	0.0043125	0.250542654	0.059808183
	16.2	0.005139793	0.006167752	0.175179748	0.122336532
136	8.7	0.00315276	0.003783312	0.346784399	0.046030599
	9.3	0.003311722	0.003974067	0.330138748	0.050789359
	10.4	0.003603154	0.004323785	0.303436349	0.060121599
160	8	0.002967303	0.003560764	0.433480499	0.04077451
	8.6	0.003126266	0.003751519	0.411439118	0.045260226
	9	0.003232241	0.003878689	0.39794931	0.048380724
	9.7	0.003417697	0.004101237	0.376355162	0.054091886
	10.9	0.003735623	0.004482747	0.344324935	0.064623567
	11.6	0.003921079	0.004705295	0.328039296	0.071199367

Table 6.5: Sherwood correlation plot data for Column A - Above flooding

Liquid Flowrate (l/h)	Rotameter reading in cm	Gas Flowrate (m³/s)	G'	x	y
20	8.6	0.003126266	0.003751519	0.05142989	0.045260226
50	6.8	0.002649378	0.003179253	0.151718175	0.03250519
60	5.3	0.002251971	0.002702365	0.214190364	0.023484999
80	4.2	0.00196054	0.002352648	0.328039296	0.017799842
100	2.8	0.001589627	0.001907552	0.505727249	0.011701868
120	2.4	0.001483652	0.001780382	0.65022074	0.010193627

Table 6.6: Sherwood correlation plot data for Column B - At flooding

Liquid Flowrate (l/h)	Rotameter reading in cm	Gas Flowrate (m³/s)	G'	x	y
20	4.5	0.002040021	0.002448025	0.078814636	0.019272327
50	3.3	0.001722096	0.002066515	0.233412576	0.013733443
60	2.3	0.001457158	0.001748589	0.331021472	0.00983282
80	2	0.001377677	0.001653212	0.466825153	0.008789403
100	1.6	0.001271701	0.001526042	0.632159061	0.007489196

Table 6.7: Sherwood correlation plot data for Column B - At loading

Liquid Flowrate (l/h)	Rotameter reading in cm	Gas Flowrate (m³/s)	G'	x	y
20	0.5	0.00098027	0.001176324	0.164019648	0.00444996
	1.5	0.001245208	0.001494249	0.129121851	0.007180396
	2.5	0.001510145	0.001812174	0.106468894	0.010560936
	3.5	0.001775083	0.0021301	0.090578015	0.01459158
	4.5	0.002040021	0.002448025	0.078814636	0.019272327
	5.5	0.002304959	0.002765951	0.069755483	0.024603178
	6.5	0.002569897	0.003083876	0.062564196	0.030584133
	7.5	0.002834834	0.003401801	0.141792687	0.037215192
50	0.4	0.000953776	0.001144531	0.421439374	0.004212673
	1.4	0.001218714	0.001462457	0.329822119	0.006878098
	2.4	0.001483652	0.001780382	0.270925312	0.010193627
	3.3	0.001722096	0.002066515	0.233412576	0.013733443
	4.2	0.00196054	0.002352648	0.20502456	0.017799842
	5.2	0.002225477	0.002670573	0.180616875	0.022935662
	6.4	0.002543403	0.003052083	0.158039765	0.029956783
60	1.2	0.001165726	0.001398872	0.41377684	0.006293005
	2.3	0.001457158	0.001748589	0.331021472	0.00983282
	3.4	0.001748589	0.002098307	0.275851227	0.014159261
	4.3	0.001987033	0.00238444	0.242749079	0.018284169
80	1	0.001112739	0.001335286	0.577973998	0.005733915
	2	0.001377677	0.001653212	0.466825153	0.008789403
	3.3	0.001722096	0.002066515	0.373460122	0.013733443
100	0.4	0.000953776	0.001144531	0.842878748	0.004212673
	1	0.001112739	0.001335286	0.722467498	0.005733915
	1.6	0.001271701	0.001526042	0.632159061	0.007489196
	2.1	0.00140417	0.001685004	0.572521414	0.009130708
120	0.2	0.000900788	0.001080946	0.892459851	0.0037576
	0.8	0.001059751	0.001271701	0.758590873	0.00520083
	1.4	0.001218714	0.001462457	0.659644237	0.006878098
	1.9	0.001351183	0.001621419	0.594973234	0.0084546

Table 6.8: Sherwood correlation plot data for Column B - Below flooding

Liquid Flowrate (l/h)	Rotameter reading in cm	Gas Flowrate (m³/s)	G'	x	y
20	9.6	0.003391204	0.004069444	0.04741193	0.053256503
	10.6	0.003656141	0.00438737	0.043976282	0.061902883
	11.6	0.003921079	0.004705295	0.041004912	0.071199367
	12.6	0.004186017	0.00502322	0.038409664	0.081145955
	13.5	0.004424461	0.005309353	0.036339683	0.090653723
50	8	0.002967303	0.003560764	0.135462656	0.04077451
	8.5	0.003099772	0.003719727	0.129673653	0.044496354
	10.1	0.003523673	0.004228407	0.114073815	0.05749843
60	6.5	0.002569897	0.003083876	0.187692587	0.030584133
	7.4	0.002808341	0.003370009	0.171756424	0.036522831
	6	0.002437428	0.002924913	0.197893271	0.027512392
	6.7	0.002622884	0.003147461	0.183900818	0.031858336
80	5.2	0.002225477	0.002670573	0.288986999	0.022935662
	6	0.002437428	0.002924913	0.263857695	0.027512392
100	3.3	0.001722096	0.002066515	0.466825153	0.013733443
	3.6	0.001801577	0.002161892	0.446229925	0.0150304
120	3.1	0.001669108	0.00200293	0.48164499	0.01290131

Table 6.9: Sherwood correlation plot data for Column B - Above flooding
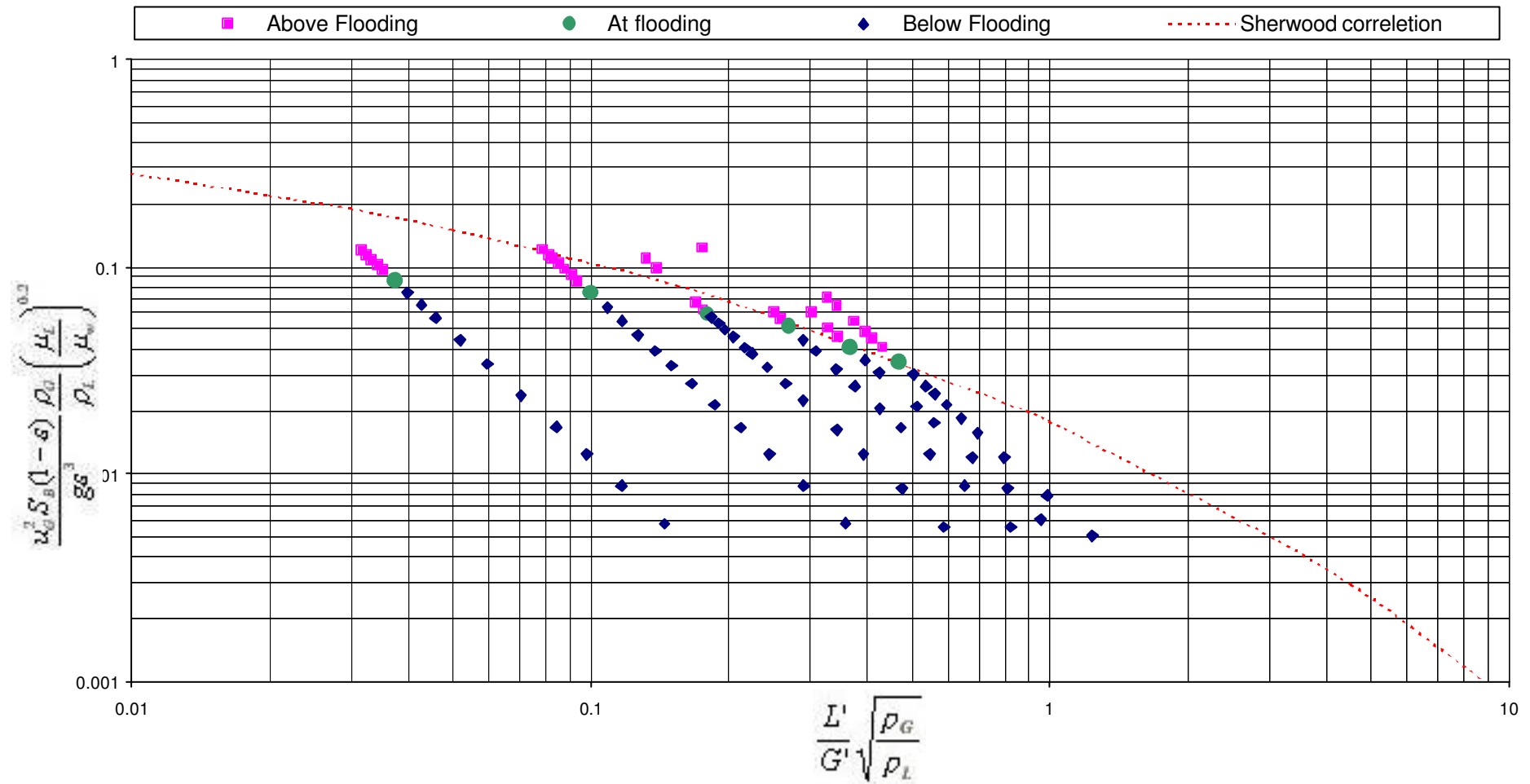
Figure 6.16: Flooding points for column A (glass raschig rings)
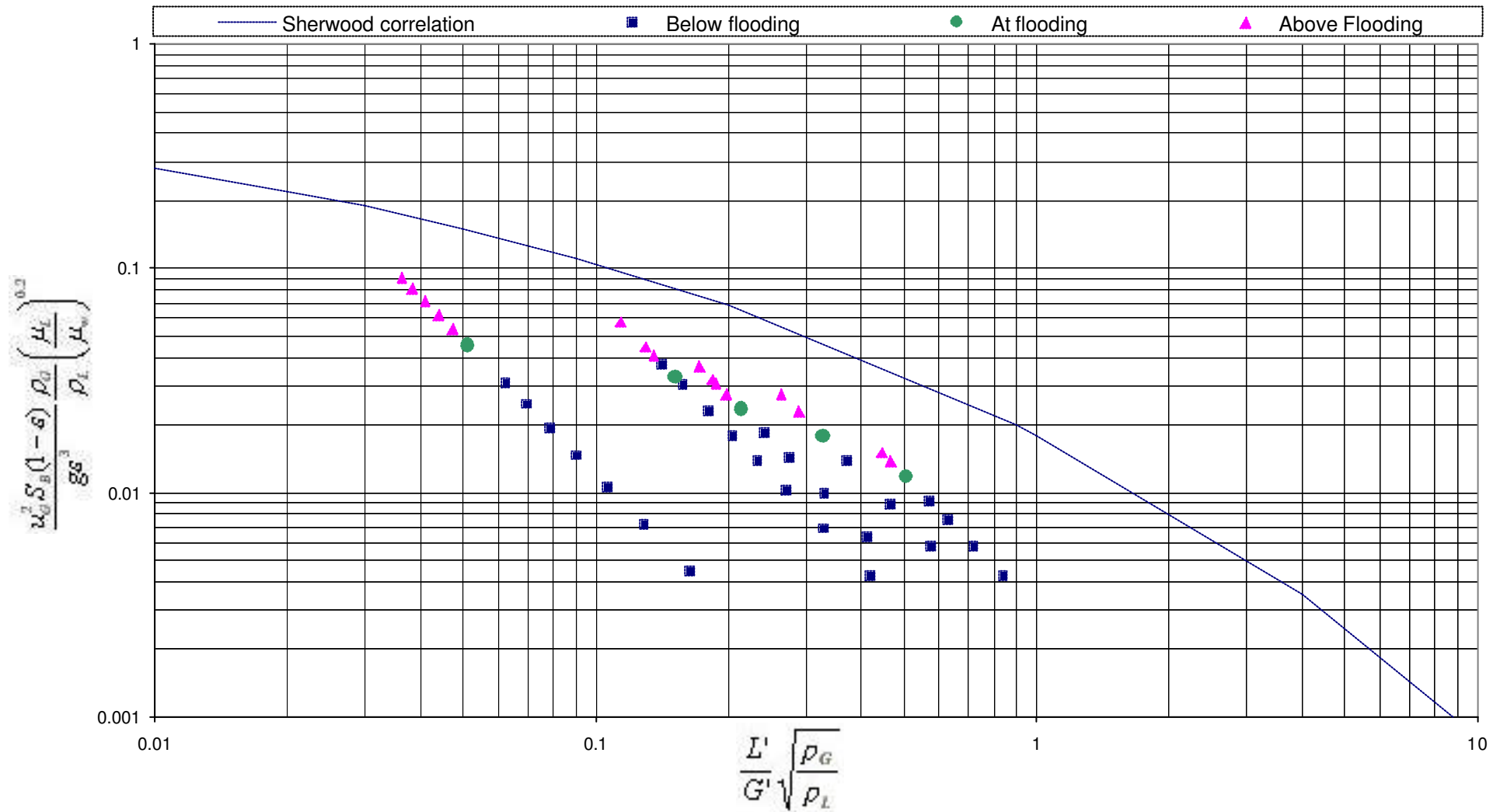
Figure 6.17: Flooding points for column B (ceramic raschig rings)

6.6 Mathematical model for pressure drop

The general form of the relation between the drop in pressure and the volumetric gas flowrate per unit area of column u_G (superficial velocity), is shown in figure 6.18.
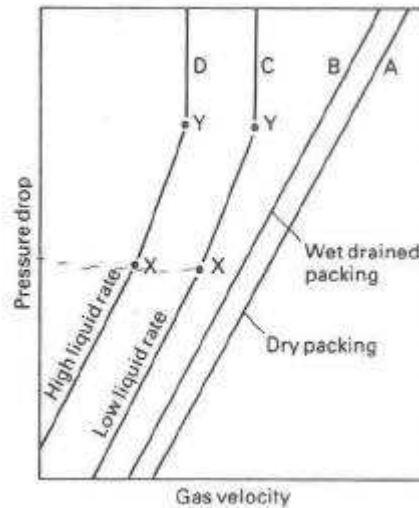
Figure 6.18: Pressure drop in the wet packings (logarithmic axes) (after Coulson and Richardson, 1998).

At high Reynolds numbers, on curve A, the pressure drop ΔP is proportional to about $u_G^{1.8}$. If in addition to the gas flow, liquid flows down the tower, the passage of the gas is not significantly affected at low liquid flow rates and the pressure drop line is similar to line A, but for a given value of u_G the value of $-\Delta P$ is increased. When the gas rate reaches a certain value, the pressure drop then rises more quickly and is proportional to $u_G^{2.5}$, as shown by the section XY on curve C (Coulson and Richardson, 1998).

The basic equation form required to calculate pressure drop ΔP from experimental data is:

$$\Delta P \propto \left(\frac{G}{R_i} \right)^{n_i} \qquad (6.6.1)$$

where i refers to one of the three segments of operation limited by floating and loading conditions (i.e $i=1$ or 2 or 3)

Having determined suitable values for loading and flooding points, the slope of each segment in the logarithmic plot determine the values of n_i. Then calculating R_i as follows:

Loading point: ΔP_l, G_l

Flooding point: ΔP_f, G_f

$$\Delta P_l = \left(\frac{G_l}{R_1}\right)^{n_1} = \left(\frac{G_l}{R_2}\right)^{n_2} \tag{6.6.2}$$

hence R_1 and R_2 were calculated

$$\left(\frac{G_f}{R_2}\right)^{n_2} = \left(\frac{G_f}{R_3}\right)^{n_3} \tag{6.6.3}$$

hence R_3 was calculated

In order to calculate pressure drop from user's chosen flowrates G(t) the following equation is used:

$$\Delta P(t) = \max\left[\left(\frac{G(t)}{R_1}\right)^{n_1}, \left(\frac{G(t)}{R_2}\right)^{n_2}, \left(\frac{G(t)}{R_3}\right)^{n_3}\right] \tag{6.6.4}$$

This equation gives results for pressure drop very close to those observed at the real packed columns. The whole procedure can be applied to each column separately.

In order to use the equation for determining the pressure drop the values of G_l, G_f, ΔP_l, ΔP_f, n_1, n_2, n_3 should be defined. The method, which is used to achieve this, is the curve fitting of experimental data against to liquid flowrate. So, using

Microcal Origin software, a number of non-linear equations are assigned which determines values for these variables in different liquid flowrates.

The following set of logarithmic graphs in figures 6.19, 6.20, 6.21 and 6.22 produced by Microcal Origin and contains the non-linear curves which were fitted to the data of x, y at flooding and loading point, G_l and G_f respectively, for each column.

The flowsheets in figures 6.23 and 6.24 illustrates the algorithm, which is used in order to determine the flooding and loading point of each column.

$$y ? \; 0.03595 \; \ln(\; ? \, 3.26103 \; \ln(\; x))$$

Parameter	Value	Error
a	0.03595	0.00194
b	3.26103	0.29576

Model: $y ? \; a \; \ln(\; ? \, b \; \ln(\; x))$
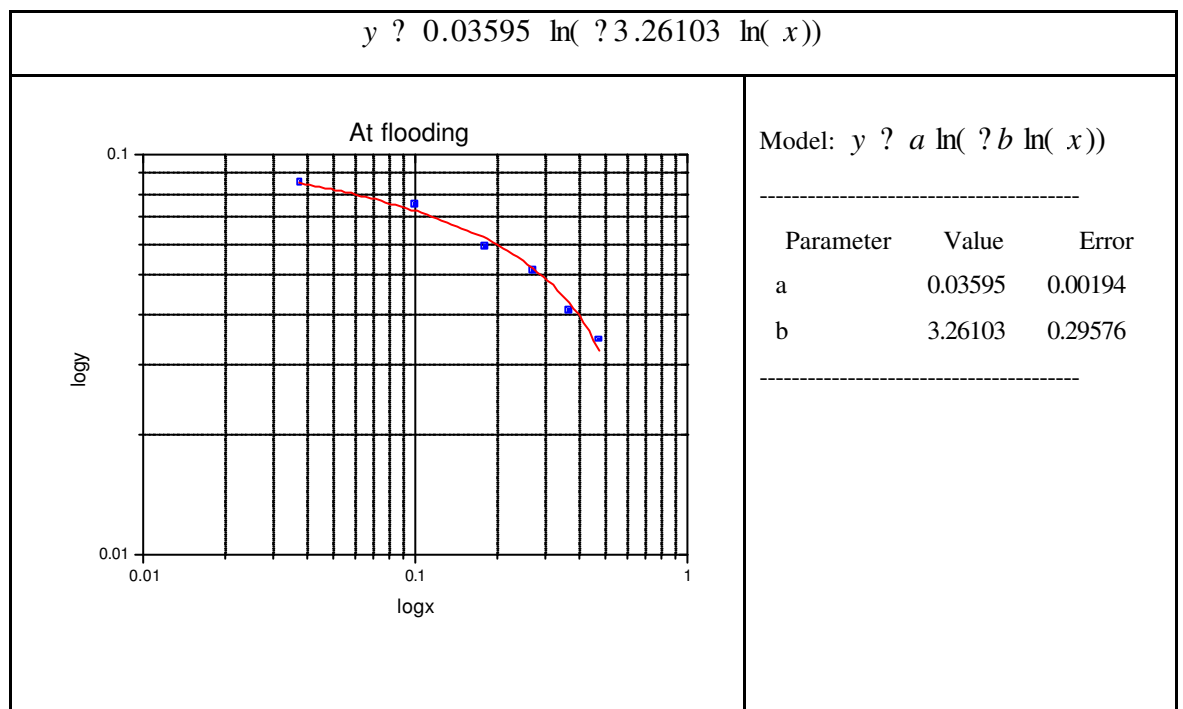
Figure 6.19: The non-linear curve for the data of x, y at flooding for column A

$$y ? \; 0.00805 \; \ln(\; ? \, 17.55338 \; \ln(\; x))$$
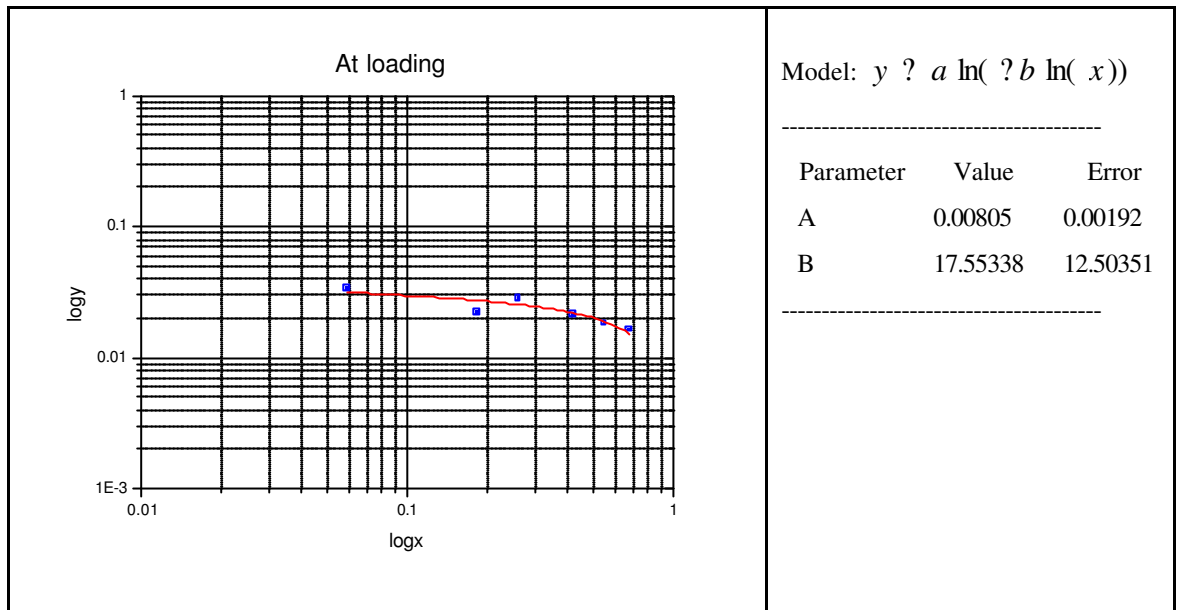
Figure 6.20: The non-linear curve for the data of x, y at loading for column A

$$y \; ? \; 0.02311 \; \ln(\; ? \, 2.12873 \; \ln(\; x))$$
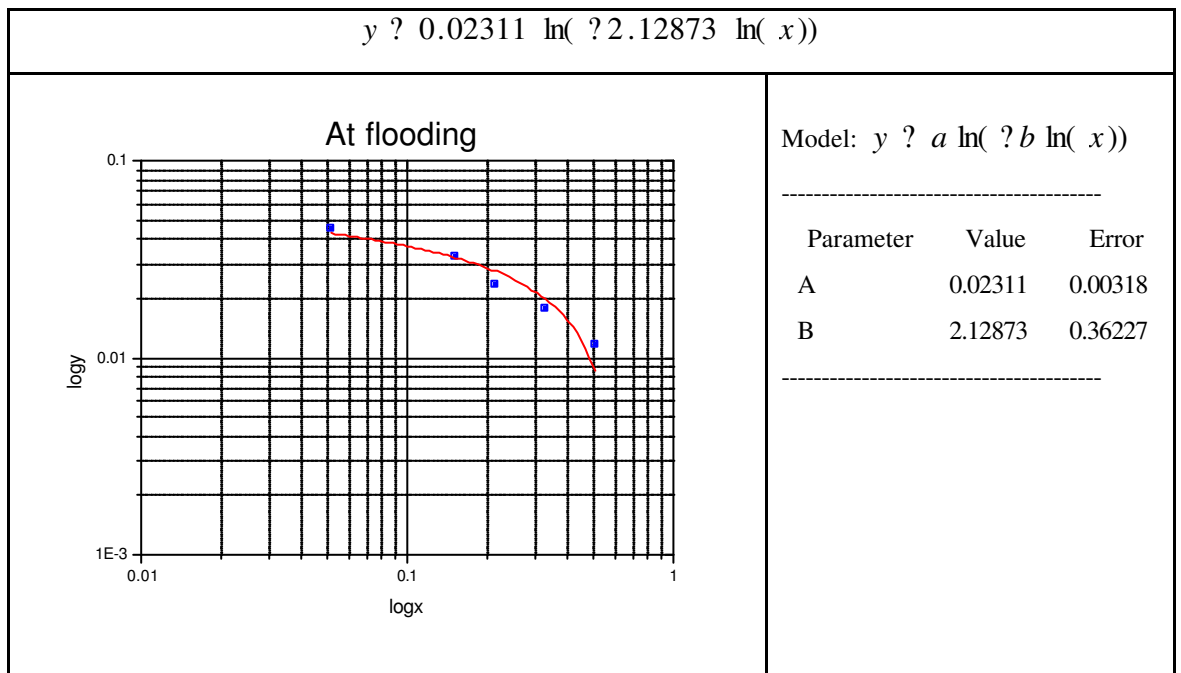
Figure 6.21: The non-linear curve for the data of x, y at flooding for column B

$$y \; ? \; 0.00696 \; \ln(\; ? \, 5.09271 \; \ln(\; x))$$
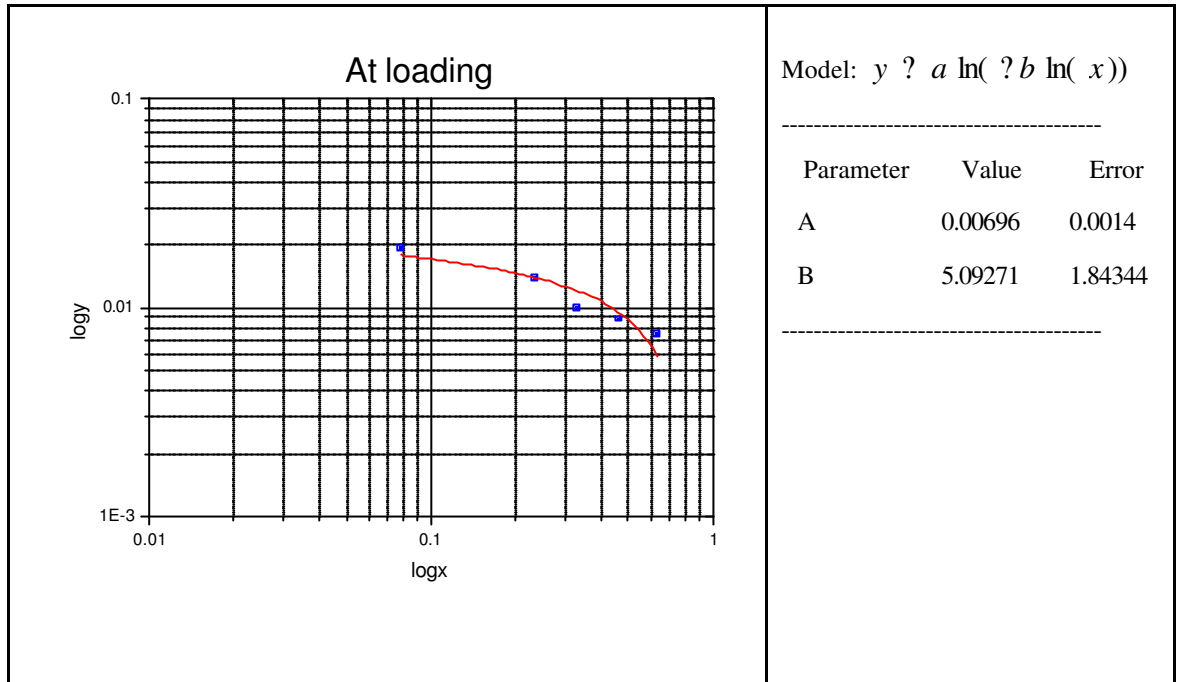
Figure 6.22: The non-linear curve for the data of x, y at loading for column A

At loading

Model: $y ? a \ln(? b \ln(x))$

Parameter	Value	Error
A	0.00696	0.0014
B	5.09271	1.84344

G_l

Yes

No | $E_2 < 0.001$

$G_l = G_l + 0.1$

$E_2 = y_l - y$

G_l

G'
L'
x
y

$y_l = 0.0085 \ln(-17.55338 \ln(x))$

L

G_f

$y_f = 0.03595 \ln(-3.26103 \ln(x))$

$E_1 = y_f - y$

$E_l<0.001$

$G_f= G_f+0.1$

No

Yes

G_f
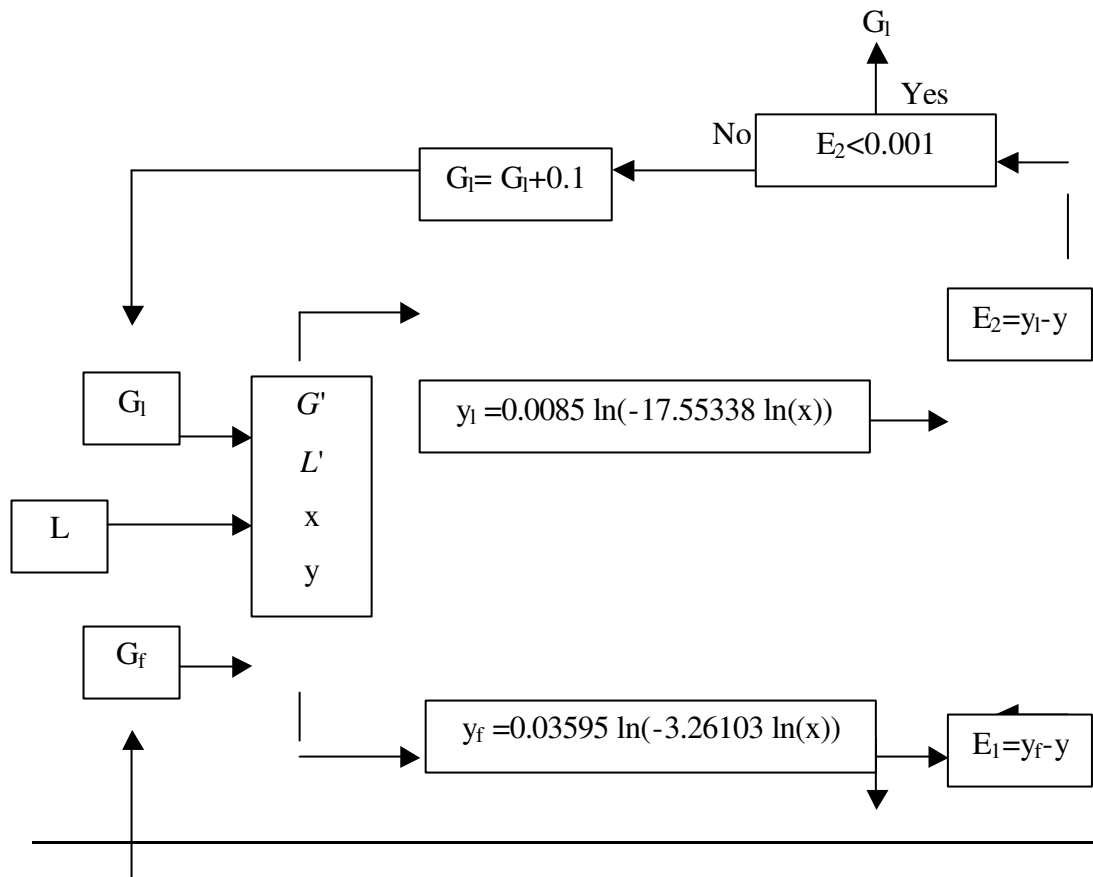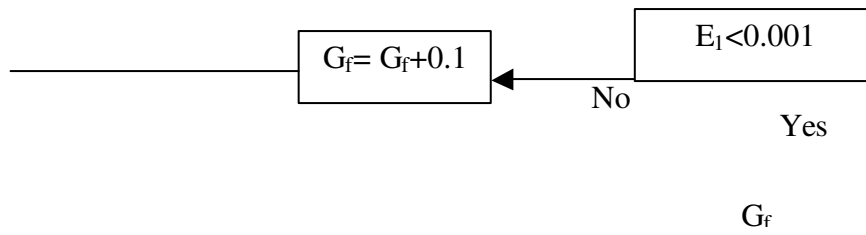
Figure 6.23: The algorithm flowsheet for the flooding and loading point of column A

G_l

Yes

No

$G_l= G_l+0.1$

$E_2<0.001$

$E_2=y_l-y$

$y_l =0.023111 \ln(-2.12873 \ln(x))$

G_l

G'
L'
x
y

L

G_f

$y_f =0.00696 \ln(-5.09271 \ln(x))$

$E_l=y_f-y$

$G_f= G_f+0.1$

$E_l<0.001$

No

Yes

G_f
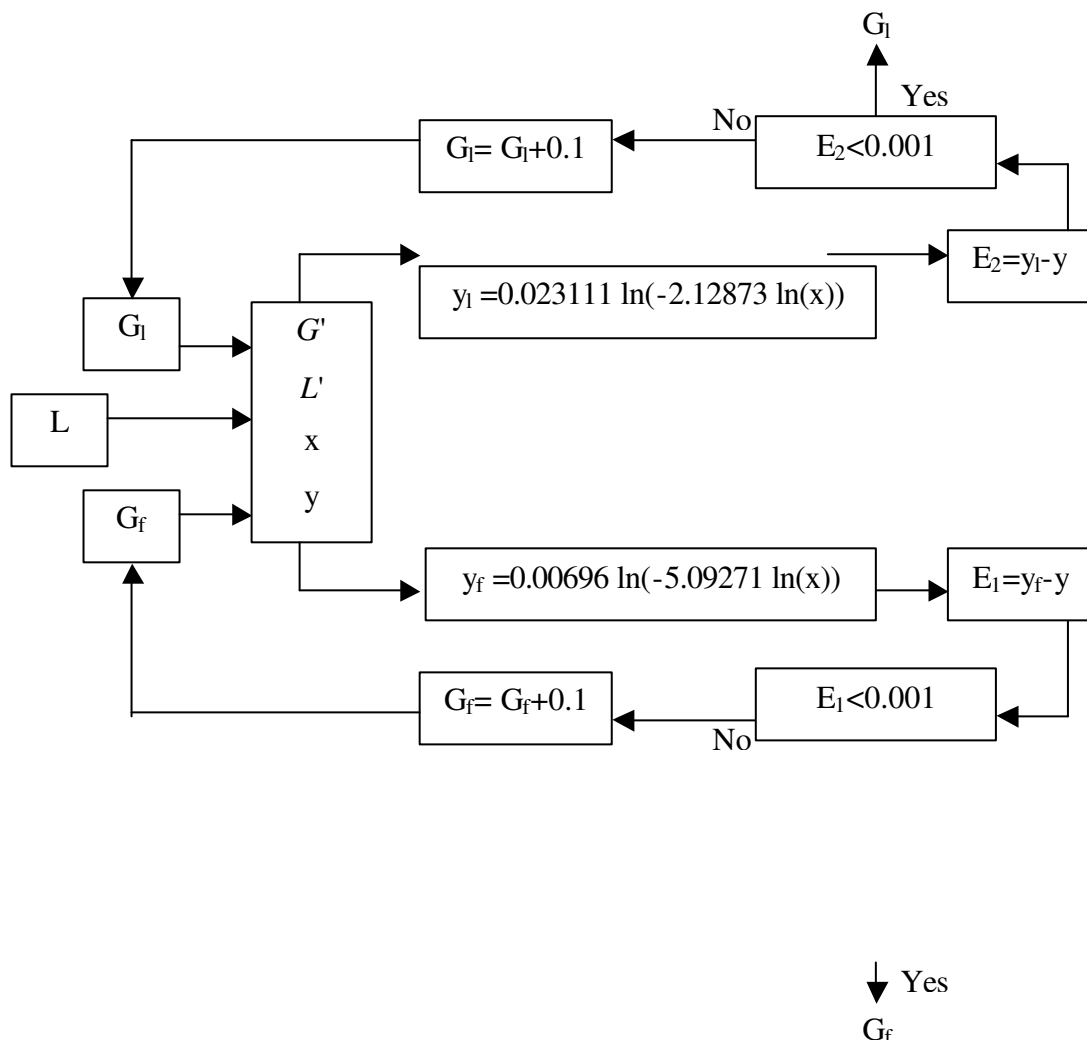
Figure 6.24: The algorithm flowsheet for the flooding and loading point of column B

A set of equations was produced by Microcal Origin and contains the non-linear curves, which were fitted to the data of ? P_l, ? P_f, n_l, n_2, n_3 respectively for each column. These equations are presented in table 6.10:

Column A	Column B
$?P_f$ $?$ 110.46 $?L^{0.0652}$	$?P_f$ $?$ 184.58813 $?L^{0.0501}$
$?P_l$ $?$ 33.27094 $?L^{0.08734}$	$?P_l$ $?$ 32.00609 $?L^{0.08501}$
n_1 $?$ 1.67397 $?L^{0.03711}$	n_1 $?$ 1.91556 $?L^{0.0353}$
n_2 $?$ 1.62988 $?L^{0.09818}$	n_2 $?$ 0.43116 $?L^{0.45017}$
n_3 $?$ 2.2134 $?L^{0.10947}$	n_3 $?$ 4.63803 $?L^{?0.09532}$

Table 6.10: The equations for $?P_l$, $?P_f$, n_1, n_2 and n_3 for both columns
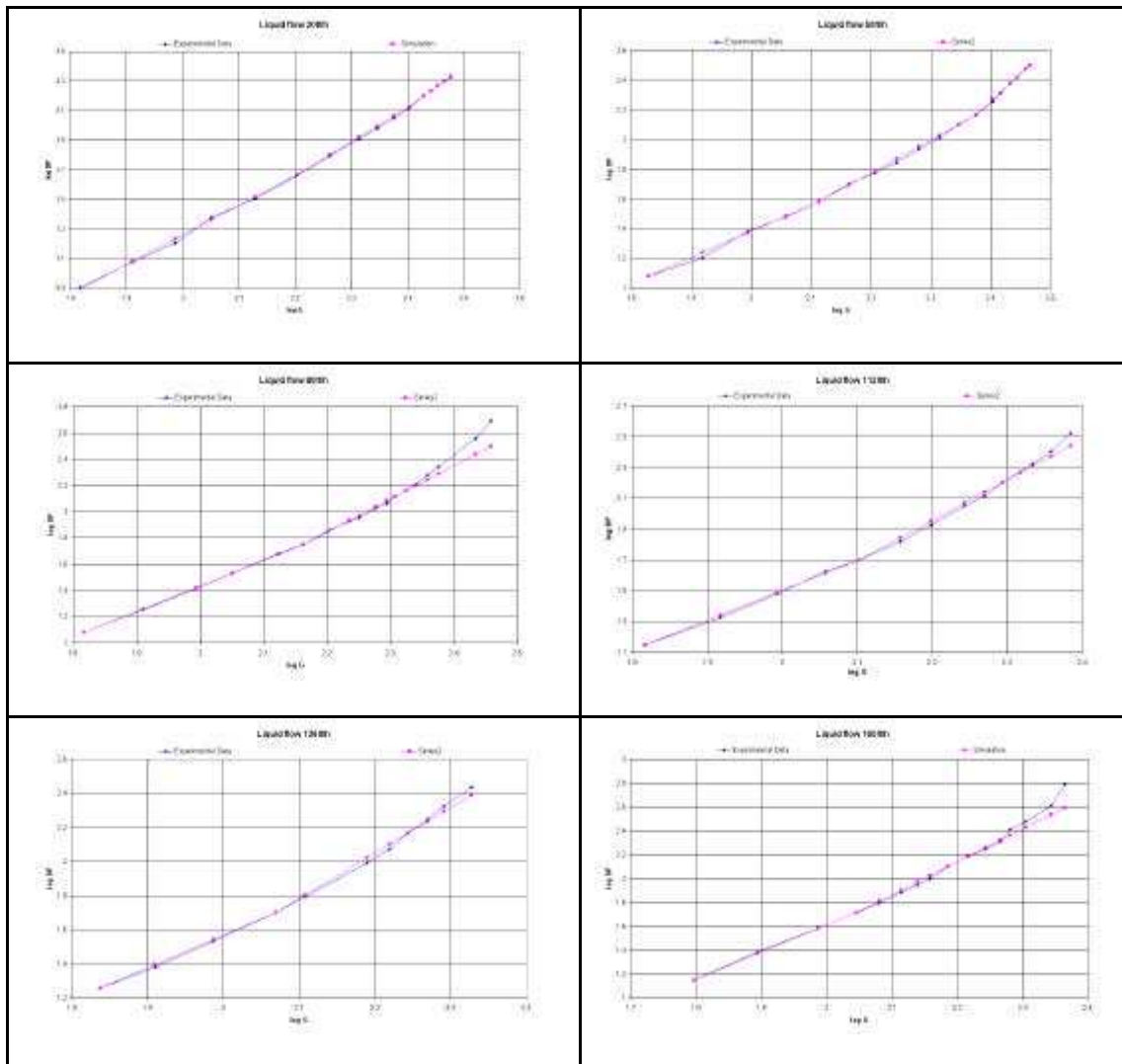
Figure 6.25: Experimental and simulator data comparison graphs for column A

The series of graphs in figure 6.25 and 6.26 demonstrate the comparison between the experimental data of pressure drop and the values of pressure drop that the simulator generates for various gas flowrates.
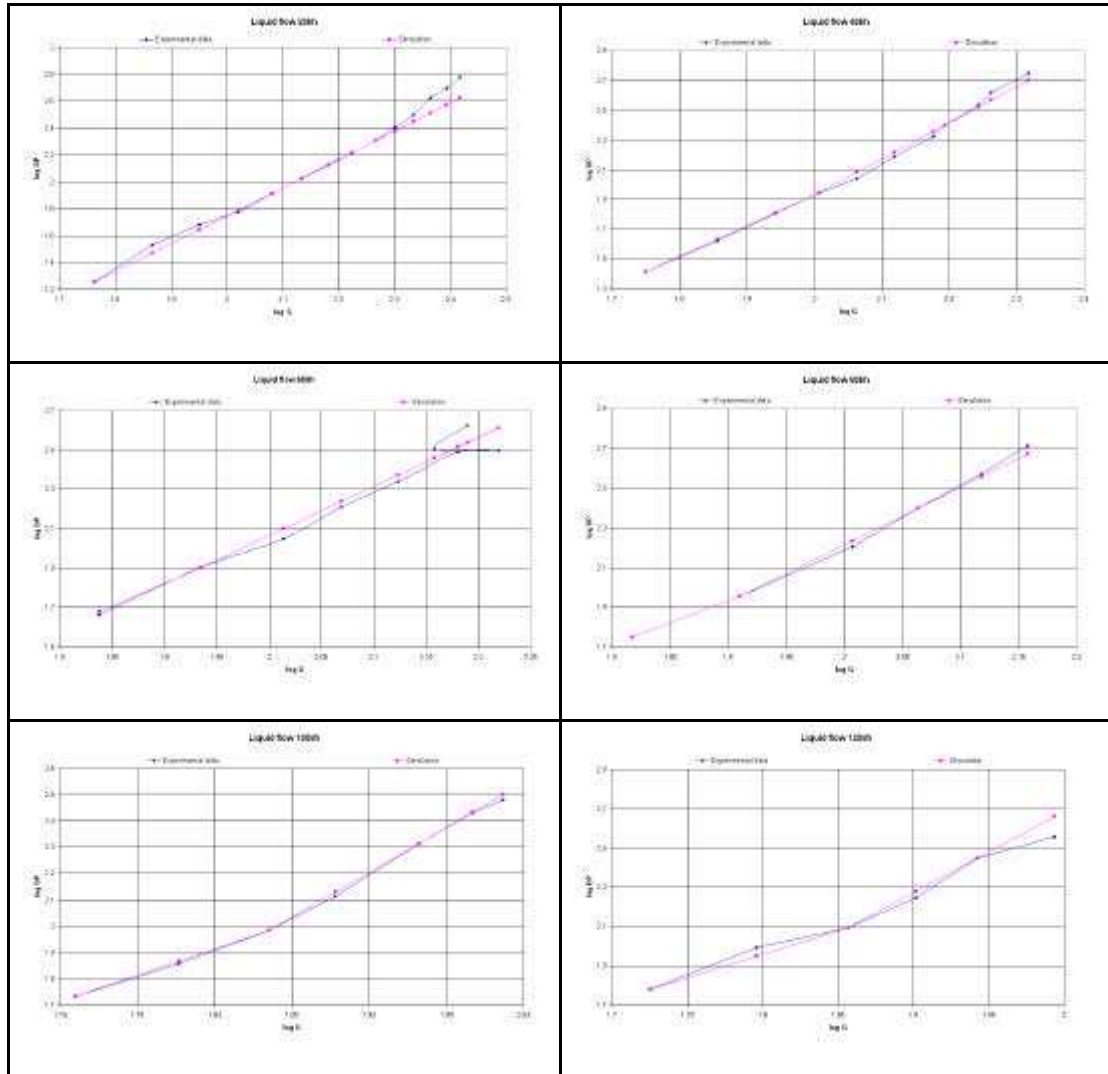
Figure 6.26: Experimental and simulator data comparison graphs for column B

6.7 Number of Transfer units (NTU), Height of Transfer units (HTU)

The Number of Transfer units (NTU) and Height of Transfer units (HTU) indicate mass transfer and absorption efficiency for each column, which are inversely related to each other. As the packing efficiency improves, HTU values are lowered, which in turn increases NTU. The efficiency and NTU is dependent upon liquid and gas flowrates through the column. Calculation of NTU requires ammonia concentrations at the column inlet and at the outlet.

Experimental runs are carried out at different liquid and gas flowrates for each column at room temperature and pressure (20°C, 1atm). For each liquid flowrate, ammonia supply to the column is fixed at a particular rotameter reading. Air flowrate alters ammonia concentration at the column inlet and the total gas (combined air and ammonia) flowrate was kept below the column loading point, in order to stay far away from its flooding point. Ammonia concentration at the top of the column is sampled using a Drager tube. The procedure is repeated, adjusting different flowrates for both columns and a similar set of results were obtained. In order to achieve the steady state condition in each run, 10 minutes was allowed before any measurement.

It is extremely difficult to use a Drager tube to determine ammonia concentration at the top of the column accurately. The maximum level measurable was 700ppm using this equipment. The readings were set to at least 100ppm in order to minimise the experimental error, which is reduced for higher concentrations measured. It was considered useful for the virtual reality training model to utilise a digital gas analyser for outlet ammonia concentration to, try to reduce the confusion that might be produced by the explanation of the operation of a Drager tube.

In each column the ammonia mole fraction changes from y_b at the inlet (at the bottom) to y_t at the outlet (at the top), over the height of the column z. Over a small height of the column dz the rate of mass transfer can be written as:

$$K_G a(y^* ? y) A dz \tag{6.7.1}$$

where K_G is the overall mass transfer coefficient (based on physical absorption)

   a is the active interfacial area for transfer per unit volume of the column

   A is the cross sectional area of the column

But the moles of ammonia diffusing are equal to the product of total moles of gas multiplied by the change in mole fraction:

$$\text{Diffusing moles of ammonia} = G' A dy \tag{6.7.2}$$

Therefore

$$K_G a(y^* - y)A\,dz = G'A\,dy \tag{6.7.3}$$

$$\frac{dy}{y^* - y} = \frac{K_G a}{G'}\,dz \tag{6.7.4}$$

$$\int_{y_b}^{y_t}\frac{dy}{y^* - y} = \frac{K_G a}{G'}\,dz \tag{6.7.5}$$

The group on the right hand side has been defined as the number of overall transfer units, simply termed as NTU.

$$NTU = \int_{y_b}^{y_t}\frac{dy}{y^* - y} \tag{6.7.6}$$

At equilibrium, there would be no ammonia present in the liquid phase due to its complete and irreversible reaction with dilute sulphuric acid. Hence, y^* or the gas phase concentration that is supposed to be in equilibrium with ammonia in the bulk liquid phase would also be zero. Therefore:

$$NTU = \int_{y_b}^{y_t}\frac{dy}{-y} = \int_{y_t}^{y_b}\frac{dy}{y} \tag{6.7.7}$$

An alternative equation based on the absorption factor $A = \dfrac{L}{mV}$ (m is the constant's of Henry law) can be used:

$$NTU = \frac{A}{A-1}\ln\frac{\left(\dfrac{y_b}{y_t}\right)(A-1)+1}{A} \tag{6.7.8}$$

The height of the transfer unit, HTU, is defined as:

$$HTU = \frac{Z}{NTU} \tag{6.7.9}$$

The experimental data are presented in table 6.11 and 6.12. NTU, calculated for various runs are shown in table 6.13 and 6.14, and HTU in table 6.15 and 6.16.

Column A				
Liquid flowrate 30lt/h Ammonia rotameter scale 5cm	Combined air & ammonia scale (cm)	4	2.5	1
	Ammonia mole fraction at bottom	0.0622	0.08	0.112
	Drager tube measurement	250	160	100
	Ammonia mole fraction at top	2.51E-04	1.60E-04	1.00E-04
Liquid flowrate 35lt/h Ammonia rotameter scale 6cm	Combined air & ammonia scale (cm)	4	2.5	1
	Ammonia mole fraction at bottom	0.06933	0.08914	0.1248
	Drager tube measurement	300	200	170
	Ammonia mole fraction at top	3.00E-04	2.00E-04	1.70E-04
Liquid flowrate 45lt/h Ammonia rotameter scale 9cm	Combined air & ammonia scale (cm)	4	2.5	1
	Ammonia mole fraction at bottom	0.09067	0.11657	0.1632
	Drager tube measurement	400	300	200
	Ammonia mole fraction at top	2.51E-04	1.60E-04	1.00E-04

Table 6.11: Column A top and bottom ammonia mole fraction determination

Column B				
Liquid flowrate 30lt/h Ammonia rotameter scale 5cm	Combined air & ammonia scale (cm)	8	6.5	5
	Ammonia mole fraction at bottom	0.04	0.0476	0.056
	Drager tube measurement	300	250	180
	Ammonia mole fraction at top	3.01E-04	2.51E-04	1.80E-04
Liquid flowrate 35lt/h Ammonia rotameter scale 8cm	Combined air & ammonia scale (cm)	6.5	5	3.5
	Ammonia mole fraction at bottom	0.0627	0.0752	0.094
	Drager tube measurement	250	200	100
	Ammonia mole fraction at top	2.51E-04	2.00E-04	1.00E-04
Liquid flowrate 45lt/h Ammonia rotameter scale 13cm	Combined air & ammonia scale (cm)	5	3.5	2.5
	Ammonia mole fraction at bottom	0.1088	0.136	0.155
	Drager tube measurement	250	100	50
	Ammonia mole fraction at top	2.51E-04	1.00E-04	5.01E-05

Table 6.12: Column B top and bottom ammonia mole fraction determination

NTU for Column A (raschig rings)				
Gas flowrate G		Liquid flowrate (l/h)		
Combined Rotameter scale (cm)	(l/min)	30	35	45
1.0	66.764	7.841	7.251	7.209
2.5	90.609	7.236	6.949	6.597
4.0	114.453	6.689	6.418	6.163

Table 6.13: Number of transfer units (NTU) for column A

HTU for Column A (raschig rings)				
Gas flowrate G		Liquid flowrate (l/h)		
Combined Rotameter scale (cm)	(l/min)	30	35	45
1.0	66.764	0.191	0.207	0.208
2.5	90.609	0.207	0.216	0.227
4.0	114.453	0.224	0.234	0.243

Table 6.14: Height of transfer unit (HTU) for column A

NTU for Column B (ceramic rings)				
Gas flowrate G		Liquid flowrate (l/h)		
Combined Rotameter scale (cm)	(l/min)	30	35	45
2.5	60.609	n/a	n/a	8.870
3.5	106.505	n/a	7.927	8.055
5.0	130.349	7.119	7.107	6.961
6.5	154.194	6.758	6.857	n/a
8.0	178.038	6.594	n/a	n/a

Table 6.15: Number of transfer units (NTU) for column B

HTU for Column B (ceramic rings)				
Gas flowrate G		Liquid flowrate (l/h)		
Combined Rotameter scale (cm)	(l/min)	30	35	45
2.5	60.609	n/a	n/a	0.169
3.5	106.505	n/a	0.189	0.186
5.0	130.349	0.211	0.211	0.215
6.5	154.194	0.222	0.219	n/a
8.0	178.038	0.227	n/a	n/a

Table 6.16: Height of transfer unit (HTU) for column B

The graphs in figure 6.27 and 6.28 show the relation between the lnHTU and $\ln G'$ at various liquid flowrates for both columns and the linear curves that apply to this experimental data.
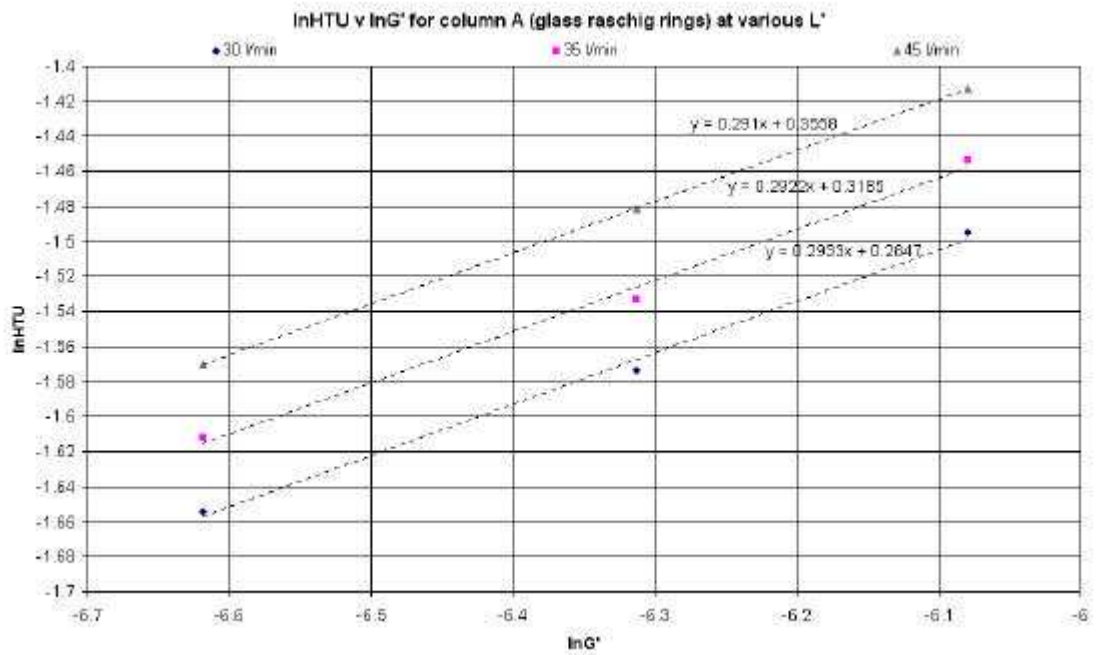
Figure 6.27: The relation between the lnHTU and $\ln G'$ at various liquid flows for column A
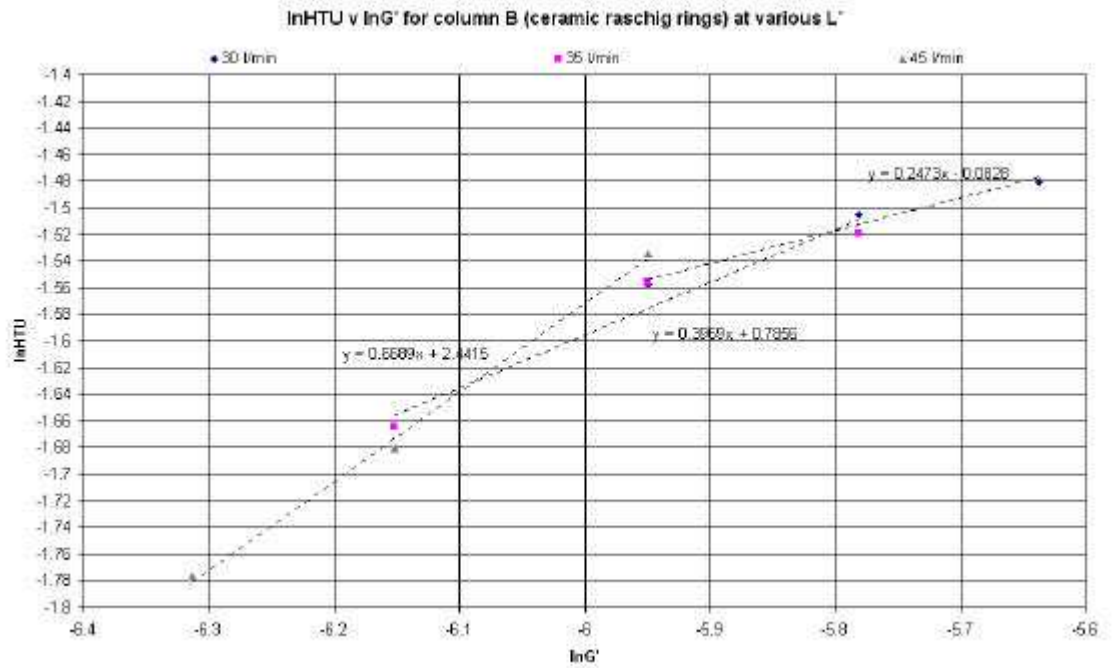
Figure 6.28: The relation between the lnHTU and $\ln G'$ at various liquid flows for

column A

Using Microcal Origin an exponential equation was developed for determining the height of transfer units for various gas flowrates at different liquid flowrates for each column. Both equations are summarised in table 6.17.

Columns	Equations
Column A	$HTU \; ? \; \exp(0.31292L^{?0.01913} \ln G' ? 0.04748L^{0.55059})$
Column B	$HTU \; ? \; \exp((?1.49074 ? 0.28109L^{0.53564}) \ln G' ? 6.99207 ? 0.50694L^{0.76803})$

Table 6.17: The equations for HTU for both columns

The flowsheet in figure 6.29 illustrates the algorithm, which is used in order to determine the concentration of ammonia at the top of the column.

Liquid rotameter reading

Combined air-ammonia rotameter

Ammonia rotameter reading

$$L'$$
$$G'$$
$$A\ ?\ \dfrac{L}{mV}$$

Column A

$$HTU\ ?\ \exp(\,0.31292\,L^{?0.01913}\ln G'\,?\,0.04748\,L^{0.55059})$$

Column B

$$HTU\ ?\ \exp((?1.49074\,?\,0.28109L^{0.53564})\ln G'\,?\,6.99207\,?\,0.50694L^{0.76803})$$

$$y_t\ ? \qquad NTU\ ?\ \dfrac{Z}{HTU} \qquad y_b$$

$$A \qquad ?\ 1$$
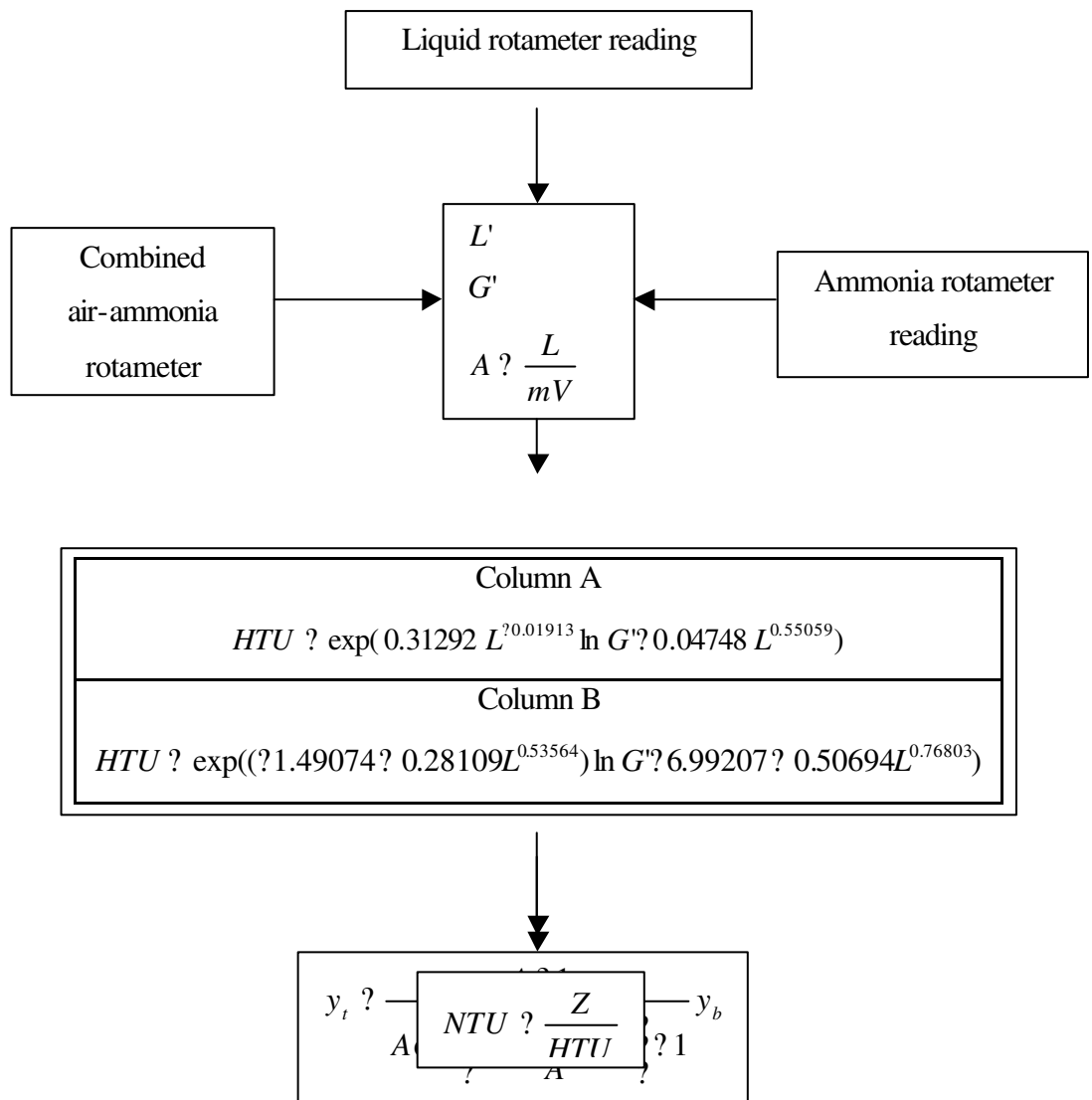
Figure 6.29: The algorithm flowsheet for output ammonia concentration for both

columns

6.8 Dynamic Model

Dynamic behaviour is described for the Kerosene manometer response and for the output concentration of ammonia. A first order time constant t was assigned for the output ammonia composition response and a second order time constant T was assigned for manometer response. The linear differential equation, which describes the dynamic model, is:

$$\overset{?}{x}(t) \; ? \; A_C \; ? x(t) \; ? \; B_C \; ? u(t) \tag{6.8.1}$$

where $x(t)$ is a $3?1$ column matrix containing the dependent state variables y_{calc} (output ammonia concentration from steady space model), $?P_{calc}$ (pressure drop from steady space model) and $?P/dt$ (ratio of pressure drop); $u(t)$ is $2?1$ column matrix containing the system unit variables y (output ammonia concentration) and $?P$ (pressure drop); A_C and B_C are matrices with constant coefficients defined as the plant matrix and the driving matrix respectively.

$$A_C \; ? \; \begin{bmatrix} ?? 1/? & 0 & 0 \\ ? 0 & 0 & 1 \\ ? 0 & ? 1/?^2 & ? 2? /? \end{bmatrix}, \; B_C \; ? \; \begin{bmatrix} ?1/? & 0 \\ ? 0 & 0 \\ ? 0 & 1/?^2 \end{bmatrix}, \; x(t) \; ? \; \begin{bmatrix} ? y_{calc} ? \\ ??P_{calc} ? \\ ??P/dt? \end{bmatrix}, \; u(t) \; ? \; \begin{bmatrix} ? y ? \\ ??P? \end{bmatrix}$$

where   t is the first order time constant for ammonia composition response

T is the second order time constant for manometer response

? is the damping ratio for the manometer oscillation

Integrating equation (6.7.1) over set time period dT=5sec and assuming $u(t)$ step change only at sample periods, we have:

$$x(k \; ? \; 1) \; ? \; A \; ? \; x(k) \; ? \; B \; ? u(k) \tag{6.8.2}$$

where

$$A = \exp\left(A_C \cdot T\right) \qquad (6.8.3)$$

$$B = A_C^{-1}\left(A - I\right) B_C \qquad (6.8.4)$$

For t=50 seconds, ?=0.3, and T=10 seconds it was built as a script using Matlab software, which calculated the matrices A and B. Figure 6.30 shows a screenshot from Matlab of the script and figure 6.31 represents a numeric presentation of A, B, A_C and B_C matrices.

```
%----Absorber model script
tau=50;
z=.3;
T=10;
a=z/T;
w=sqrt(1-z^2)/T;
phi=atan(w/a);
d=sqrt(1-z^2);

%---numerical solution----
Ac=[-1/tau 0 0;
    0 0 1;
    0 -1/T^2 -2*z/T];
Bc=[1/tau 0; 0 0; 0 1/T^2];
ST=5;
A=expm(Ac*ST);
B=inv(Ac)*(A-eye(3))*Bc;

%---analytical solution---
Ac1=[tau 0 0;
     0 -2*z*T -T^2;
     0 1 0];
Aa=[exp(-ST/tau) 0 0;
    0 sin(w*ST+phi)/d  T*sin(w*ST)/d;
    0 -sin(w*ST)/(T*d)  sin(w*ST+pi-phi)/d];
Aa(2:3,2:3)=Aa(2:3,2:3)*exp(-a*ST);

Ba=[1-exp(-ST/tau) 0;
    0 1+exp(-a*ST)*sin(w*ST-pi+phi)/(w*T);
    0 exp(-a*ST)*sin(w*ST)/(w*T*T)];
```
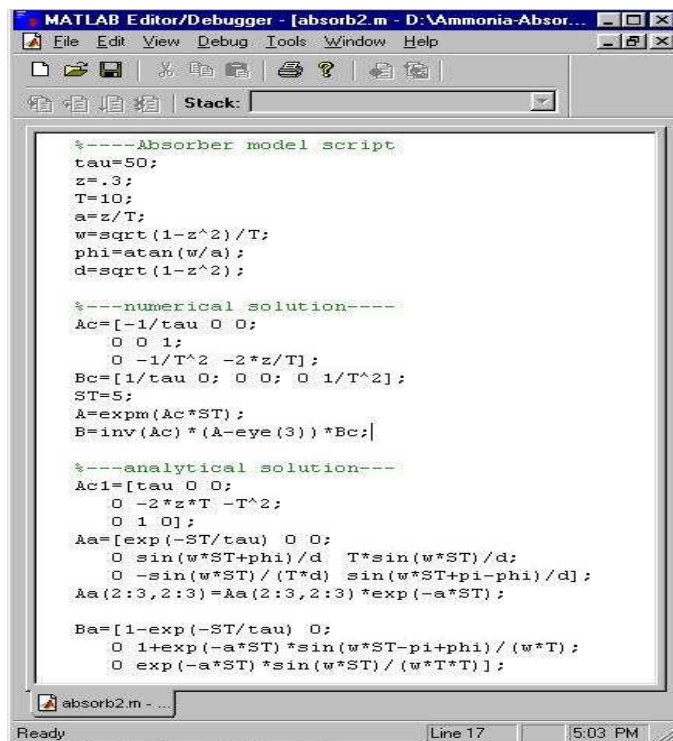
Figure 6.30: The Matlab script for the dynamic model

$$A_C = \begin{bmatrix} 0.02 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -0.1 & -0.06 \end{bmatrix}$$

$$B_C = \begin{bmatrix} 0.02 & 0 \\ 0 & 0 \\ 0 & 0.01 \end{bmatrix}$$

$$A = \begin{bmatrix} 0.9048 & 0 & 0 \\ 0 & 0.8889 & 4.1422 \\ 0 & -0.0414 & 0.6404 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.0952 & 0 \\ 0 & 0.1111 \\ 0 & 0.0414 \end{bmatrix}$$

Figure 6.31: A, B, A_C and B_C matrices

The graphs in figures 6.32 and 6.33 show the response of the manometer and the ammonia composition output for liquid flowrate 30lt/h, air rotameter reading 8cm and ammonia rotameter reading 5cm.

Pressure Drop indicated on manometer
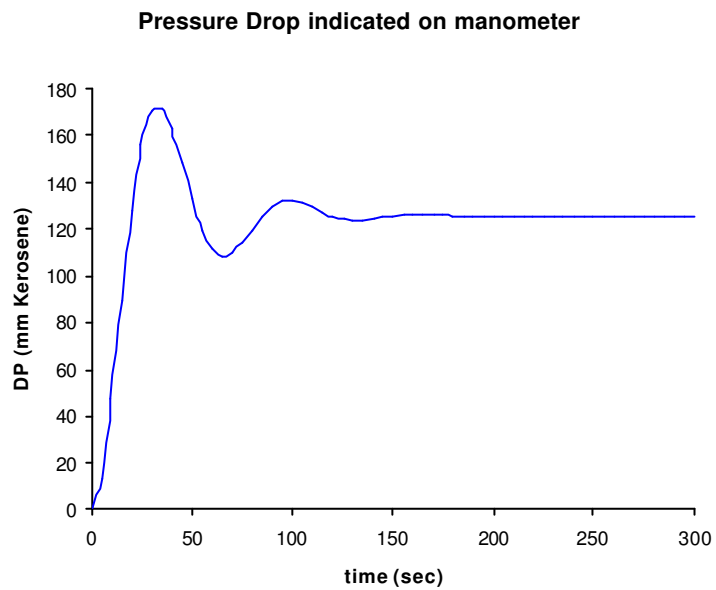
Figure 6.32: The second order response of manometer

Displayed Ammonia Composition (on analyser)
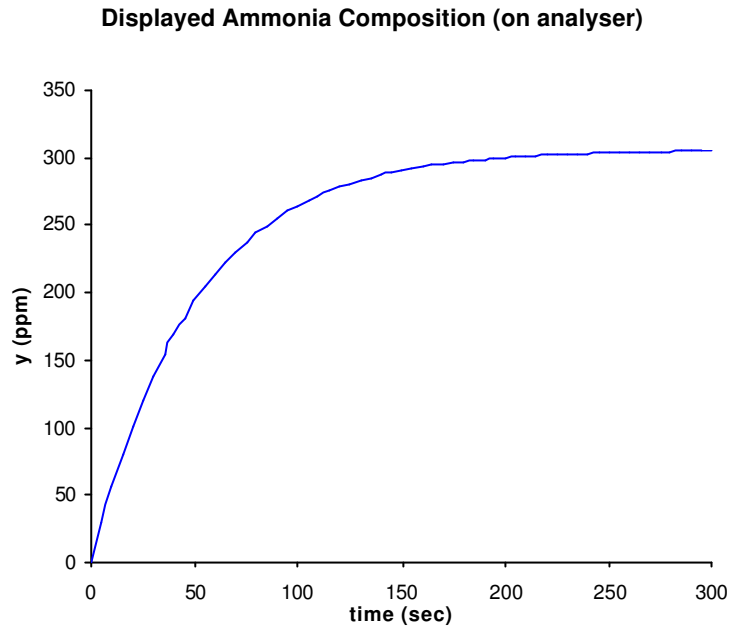
Figure 6.33: The first order response of output ammonia composition

The above sections described the algorithms, which were used to simulate the steady state and dynamic models of both the flooding and gas absorption processes. The implementation of these algorithms within the SAFE-VR development environment and the development of the three-dimensional model of the laboratory rig are discussing in the following sections.

6.9 Development of the three-dimensional model

The three-dimensional model of the ammonia absorption column was constructed using 3D Studio Max software. The type and the construction of the object is a vital issue in the development of the virtual reality training system. The total number of polygons have been kept to a minimum as this has an impact on the rendering speed of each frame. Objects needed to be constructed with appropriate number of details in order to be easily recognisable. A high number of texture maps were used and a suitable portion of carefully chosen and scanned-in photographs were obtained in order to bring a sense of reality to the virtual environment. This section describes the construction of the objects, which are used to build the virtual environment.

6.9.1 Rig scaffolding

The construction of the scaffolding, which would hold the two columns and the pipelines, was built from the real dimensions and photographs of the laboratory rig. The colours and the texture maps, which have been mapped on to the three-dimensional object, were manipulated using Adobe Photoshop software. Figure 6.34 shows a perspective view from 3D Studio Max of the scaffolding object.
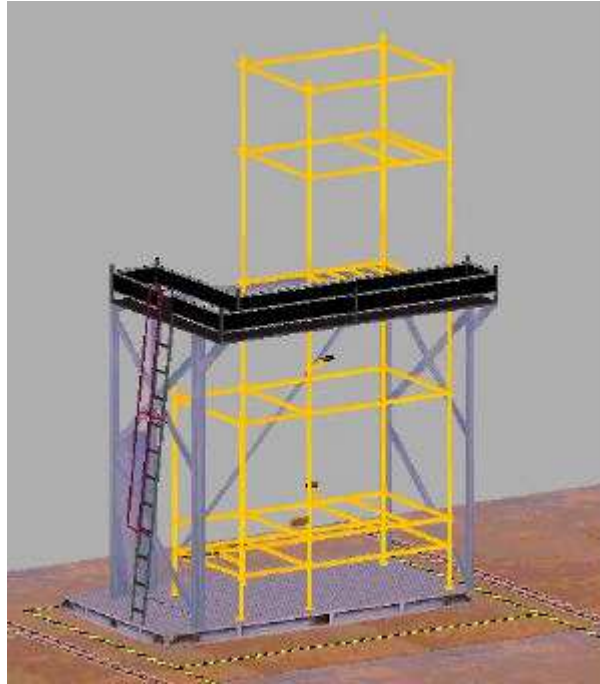
Figure 6.34: Perspective view of the rig scaffolding object

6.9.2 Glass pipes

Glass pipes are made from heat and chemical resistant borosilicate glass, which is highly stable to acids and resists attack by alkalies. The three-dimensional pipeline construction was made with the same technique as in the previous case studies. The main problem for the virtual pipelines of this model was the texture mapping of them. All the pipes of the real rig were made from glass making their virtual construction quite difficult. In order to build these, a texture map was constructed with a light blue colour and its opacity was adjusted to a suitable level to make the three-dimensional object transparent. The texture map, which was used for the pipelines and a view of the pipeline layout, is illustrated in figure 6.35.

Figure 6.35: The three-dimensional pipes objects and the texture image, which was used

6.9.3 Manometer

The height or head to which fluid rises in an open vertical tube attached to an apparatus containing a liquid is a direct measure of the pressure at the point of attachment and is frequently used to show the level of liquids in tanks and vessels. This same principle, applied with U-tube manometers, is the one that is used in the laboratory experiment. The differential U-tube manometer of this experiment consists of the glass U-type tube and the measured liquid, which is Kerosene. The manometer is placed on the front side of the laboratory rig and is used to measure the pressure drop across the column. There are two valves on its faceplate. The top valve switch the manometer for one column to another and the other valve is used for output ammonia concentration measurements. A front and a rear view of the manometer object is shown in figure 6.36.
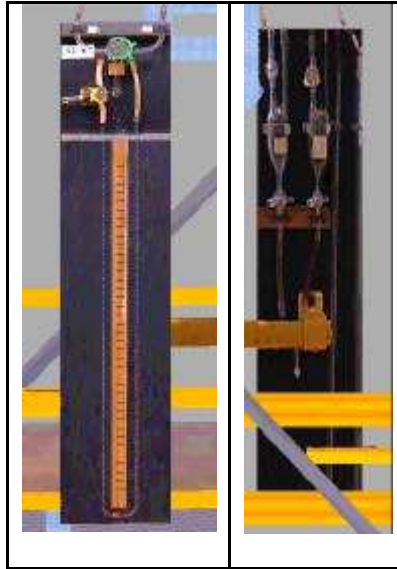
Figure 6.36: Front and rear face of manometer object

By adjusting the appropriate values for the opacity level of the texture map for the manometers tube it becomes recognisable the inner red tube object, which represents the liquid kerosene. The liquid kerosene object is animated and the distance between its upper surfaces indicates the pressure drop value.

6.9.4 Rotameter

The rotameter has become one of the most popular flowmeters in the chemical process industries. It consists, essentially, of a plummet, or "float", which is free to move up and down in a vertical, slightly tapered tube having its small end down. The fluid enters the lower end of the tube and causes the float to rise until the annual area between the float and the wall of the tube is such that the pressure drop across this constriction is just sufficient to support the float. The tapered tube is of glass and carries etched upon it a nearly linear scale on which the position of the float may be visually noted as an indication of the flow.

There are three rotameters in this experiment, which are used for measure the flow of gases and liquid streams. One of them measures the inlet air flow and is placed next to the manometer, the other measures the ammonia flow, which comes from the cylinder at the back of the rig and the third one measures the liquid flow which enters on the top of the column. Figure 6.37 shows a schematic representation and a perspective view of the rotameter object in 3D Studio Max.
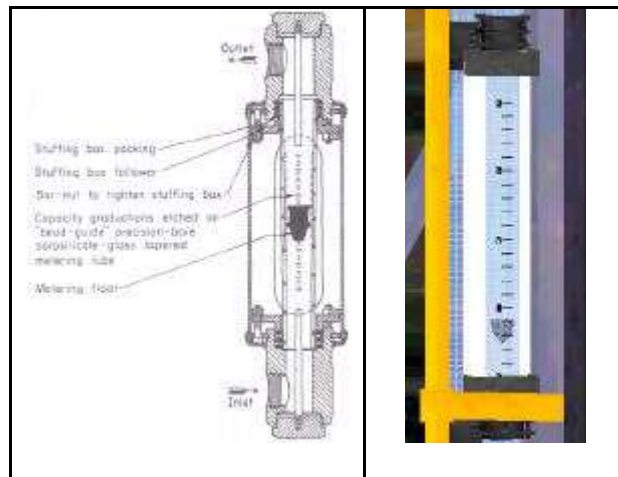
Figure 6.37: Schematic representation and a perspective view of rotameter

6.10 Virtual reality model

The virtual reality training system for the gas absorption experiment is running using the SAFE-VR software. The recent versions of SAFE-VR software give the opportunity for more complex simulation as the numbers of mathematical equations, which are supported, are increased from earlier versions. Also, the virtual laboratory experiment contains an extremely large number of polygons and a great variety of texture images. A general screenshot of the virtual training system is shown in figure 6.38.

Figure 6.38: General view of the virtual reality absorption column experiment

One of the main purposes of the virtual reality system is to help the trainees to identify the chemical process equipment on the rig and to become familiar with its

operation. Some default hotkeys have defined to help user's navigation and are presented in table 6.18.

Hotkey	Location
Num1	Manometer's position
Num2	Air rotameter position
Num3	Liquid rotameter position
Num4	Ammonia rotameter position
Num5	Air inlet valve position
Num6	Calibration graphs position
Num7	Gas analyser position
Num8	Ammonia valve position
Num9	Liquid valve position

Table 6.18: Hotkey navigation around the virtual environment

By pressing the "I" button on the keyboard at any time the virtual reality training system informs users which column is running, which are the readings of air, liquid and ammonia rotameters and the value of the pressure drop. Figure 6.39 presents a message box, which is launched by pressing the "I" button.
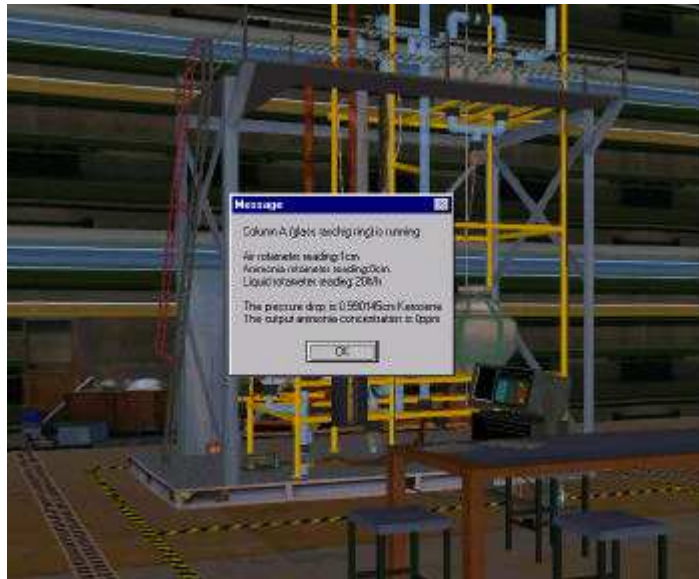
Figure 6.39: Informative message box from virtual reality model

Approaching the ladder, which is placed on the left side of the laboratory rig a message box, launches and asks the users whether they would like to climb up as shown in figure 6.40. If their answer is affirmative the virtual model responds immediately and automatically moves the users up. Users need to climb up to the upper level, in order to check two valves for proper column operation.
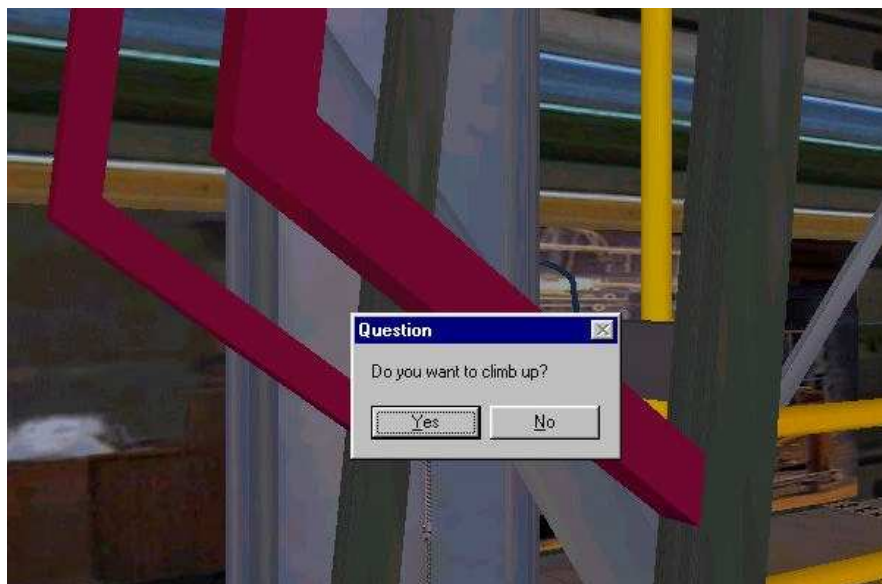
Figure 6.40: Question message box from the virtual training system

Collision detection simulations have been written using ladder logic diagrams in SAFE-VR, as shown in figure 6.41, to prevent user view to move through the

three-dimensional objects. The SAFE-VR simulation sheet, which is presented in figure 6.39, defines a square area around the rig scaffolding, preventing user to move through it.

The principle of a collision detection routine is to continuously check whether the object representing the user's body has intersected any of the other objects making up the virtual world. It is an important aspect of bringing realism to the behaviour and functioning of a virtual reality system. For instance the users should follow the same path as in the real world if they decide to go to the ammonia cylinder, which is placed on the rear of laboratory rig.
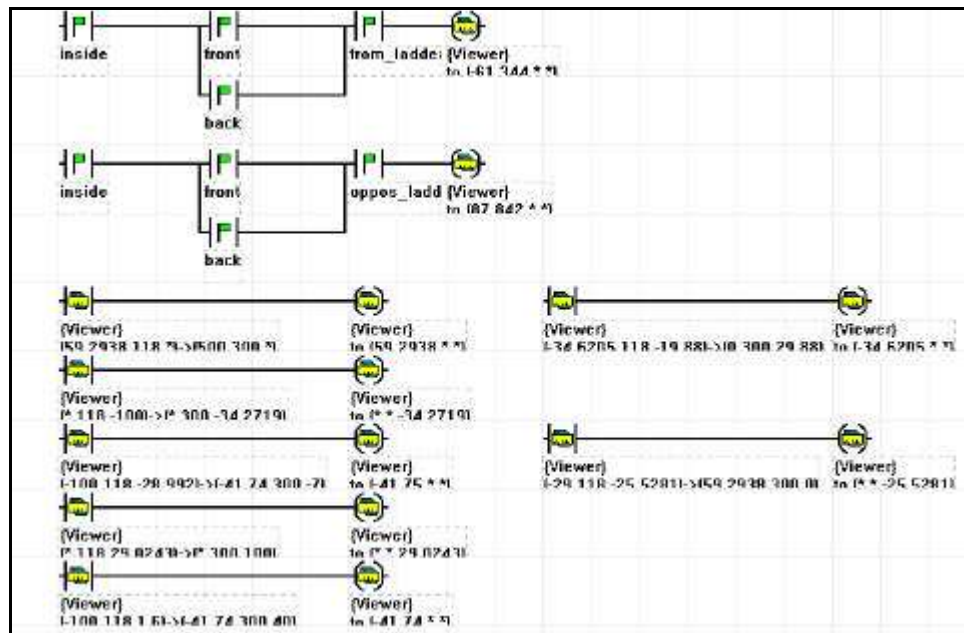
Figure 6.41: SAFE-VR ladder logic diagram for collision detection routines

6.10.1 Valves operation

There are three valves which open and close in stages, controlling the air, ammonia and liquid flows that enter to the packed column and three rotameters which measures the flowrate of these streams. Calibration graphs are provided for air and ammonia rotameters in order to convert their measured units to litres per minute and are placed on the table in front of the laboratory rig. The liquid rotameter is already calibrated and measure litres per hour liquid flow. Screenshots from the air, ammonia and liquid inlet valves and the air, ammonia and liquid rotameter are shown in figures 6.42, 6.43 and 6.44.
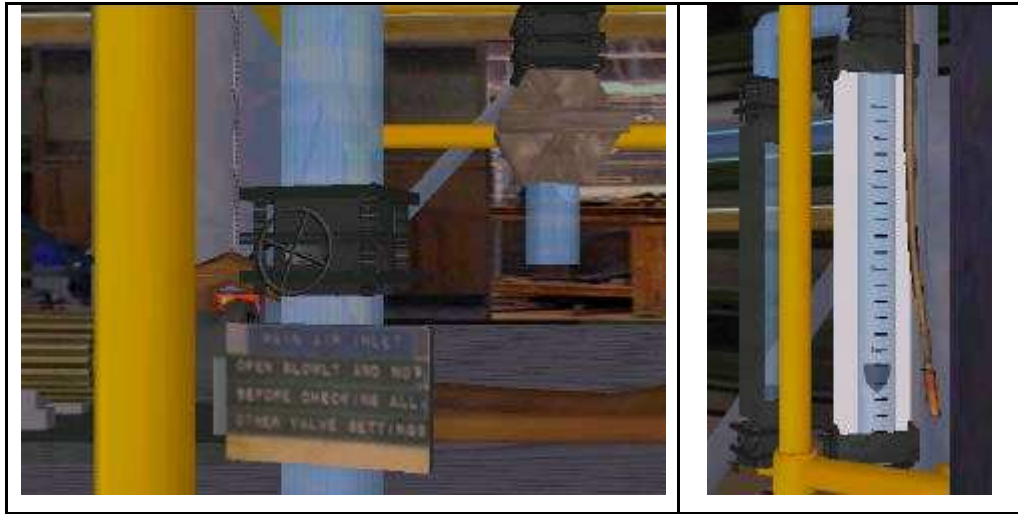
Figure 6.42: Screenshots from air inlet valve and air rotameter

Figure 6.43: Screenshots from liquid inlet valve and liquid rotameter
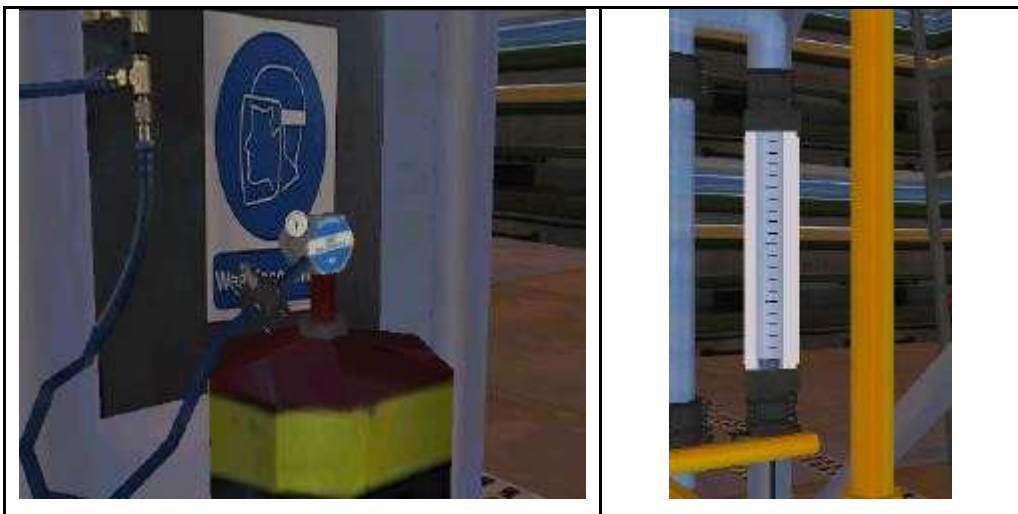
Figure 6.44: Screenshots from ammonia inlet valve and ammonia rotameter

Several hotkeys have been defined in order to control the air, liquid and ammonia inlet valves and they are summarised in table 6.19.

Operation	Air inlet valve	Liquid valve	Ammonia valve
Step open	"G"	"L"	"A"
Step close	"B"	"."	"Z"

Table 6.19: Hotkeys for liquid, air and ammonia valve operation

Exponential equations control the float object animation inside the rotameter tube in order to make its movement more realistic. As a result the float is not going directly to its following step as the users switch the inlet valve. Figure 6.45 shows a part of the SAFE-VR simulation sheet which controls the float's animation.
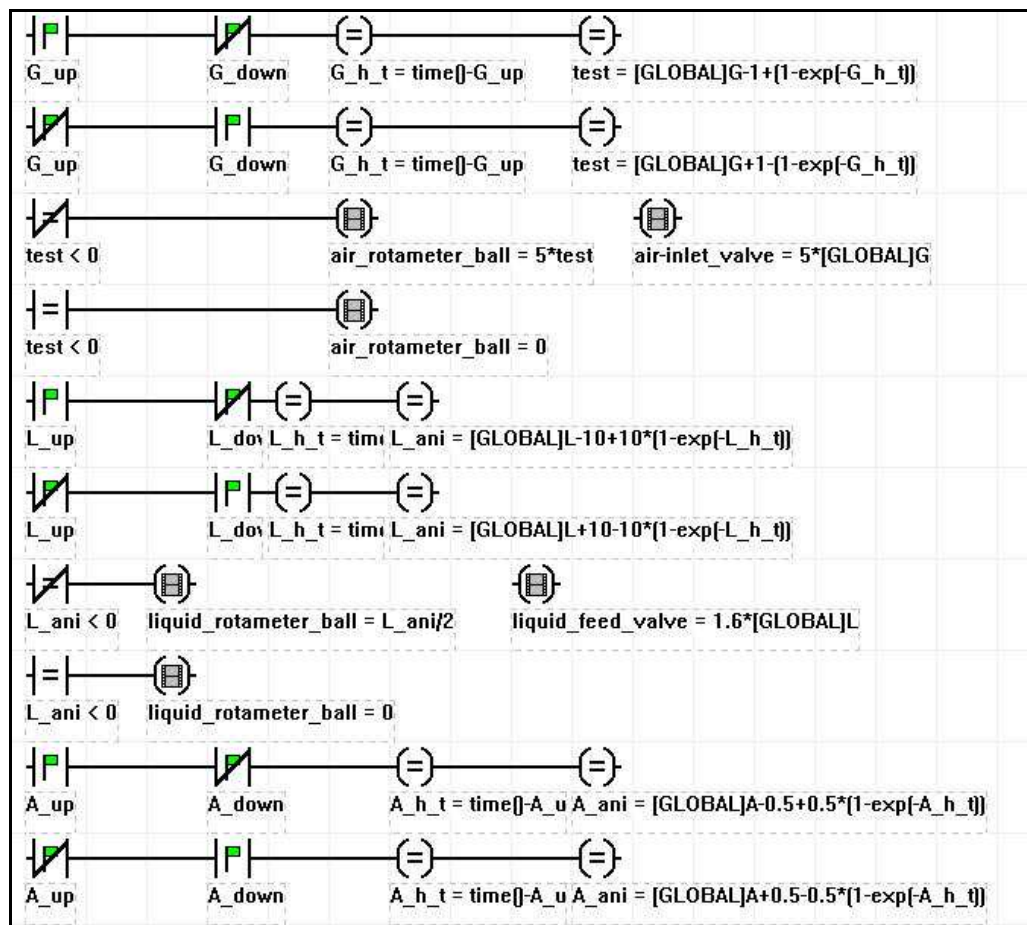
Figure 6.45: Screenshot from SAFE-VR simulation module for float animation

6.10.2 Manometer operation

The manometer, which measures the pressure drop across the packed column, is a differential U tube liquid column manometer. The manometric fluid that constitutes the measured liquid is kerosene. The height difference between taps A and B is the pressure drop value in millimetres kerosene. The pressure can be converted from mm Kerosene to Pascal by applying the following equation.

$$P = \rho_{Kerosene}gh$$

where   P is pressure in Pa

$\rho_{Kerosene}$ is density of kerosene of 782.592 kg/m^3

g is the acceleration due to gravity of 9.81 m/s^2, and

h is height of Kerosene in cm

By clicking the faceplate of manometer object a message box launches giving to users the pressure drop in cm Kerosene as shown in figure 6.46.

Figure 6.46: Pressure drop reading

Two valves are present on its faceplate. The top one switches the manometer from one column to other and the other one opens the sample point for measurement of output ammonia composition. At the edge of the pipe, which is connected to the second valve the students place the Drager tube instrument taking measurements for output ammonia concentration. By clicking the valve object the valve animates

and at the end of animation a message box launches giving information on which column's pressure drop the manometer is measuring.

6.10.3 Gas analyser operation

In the real laboratory rig the students measure the output ammonia concentration using a Drager tube instrument but in the virtual environment a gas analyser is connected to the output pipeline of the packed column. There is a monitor screen on a gas analyser where a graph is displayed that indicates the values of output ammonia concentration in ppm. The graph consists of thirty animated square objects, which look like small dots. Different variables are assigned to each object's animation, these are controlled by the value of the output ammonia concentration. Every second the first variable of this sequence receives a new value for the output ammonia concentration and passes the previous ones to the variable that controls the animation of the next object. The graph is drawn dynamically and updated every second giving users the possibility to follow the value of output ammonia concentration over a long period. Figure 6.47 shows a screen shot from the graph, which is produced on the gas analyser.

Figure 6.47: Screenshot from gas analyser

Two hotkeys were assigned to gas analyser operation, which are summarised in table 6.20.

Operation	Hotkey
Gas analyser online	"O"
Gas analyser offline	"P"

Table 6.20: Hotkeys for gas analyser operation

Using the action button on the SAFE-VR toolbar and by double clicking on the gas analyser faceplate the users can have the reading of ammonia concentration at the outlet of the absorption column as shown in figure 6.47.

6.10.4 Pressure drop measurement

During the initial stage while the glass raschig ring column is running, the liquid and air flow are configured to steadily values and the inlet ammonia valve is closed. The trainees prior to carry out absorption runs, they should determine the loading and flooding points for each column. They have to measure pressure drop across each column as a function of various gas flowrates for a series of fixed liquid flows. During each run an appropriate time should be allowed for the column to reach a steady state condition before any measurements are taken. Repeated measurements can be taken if necessary. The set of data, which will be collected for each column, are going to help users to determine the flooding and loading points for each packing section by making a series of mathematical calculations.

6.10.5 Measurement of ammonia concentration at the outlet

Finding the loading and flooding points for both columns the users should decide the flow range of liquid, air and ammonia in order to carry out experimental runs for determining ammonia concentration measurements at the outlet of each column. Using the gas analyser they are able to determine ammonia concentration in ppm. However, the air and ammonia combined flowrate should be kept below the column loading point, in order to stay far away from its flooding point. The users should allow appropriate time before any measurements in each run in order to achieve steady state condition. The dynamic graph, which is displayed on the

gas analyser monitor, helps them to determine the time that the steady state condition has been reached.

6.11 Work arising from this research

Towards the end of this research study the School of Chemical, Environmental and Mining Engineering at the University of Nottingham, using funding from the rapid response fund from the Centre for Teaching Enhancement, developed a virtual learning environment using standard multimedia and internet technology for the flooding and gas absorption experiment. This was based on the last virtual training system of the current research and is used as part of a third-year module of the chemical engineering course.

This is an attempt to provide the students with more than traditional training and teaching methods in terms of retention of solid knowledge of subject content, to increase the depth of understanding, and also give an increased sense of ownership and enjoyment of the learning experience. The virtual environment allows the students to learn by their actions and control the interaction and investigation of the knowledge contained within the world. A virtual reality based learning system provides an ideal environment to facilitate student exploration and student-centred learning. The whole learning process is totally experiential, as the students must actively interact with the simulation behind the virtual environment to achieve carefully selected aims and objectives. The figure 6.48 shows the introduction page of this learning environment.

Figure 6.48: The introduction page of the virtual gas absorption column experiment

This interactive learning environment is made up of three different modules related to the rig's components identification, hazard identification and procedural operation respectively. The large items of laboratory equipment involved in the project process chemical substances (the absorption column processes ammonia gas and dilute sulphuric acid), often at concentrations high enough to present a serious hazard, and health and safety risks are always present. The virtual absorption column will lead to an increase in the safety awareness of the students, and an increased familiarisation with the equipment when they perform the real experiment.

The VRML chemical rig environment.

Information for the rig component that user identified in the virtual environment
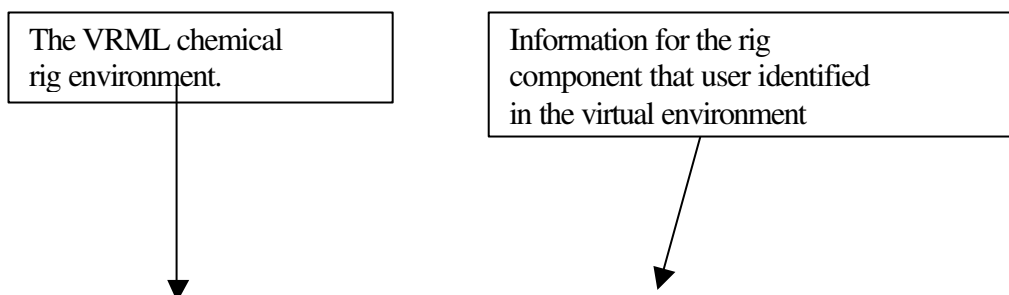
Figure 6.49: The VRML model with an explanation of manometer operation

The virtual laboratory rig built in VRML allows students to navigate easily within the virtual world identifying chemical equipment. A number of detailed web pages with all the components of this chemical engineering rig are provided to the students helping them to have a better knowledge of rig's layout and equipment's use. By clicking any object of the VRML model the system provides relevant information, explains to students its use and teaches them the basic steps for its operation as shown in figure 6.49.

The dual framed web page with integrated VRML sections provides a highly interactive interface for the student because they can easily move within the virtual rig in the left frame and in the same time they can read the information that is available for the ammonia rig components in the right frame as shown in figure 6.49.

Figure 6.50 shows a screenshot, which came from the hazard identification module of this virtual learning environment. This web page contains an integrated source of information about the hazards that are associated with particular components of the laboratory rig layout implemented in a tree-structured design.

The three frame web page provides the VRML model on the left, the tree-structured design for hazards on the right and the explanation of each hazard or action that the students have to carried out of the bottom as shown in figure 6.50.
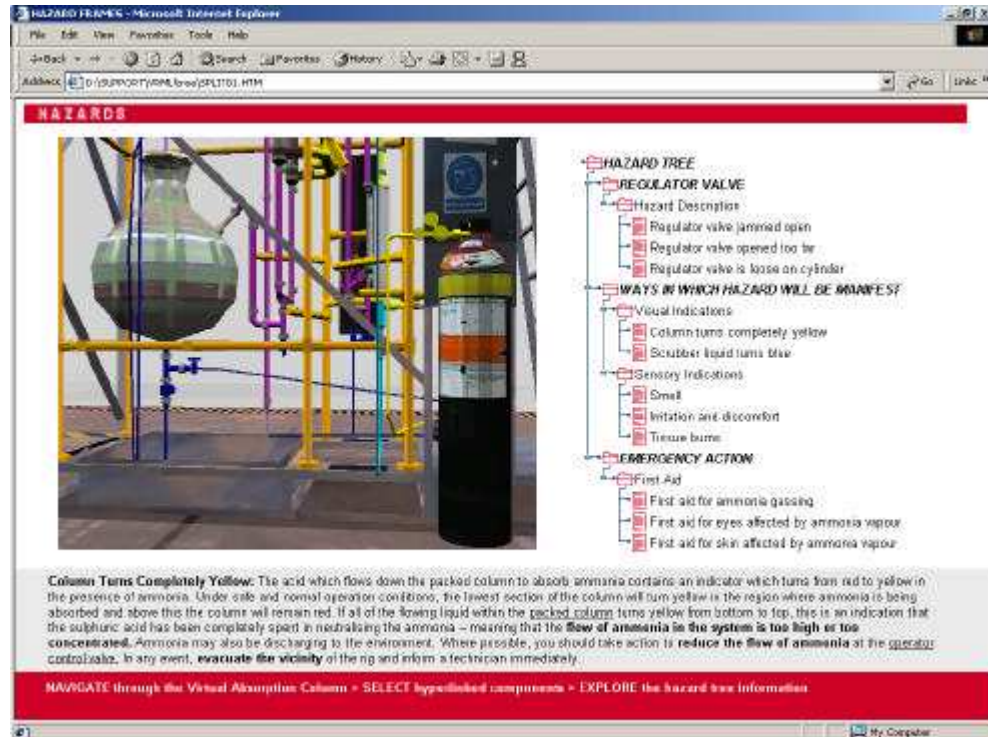
Figure 6.50: A screenshot from the hazard identification module

The virtual experiment will undoubtedly widen the variety of teaching media used in the chemical engineering course, and introduce new teaching methods in executing and interpreting 'real' experimental laboratory projects. It is intended that the assessment for the laboratory module will involve both the 'virtual' experiment, and in the 'real' laboratory experiment.

6.12 Summary

This chapter has discussed a virtual world based on an undergraduate laboratory experiment for the Chemical Engineering degree course at the University of Nottingham, focusing primarily on training and safety issues of students. This virtual experiment will not only familiarise the undergraduate students with fundamental features of the absorption column experimental apparatus, but also teach its procedural and safety aspects.

The dynamic features of the virtual absorption column simulation give high level of realism in the virtual environment and help the users to a deep understating of chemical engineering principles which govern this mass transfer process. The time, which is needed before the system reaches its steady stage, constitutes one of the most powerful features of the virtual gas absorption experiment. The operation of chemical engineering instruments and the knowledge of this laboratory rig layout using the virtual reality system help students to know exactly what tasks they should follow and what precautions they should take before they implement the experiment in the real laboratory. Students are able to set experimental tasks in the virtual world, and if they make any mistakes they will learn what went wrong without damaging equipment or themselves.

The virtual absorption column should not be considered as a replacement for the real experiment but a new teaching method that can help students to execute and interpret 'real' experimental laboratory projects. However that implementation is not straightforward, and it should be remembered that virtual reality is mainly used as a supplement to real experiences, or in situations where the real experience is inaccessible. Universities have to encourage the development of virtual reality as a useful tool in engineering, science, and education, initially in the areas of higher-dimensional scientific visualization and the development of virtual accident scenarios for the reduction of laboratory accidents.

Chapter 7

Evaluation of virtual reality usage

7.1 Introduction

This chapter reviews some examples of the evaluation studies that researchers and industry have conducted on their various uses of virtual environment technology. There are very few examples of evaluation studies in industry. The reasons for this may include maintenance of confidentiality so that the competitors are unaware of their activities especially if they are providing cost and time saving solutions.

In order to assess the relevance and the acceptability of the virtual gas absorption experiment a number of subjects from the School of Chemical, Environmental and Mining Engineering of the University of Nottingham were used. Two different groups were selected for these evaluation tests, one constituted of postgraduate chemical engineering students and the other group came from the AIMS research unit. These trials consisted of evaluation interviews on the virtual packed column simulator. The results of these evaluations are discussed and presented in terms of their relevance for the application of virtual reality based systems for training in undergraduate laboratories.

During these trials the trainees made a number of suggestions for the improvement of the virtual reality training system and these have been recorded for consideration in future training simulators.

7.2 Evaluation theory

Evaluation is concerned with gathering data about the usability of a design or product by a specified group of users for a particular activity within a specified environment or work context (Squelch, 1998). The evaluation of training is closely linked to the development process of training and is ultimately concerned with measuring how far the training has achieved the objectives defined in terms of efficiency and effectiveness. The evaluation of training can help to improve the

quality of training when the training method may be an old approach that needs modifications. In this way the evaluation meshes closely with design and guides the design of the training system by providing feedback. This kind of evaluation is called formative. In contrast, evaluations that take place after the product has been developed are known as summative because they are concerned with making judgements about the finished model.

The main methods, which are used for user analysis during the evaluation of training tends to be interviews and questionnaires. The main advantages of interviews and questionnaires is that they are usually quick to administer and can yield a large amount of data but they need to be carefully designed in order to be effective. Generally there are three types of questions that can be employed, these are categorised into structured, semi-structured and open questions. Structured questions involve some type of multiple-choice where a list of answers or a rating scale, are provided to the respondent, who has to choose the most appropriate answer. Semi structured questions are those that have a set of questions followed by an opportunity to elaborate on their chosen answer. Open questions are questions, which allow the respondent to provide further information. The actual design of a questionnaire depends on the type of information that is required (D'Cruz, 1999). The questionnaire, which was provided for this virtual reality training system, was constituted from structured and open questions and is presented in Appendix III.

7.3 Examples of evaluation studies on virtual training applications

The United States Army Research Institute Simulator System Research Unit in Orlando, Florida, and the Institute of Simulation and Training at the University of Central Florida constructed an experiment in order to evaluate the transfer of route knowledge from a virtual reality environment of a complex office building to the actual building. Sixty participants from the university environment were recruited, they all studied route directions and landmark photographs and then they were divided into three groups, a virtual reality training group, a real world group and a "symbolic" group. The virtual reality training group rehearsed the procedure using the virtual reality model, the real world model group used the actual building and the "symbolic" group verbally rehearsed the directions out aloud and had

landmark pictures to view. All the participants then completed the procedure in the actual building, configuration was measured by getting the participants to estimate the distance and direction of their initial position to another position. The results showed that the virtual reality training group was able to transfer more route knowledge than that "symbolic" or verbal rehearsal, but less than rehearsal in the actual building. However, type of rehearsal had no effect on configuration knowledge. The conclusions were that virtual reality training systems can train navigation skills in complex buildings and therefore should be considered whenever the real world environment is unavailable for training (Mirabelle D'Cruz, 1999).

The development of the Vicher 1, Vicher 2 and Safety World applications at the University of Michigan has been part of a research effort for determining which educational situations in engineering will benefit most from virtual reality technology and for developing techniques for the display of and interaction with scientific and technological information. Vicher 1 is a virtual simulation of a modern chemical plant, focusing on catalyst decay and different methods of handling this problem on an industrial scale. Vicher 2 is another interactive virtual chemical plant simulation, focusing on non-isothermal effects in chemical kinetics and reactor design. Figure 7.1 shows the catalytic reactor with multiple fixed beds of catalyst in series with interstage heating, used to overcome equilibrium limitations at lower temperatures. The program of evaluation of these applications showed an improved understanding of the pertinent engineering concepts. Most of the students felt that they learnt through the experience of the virtual environment and they appreciated the three-dimensional colour graph of the reaction kinetics and its relationship to the packed bed reactor as an example of how the virtual world gave them a more tangible grasp on the meaning behind the relevant equations (Bell and Fogler, 1996).

The VIRART group at the University of Nottingham has conducted evaluations looking the effectiveness of virtual reality training applications. One of the experiments, which took place in the VIRART laboratory involved training participants to change a network card in a computer using a virtual reality simulator. A still from this application is shown in figure 7.2.
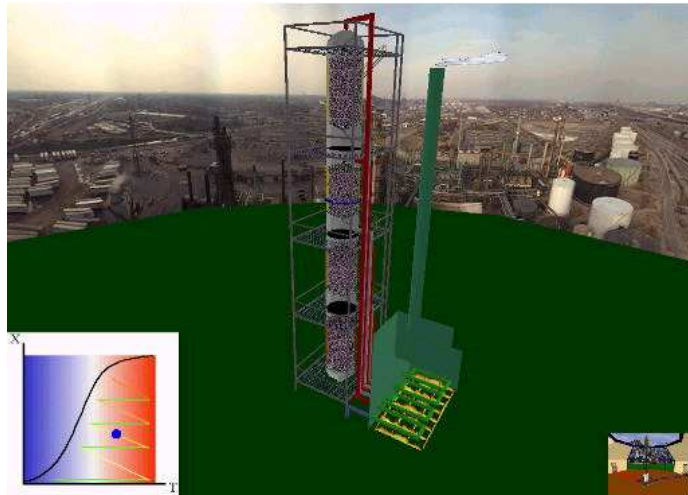
Figure 7.1: A screenshot from the stage reactor area in Vicher 2 project.
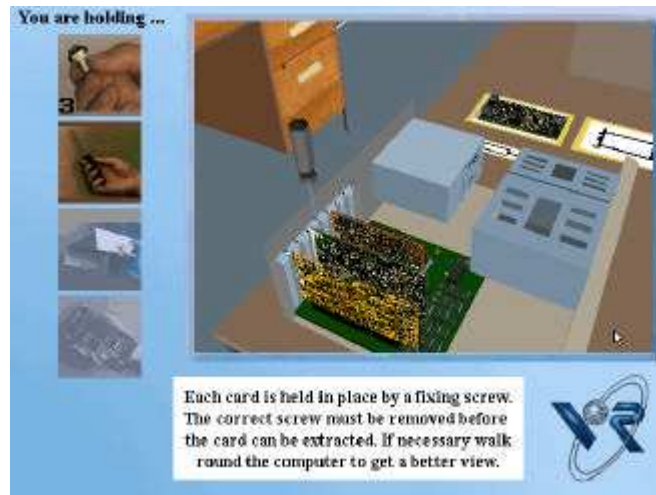
Figure 7.2: Virtual environment training application for changing a network card
in a computer

Three groups were used for evaluation. A group that received no training, a group trained by a video and a group trained by a virtual reality training system. Data was collected from questionnaires and through observation of the training and the performance trial. The results showed that there was a difference in the reactions of the groups to the training methods but little difference in performance times. Generally, the group trained by the virtual reality system mainly found the method "interesting" and "enjoyable" but experienced usability problems with the input device. The group trained by video found it "clear" and "straightforward" but "uninteresting" and "boring". Finally the group that had no training did find the

task difficult, made the expected errors and felt that they would have benefited from training. However this was not reflected in the performance times as they did not prove to be significantly different. This may have been because of the varying abilities of the participants. The task actually required more practice in motor skills than psychological skills and the desktop virtual reality system was unable to represent this adequately (Mirabelle D'Cruz, 1999).

Ford Powertrain Operations using technology from Division Ltd. developed the Ford Vulcan Forge application, which was a virtual reality simulation system for training workers in a forge hammer. A screenshot from the Ford Vulcan Forge application is shown in figure 7.3. The first evaluation tests of this virtual reality training system show that virtual reality trained operators were ten per cent more efficient than operators who had trained with a real hammer that was taken off-line. After the second evaluation tests when more realism features were added, such as plant noises and ergonomic enhancements, the virtual reality trainees scored twenty per cent higher. Ford is continuing to evaluate the system productivity benefits. (Ford Powertrain Operations, 2000).

The validity of these statistics from Ford cannot be fully justified because the company did not publish the structure and design of the evaluation trials and the sample population size and quality were unknown.

Figure 7.3: A screenshot from Ford Vulcan Forge application (after Ford Powertrain Operations, 2000)

In 1994, Motorola in close collaboration with Adams consulting began to explore the possibilities of developing a virtual reality environment application, which would provide the trainees with "hand-on" experience of the Pager Robotics Assembly Line (see section 3.3.7.4). The aim of the project was to compare the performance of groups trained by this virtual reality training system with groups trained in the real environment. It is regarded as the first industrial study to actually evaluate a virtual training environment application against an existing training method. The virtual reality environment training application was developed using a standard instructional design stage and the training system consisted of the tasks of starting-up, setting-up, running and shutting down equipment on an automated assembly line without any job aids or checklists. Twenty-one associates from the manufacturing facilities in Northern Illinois were selected for evaluation trials. They were divided into three groups and were given the same instructions to all the participants. One group went to the manufacturing laboratory where they used the existing training approach, the second group were taken to another room and began training on a desktop virtual reality system and the third group were trained by the same system but with a head mounted device added. The results show that, on average, in the most complex parts of the activity (start-up and set-up), the participants who had learnt in the real laboratory made an average of fourteen errors where both virtual environment groups made an average of one error (CyberEdge, 1994; VR News, 1996 and Wilson et al, 1996).

7.4 Examples of evaluation studies on virtual reality training applications developed by AIMS

Virtual reality technology has been investigated for application in the South African mining industry to provide improved hazard identification training for underground workers. This work was conducted as a jointly funded two years long project of the Safety in Mines Research Advisor Committee (SIMRAC) and the mining technology division of CSIR (see section 3.3.5). The developer of this project completed a Ph.D. in virtual reality in the AIMS Research Unit at the University of Nottingham (Squelch, 1998).

This virtual reality stope model has been tested by a group of underground workers and a series of evaluation trials was conducted at Elandsrand Gold Mine

Training Centre in South Africa. These trials consisted of preliminary evaluation interviews during the development phase and a final detailed evaluation of the virtual reality simulator and classroom training sessions. The results showed an encouragingly high level of acceptance and understanding of the virtual reality mine training simulator by the group of underground workers. The detailed evaluation confirmed that the application of virtual reality has relevance and potential in the field of mine hazard identification. Aspects found to be particularly favourable were the interactive and practical "hand-on" nature of the virtual reality system, an acceptable level of realism of the visuals and sounds and the implied message that mine management is treating the workface with more respect (Squelch, 1998).

A virtual environment training application for landfill site inspection was developed by the AIMS Research Unit using the SAFE-VR software. The virtual reality system was used for training novice site inspectors to perform an environmental audit of a landfill site. The trainee's task was to go around the virtual landfill site spotting and identifying all the safety hazards within the site. Figure 7.4 shows a still from the virtual landfill site application.

Figure 7.4: Virtual landfill site

Twenty-seven undergraduates in their second or third year majoring in environmental engineering originally took part in a series of evaluation trials of this virtual reality training system. In the first part of the experiment the trainees

watched a video, which was produced by accompanying an expert navigating the virtual landfill site, spotting and identifying hazards. In the second part of experiment each of the subjects used the virtual reality training system and for twenty minutes they tried to spot all the hazards that were present in the virtual landfill site. The results of this experiment showed that virtual reality training was more effective than video training. Subjects mentioned that the virtual reality training system had made hazard spotting easy and it had helped them learn and understand issues related to environmental safety in a landfill site (Rajarathnam, 2000).

The Environment Agency in United Kingdom in conjunction with the Nottingham based virtual reality research unit, AIMS Solutions, developed a virtual landfill site to enhance staff training and provide greater consistency in site inspection. The computer-based simulation enables users to navigate around a landfill site and randomly encounter a typical range of scenarios, hazards and events (Environment Agency, 2001).

Environment Agency project manager Howard Thorp is delighted and he said (Environment Agency, 2001):

"Whilst the simulation does not seek to replace real life experience, it does offer some real benefits. Users can get quick and easy access to training without waiting for training courses, training budgets or experienced trainers to become available."

"The programme is cost and time effective, and early feedback from users indicates the retention of key information is enhanced because the approach to training is memorable and stimulating. Many staff is amazed by how much they remember when they come for their second training session."

"The virtual reality landfill site will provide greater consistency in site inspection and will be a massive benefit to both the Agency and the industry."

The site has been constructed so it can evolve as needs dictate. A transfer station linked to the site is currently under development to supplement the existing landfill site. All Agency area offices will have access to the programme in the future (Environment Agency, 2001).

The Aims Research Unit has also developed a virtual reality training application for teaching and testing hazard awareness in the construction industry. A virtual construction site was modelled and represented in SAFE-VR. A screenshot from the virtual construction site is shown in figure 7.5. Typical hazardous situations that often occur on construction sites were identified, and incorporated into the site model.

Figure 7.5: A screenshot from virtual construction site (after Burton *et al*, 2001)

A group of students from Chesterfield College in the United Kingdom were selected for evaluation trials of this virtual reality hazard spotting application. They undertook use of the virtual construction site as part of a course about safety on building sites. The results of this testing were very positive for the use of the virtual reality technology for hazard spotting. The majority of students found the virtual training system enjoyable and very useful for understanding issues related to health and safety. They considered the virtual reality a high successful medium for training personnel in hazardous situations and they were impressed by the highly detailed construction site virtual environment (Burton *et al*, 2001).

7.5 Evaluation procedure

Simple evaluation trials were decided to carry out for the virtual flooding and gas absorption experiment towards the end of this research study. These evaluation trials can be justified, as it was an effort to explore and investigate issues related to usability of the virtual reality environments. This task was undertaken, even though it was considered to be outside of the main research area. The population of a random sample was chosen by the author and came from the School of Chemical, Environmental and Mining Engineering at the University Nottingham.

For the virtual gas absorption column, training sessions were conducted with two different groups. One group was made up of twelve subjects from the School of Chemical, Environmental and Mining Engineering at the University Nottingham. Ten subjects of this group were chemical engineers, undertaking postgraduate studies at the University of Nottingham, and two of them were the technicians who were responsible for this laboratory rig, who explain to students how to perform the experiment. This group was chosen because of their chemical engineering background. Eleven researchers from the AIMS Research Unit also took part on these evaluation trials for the virtual gas absorption experiment. This group was made up of people who have experience in computer graphics and virtual reality technology.

For the purpose of this evaluation exercise the virtual gas absorption experiment was installed on a 750MHz, Pentium-III personal computer in the demonstration room of the Aims Research Unit. A joystick was used to navigate around the virtual environment as shown in figure 7.6.

A detailed instruction sheet explaining the usability of packed towers, the detailed operation of the system and the task to be performed was given to the users (Appendix II). A table showing the different hotkeys used for easy navigation and for the operation of the system's control valves was also produced and is shown in figure 7.7. This was placed on the table next to the joystick so that the user could read it as they navigated around the virtual laboratory rig.

Figure 7.6: Photos from evaluation trials of the virtual absorption column experiment

Trainees participated individually in the laboratory experiment. Each trainee was given simple instructions in the use of the joystick, in the functionality of the virtual chemical engineering instruments and allowed some time to move around and get used to navigation within the virtual laboratory rig. The trainer then proceeded to verbally "walk them through" the basic steps needed to use the system. The procedure was kept standard for all the subjects and the trainer was present to help them with any difficulties that they had using the system. A series of questions about personal protective equipment for laboratory safety was asked by the virtual reality system at the beginning of each training session.

In the first part of the experiment the trainee was asked to make pressure drop measurements of various liquid and gas flowrates for both columns in order to determine the flooding and loading points. The trainees should wait long enough before any measurement, so as to allow the system to reach a steady state condition.

Figure 7.7: Table with hotkeys, which was provided to the subjects

Having determined the flooding and loading points for both columns from the first part of the experiment, the trainee is now able to perform the absorption runs. They should select suitable liquid and gas flowrates in order to carry out ammonia absorption runs. Again the system should be allowed to reach a steady state before any ammonia concentration measurements are taken.

At the end of each training session they were questioned on issues related to the virtual reality based system. The questionnaire, which was provided for the virtual flooding and gas absorption experiment is presented in Appendix III. The results of this assessment are presented in the following section.

7.6 Results
Several biographical variables were recorded for all subjects as background data and to determine their impact on the subjects' performance. The majority of the

subject group was between twenty and twenty five years old as shown in the figure 7.8.
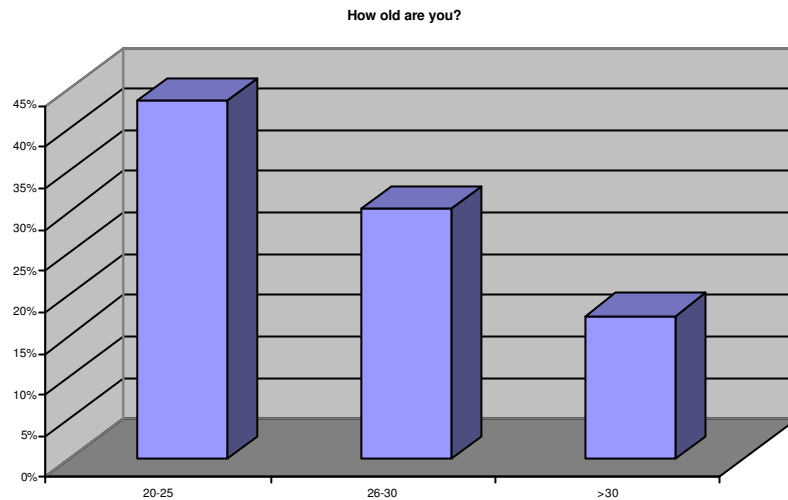
Figure 7.8: Age of subjects

The level of enthusiasm of younger subjects was higher, but all the subjects were impressed with the visual representation of the laboratory rig. This reaction of subjects overrules any suggestion of a reluctance to accept new technology. Factors such as age and experience do not appear to affect the choice of a virtual reality based training system but these factors may influence the way in which people learn. Through appropriate programming the complexity of the virtual world and the level of content can be varied and designed to meet the diverse needs of trainees and the different work situations in which the trainees operate.

The previous exposure to a computer medium was quite high with 48 per cent of subjects having experience of playing computer games. All the subjects had computing experience and all used computers everyday. The whole group had experience in word processing, internet and e-mail. Figure 7.9 illustrates in details how the subjects usually use computers.

Only 35 per cent of the subjects had experience of similar virtual reality training systems as shown in figure 7.10. Subjects also were asked about previous exposure to chemical process equipment. In particular they were asked if they have been in a chemical engineering laboratory before. The postgraduate students from School of Chemical, Environmental and Mining Engineering were familiar

with the operation of chemical process equipment. The results from this question is summarised in figure 7.11.
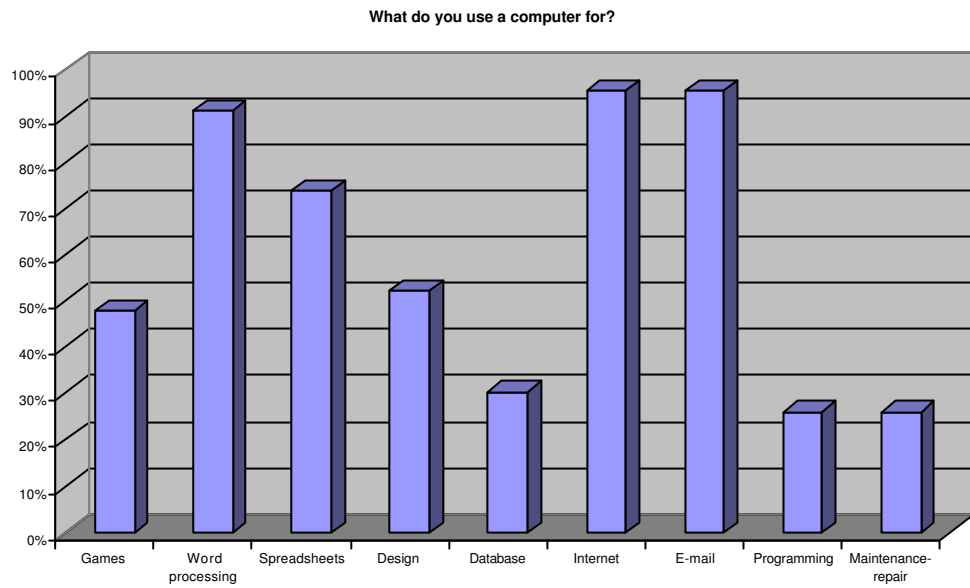
Figure 7.9: For what purposes subjects use computers
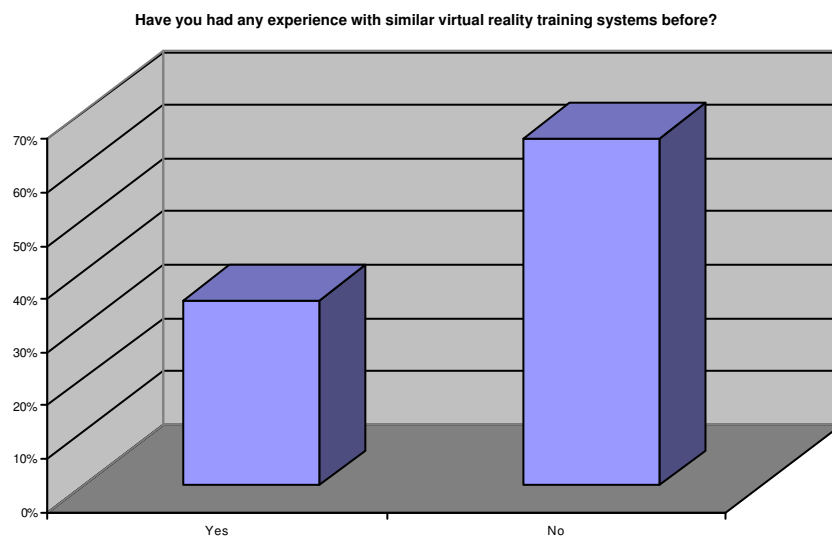
Figure 7.10: Previous exposure to virtual reality training systems
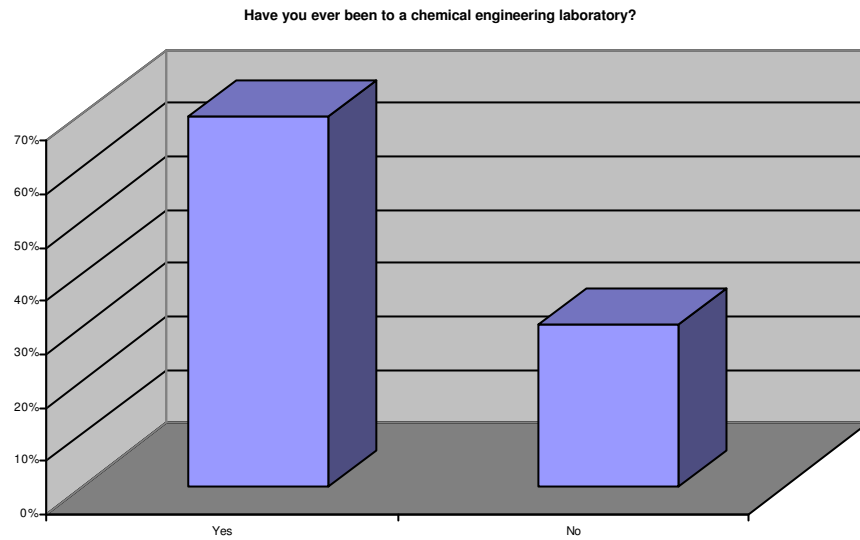
Figure 7.11: Subjects experience of chemical engineering processes

Subjects were asked to assess the duration of the virtual reality training session. The majority of them mentioned that they had enough time for training but they would like to have longer experience with the virtual reality medium as figure 7.12 shows. They also said that they required more time to become familiar with navigation techniques within the virtual environment at the beginning of the training session, which is not unreasonable to expect.

Was enough time given for training?
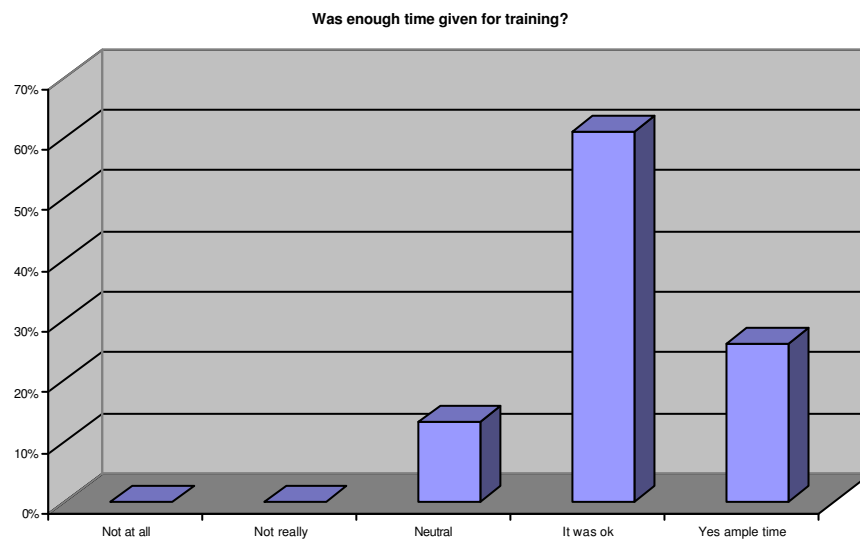
Figure 7.12: Subjects opinion about the duration of training session

The majority of the subjects felt that they had benefited from the training and all the necessary information had been provided. They also found the virtual absorption experiment enjoyable and interesting as shown in figure 7.13.

Did you enjoy using the virtual reality program?
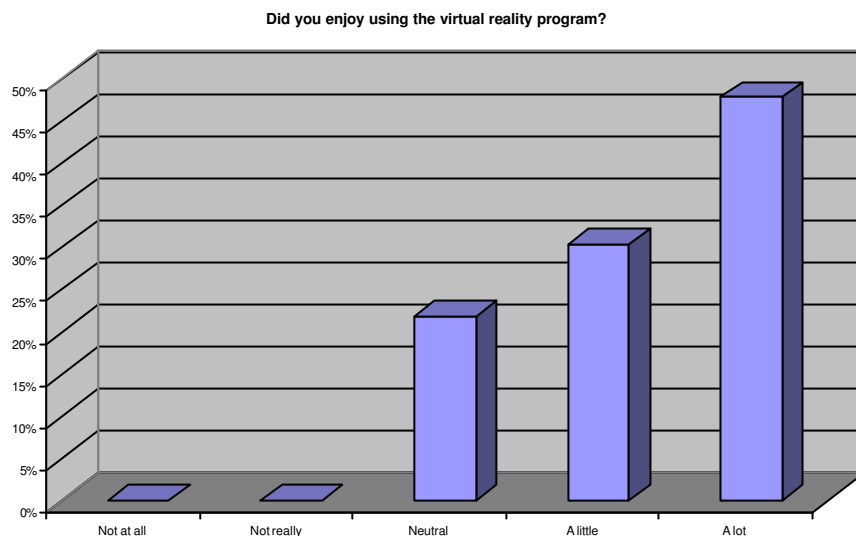
Figure 7.13: Opinions about enjoyment and interest of virtual world

The subjects were also asked to evaluate the ease with which they were able to understand the chemical processes and the experimental procedures in the virtual gas absorption column. No extreme viewpoints were recorded and the majority of subjects indicated high levels of comprehension as shown in figure 7.14.

Did you find easy to understand and use?
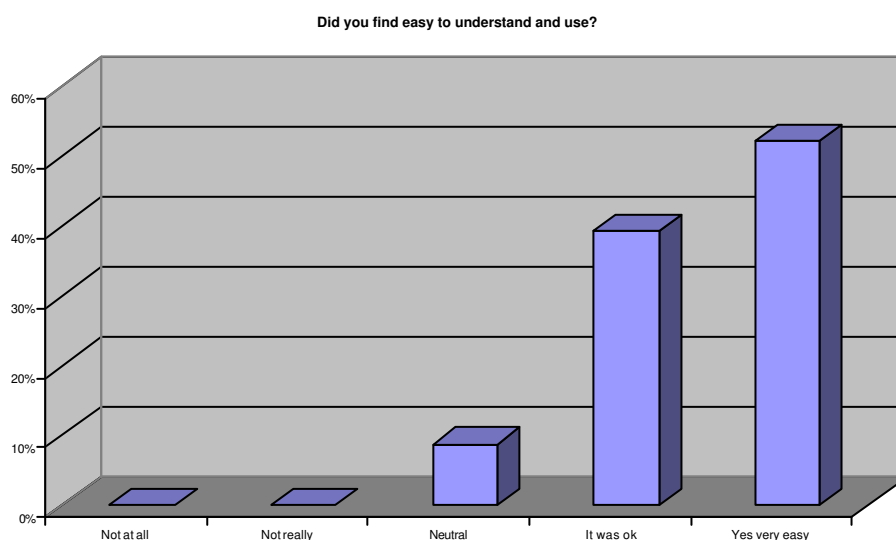
Figure 7.14: Ease of understanding and using the virtual training system

Subjects were also asked whether they considered that the virtual training system could help students to understand the real experiment. Almost all subjects answered affirmatively and they made very positive comments about the educational use of the virtual absorption experiment.

Do you think that it would help students to understand the real experiment?
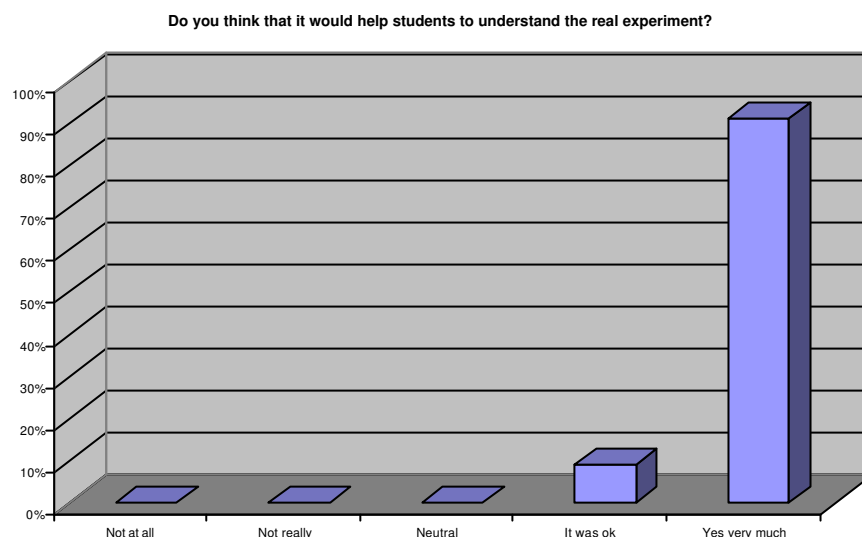
Figure 7.15: Would the virtual training system help the students to understand the real experiment?

They suggested that this was a valuable and useful tool for enhancing the teaching of chemical process fundamentals. The graph, which is presented in figure 7.15, indicates the positive comments of the subjects.

Subjects were also asked to indicate the level of realism they felt to be depicted in the visual material contained in the training program. They were asked if the system gave to them a sense of reality, i.e. "being there" in the environment. Again no extreme answers were expressed and the subjects indicated that they considered the respective virtual absorption experiment to be a realistic representation as shown in figures 7.16 and 7.17. In a similar question whether they felt as they were visiting the place rather than simply seeing images, the views were very positive and the vast majority of subjects indicated that virtual reality has the capacity to present visual content which is not markedly less

understandable or realistic than that shown in photographs. These results are shown in figure 7.18.
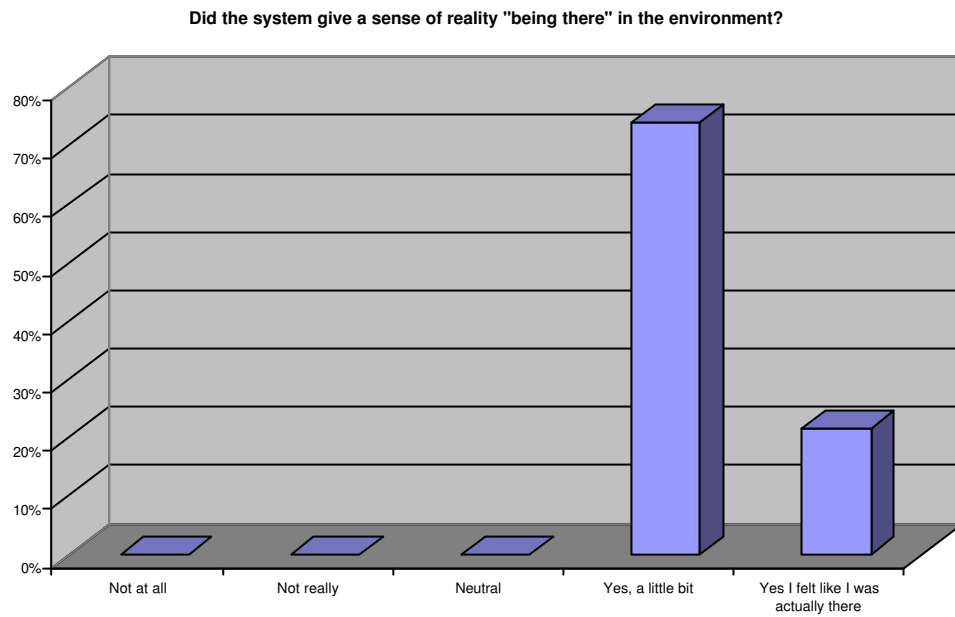
Figure 7.16: Perceived level of realism in the virtual gas absorption experiment
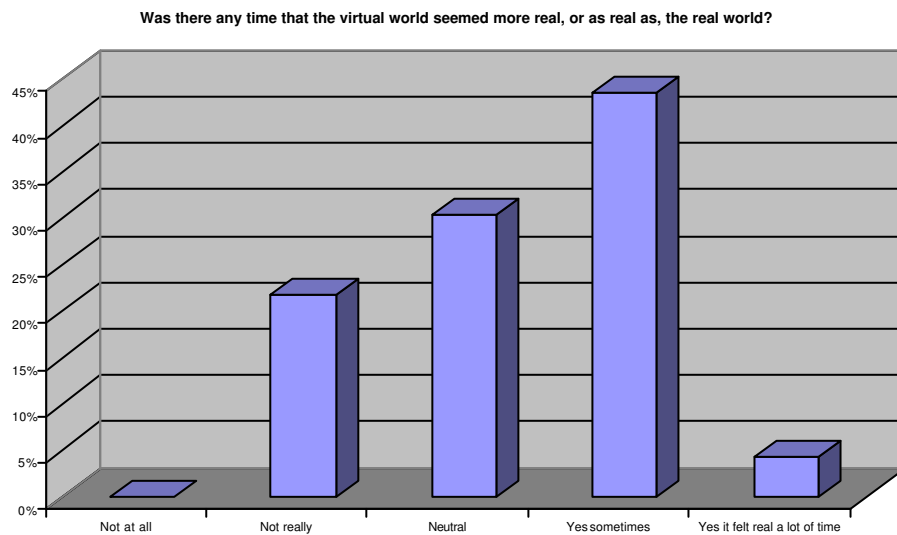
Figure 7.17: Results on realism issue of virtual system comparing with real experiment

Did you feel as if you were visiting the place rather than simply seeing images?
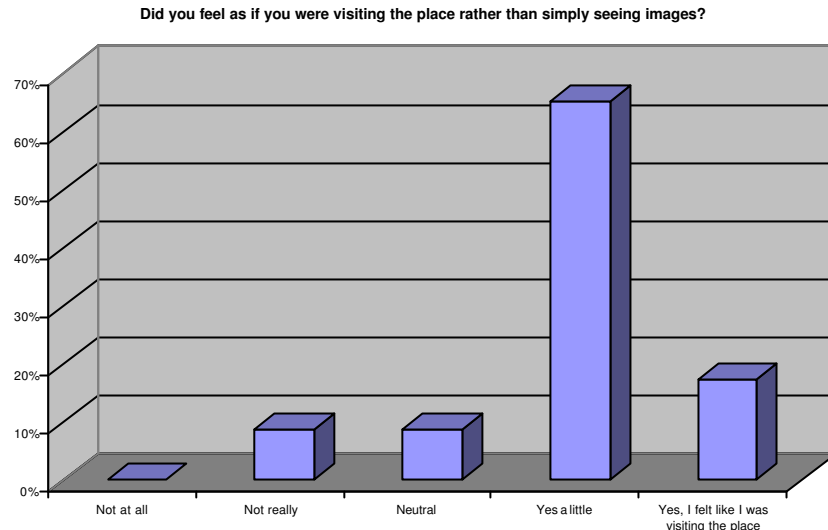
Figure 7.18: Comparison of the virtual world with pictures from real rig

The primary purpose behind the current research into the application of virtual reality as a chemical engineering training medium is to improve the operational training and hazard awareness of the employees. The trainees were asked to express their opinions about the simulation of the virtual chemical process. The majority of them believed that the simulation corresponds to the chemical engineering fundamentals of the real experiment and they were impressed with the time which was needed the system to reach the state stage condition. The comments made by interviewees on the simulation of the chemical process in the virtual gas absorption experiment included the following:

"The time needed to reach steady state condition gives realistic feature to the simulation process."

"The simulation, which was controlling the virtual world was very sophisticated"

"It has the potential as both a safety awareness tool and also an interesting way for students to learn simple chemical engineering concepts"

The comments of subjects about the virtual gas absorption experiment are summarised in Appendix IV.

The subjects who came from the AIMS Research Unit answered neutrally to this question because their educational background was different to those from chemical engineering field. Figure 7.19 presents the opinions about the simulation of the chemical process in the virtual gas absorption experiment.

Did the simulation of chemical process correspond to the real experiment?
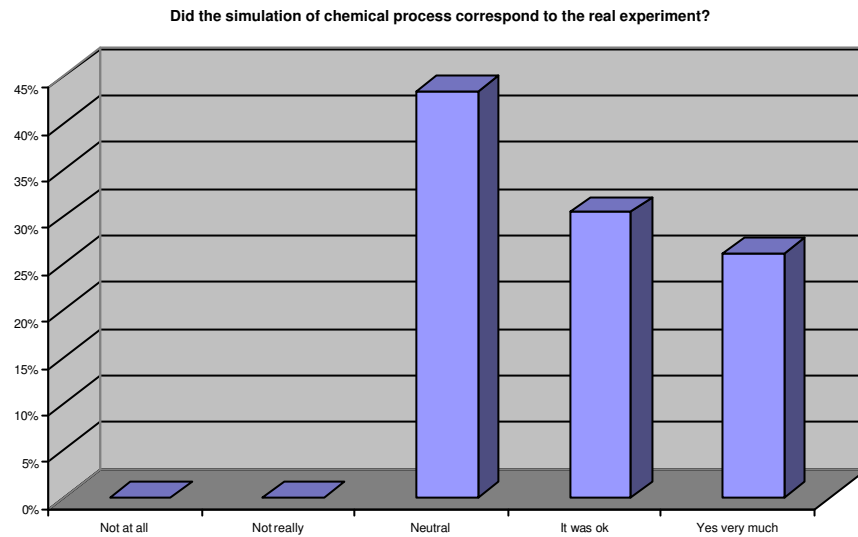
Figure 7.19: Views about the chemical process simulation of the virtual training system

7.7 Summary

The evaluation of the virtual reality gas absorption experiment produced encouraging feedback indicating the suitability of applied virtual reality technology and concepts. These trials provided useful comments for incorrect and missing components and confirmed the hypotheses that virtual reality has relevance and potential in the field of chemical engineering. Trainees found particular favour with the interactive and practical "hands-on" nature of the virtual reality system, acceptable realism of visuals and sounds, and the dynamic simulation of the chemical process. The use of the joystick provided some initial difficulty in the use of virtual reality system but this was limited to only a few of the subjects. The majority of users said that they required more time to become familiar with the device and the virtual reality system, which is not unreasonable to expect.

The simplicity of these evaluation trials can be justified, as it was an effort to explore and investigate issues related to usability of the virtual reality environments. This task was undertaken, even though it was considered to be outside of the main research area. The need for more rigorous evaluation methods such as the choice of methods between and within of studied groups of the sample and the separation of the different subjects groups during the analysis of the evaluation data may be provide more conclusions on the usability of the virtual gas absorption experiment.

Chapter 8

Conclusions and recommendations

8.1 Introduction

This research has set out to investigate aspects of the application of virtual reality to the chemical engineering safety training field. In this chapter a brief overview of the thesis is given followed by a number of conclusions and recommendations based on the research, regarding the suitability and future applications of virtual reality in chemical engineering.

8.2 Overview of thesis

Virtual reality was identified as a rapidly developing computer based technology that is already used for a variety of applications. The development of computer hardware technology has improved the quality of virtual reality systems and has reduced the cost associated with such systems. This has allowed virtual reality technology to be considered in a variety of engineering areas.

The virtual reality applications that were produced demonstrate the potential of virtual reality to improve training and safety awareness in the chemical engineering industry. Virtual reality training environments have successfully been applied when the workplace or the trainee operation is dangerous or when it is expensive or impractical to recreate the physical environment. Virtual reality training systems can allow trainees to experience unusual or potentially dangerous occurrences from a position of safety. The greater levels of interactivity from the virtual reality systems provide intuitive interfaces that can be used for a wide range training applications. Chemical engineering industries are dangerous and complicated environments where virtual reality technology can have a great potential for application in the field of safety and training.

The initial desktop virtual training systems, which were developed during this research focused on safety awareness and operational training without considering aspects related to chemical process simulation. The pump training system is one

such example and constitutes a chemical engineering virtual training application, which gives trainees the opportunity to obtain experience on the start up and shut down procedures of a centrifugal pump without taking the real equipment offline and without the fear of causing any damage to the equipment or to themselves.

The implementation of a multimedia hazard spotting exercise from the ICHEME in a virtual reality environment contributes to the improvement of hazard awareness training and shows the effectiveness of the virtual training environment.

The virtual boiler plant constitutes a very detailed and complicated virtual reality training application, which focuses on a realistic representation of a steam generation chemical process. The integration of dynamic simulation of the chemical process adds enormous flexibility to the virtual environment and makes this virtual reality system a powerful training tool for different scenarios and a range of dangerous situations. The design of a range of hazard process scenarios help the trainee to gain experience with dangerous and emergency situations which would be difficult to implement using conventional training methods.

The last virtual reality training system of this research study was the flooding and gas absorption experiment, a virtual world based on an undergraduate laboratory experiment for the Chemical Engineering degree course at the University of Nottingham, focusing primarily on training and safety issues of students performing the experiment. This virtual experiment will not only familiarise the undergraduate students with fundamental features of the absorption column experimental apparatus, but also teach its procedural aspects.

The mathematical model development of the gas absorption column and the implementation of this dynamic simulated process within the virtual rig environment increases the level of realism and help the users to a deep understating of chemical engineering principles which govern this mass transfer process. The time, which is needed before the system reaches its steady stage, constitutes one of the most powerful features of the virtual gas absorption experiment.

Two different groups were selected for the evaluation trials of the absorption column virtual training environment, one comprised of postgraduates chemical engineering students from SCHEME and the other group was from the AIMS Research Unit. These trials consisted of evaluation interviews after individuals had used the virtual packed column simulator. The evaluation of the virtual reality gas absorption experiment produced encouraging feedback indicating the suitability of the applied virtual reality technology and concepts.

8.3 Conclusions

This section presents a number of conclusions arising from the research study.

8.3.1 Improvement of training using virtual reality

Conventional training methods have difficulties in helping employees obtain a deep knowledge of unusual or potentially dangerous occurrences from a position of safety. It is also extremely difficult for conventional training methods to simulate processes in the chemical engineering field giving the opportunity for trainees to practice and test their abilities and their knowledge. Traditional methods of training do not allow trainees to experiment with the different types of equipment involved in the chemical process, without actually taking the machinery off line.

Virtual reality technology takes advantage of these shortcomings of existing training methods to improve safety and hazard awareness. The ability of virtual reality training systems to simulate complex chemical engineering processes in real time allows a trainee to have experience of an environment that changes over time. Using computer models of real equipment is risk free and allows endless experimentation without ever taking the real equipment off line and risking production. Allowing users to learn within computer generated environments provides the opportunity for them to make mistakes and suffer the consequences without necessarily putting themselves at risk.

8.3.2 Initial virtual training applications

The virtual pump training systems and the virtual hazard spotting exercise were the initial virtual training applications, which were developed during this research

study. Those represent two simple safety training applications in the chemical engineering field, which were developed using the SAFE-VR virtual engine. Both of these are desktop virtual reality systems and they are capable of training the participants allowing them to navigate freely around the virtual chemical environment and perform certain tasks such as the correct start-up operation of a centrifugal pump.

The main purpose of the pump training system is to make users familiar with the appropriate steps that they should be taken in order to make sure the pumps are running properly and safely. Having experience of the virtual pump training system the users can improve their knowledge about pumps and can reduce fault occurrence, when they are placed in the real environment.

On the other hand, the main purpose of the virtual hazard spotting exercise is the improvement of users' safety awareness on issues related to electrical and occupational hygiene hazards. The users are immersed in a virtual pilot chemical plant and they should spot process equipment and areas dangerous for occupational hygiene and electrical safety. The conversion of a multimedia training exercise from the ICHEME to a virtual hazard spotting training environment illustrates the effectiveness and the flexibility of virtual reality technology in training applications. The three-dimensional view of the pilot plant layout in the hazard spotting exercise, allows the immersion of users in the virtual world and makes the hazard spotting more effective and more realistic than the two-dimensional static image of the chemical process from the original multimedia exercise.

8.3.3 Virtual boiler plant

The virtual boiler plant is a complicated and highly detailed virtual training environment, which is characterised by its enormous flexibility and by a number of features each of which contributes to the sense of "reality" in the experience. The virtual boiler plant environment can be used as a basis for training in any number of different scenarios related to steam generation processes so that trainees can learn to cope with many different situations, some of which are difficult to prepare for in any other way. The virtual boiler plant gives trainees the

opportunity to learn by performing actions. This has a significant effect on their ability to retain what they learn, and is clearly superior to passive techniques such as video or books, for training where spatial understanding is important.

The detailed panels and the interactive flow sheet display which are placed in the control room of the virtual boiler plant constitute a intuitive feature of this training environment contributing to integrated knowledge and experience issues related to boiler plant operation. The easy access to very complex data is an innovative feature of this virtual training environment. The control room of boiler plant helps trainees to control and operate the plant, performing actions in different dangerous situations, which arise from bad maintenance or operational failure of various items of chemical equipment.

The steam generation process of the virtual boiler plant is dynamic, making training and navigation realistic. This dynamic model driven, chemical process simulation helps the chemical plant operator in developing skills and gaining satisfactory responses to emergency situations that may arise. It also provides a realistic system view to operators and improves their understanding of how the boiler process plant is operating. Instead of viewing a still life drawing of the chemical plant the users can actually practice real time operational steps, watching and analysing a considerable amount of process data that is provided. Consequently, the dynamic simulation of the virtual boiler plant model is a extremely valuable teaching and training tool which demonstrates and clarifies fundamental process and control aspects for plant operators.

8.3.4 Virtual gas absorption experiment

This virtual environment was based on an undergraduate laboratory experiment for the Chemical Engineering degree course at the University of Nottingham, focusing primarily on training and safety issues of students. The virtual flooding and gas absorption experiment will not only familiarise the undergraduate students with fundamental features of the absorption column experimental apparatus, but also teach its procedural and safety aspects.

8.3.4.1 The virtual model of the gas absorption experiment

It was envisaged that the three-dimensional visualisation of the equipment operation would provide the users with a better understanding of the layout, the size and the movement of objects within the environment. Three-dimensional visualisation provides a good alternative in situations where it is impossible to gain first hand experience of an environment. The application of the virtual flooding and gas absorption experiment allows the rig and the chemical process equipment to be viewed from any position and angle, including many which are not possible in the real laboratory.

The dynamic features of the virtual absorption column simulation give a high level of realism in the virtual environment and help the users to gain a deep knowledge of chemical engineering principles which govern the mass transfer process. Using a paper based approach limits on the transfer on knowledge and sometimes the trainees have difficulties in understanding the order of procedures and the time taken to complete them. The three-dimensional and real-time representation of operations allows the users to become familiar with both the spatial and time relationships within the chemical process operation. The operation of chemical engineering instruments and the knowledge gained by using this virtual laboratory rig layout will help students to know exactly what tasks they should follow and what precautions they should take before they implement the experiment in the real laboratory. Students are able to set experimental tasks in the virtual world, and if they make any mistakes they will learn what went wrong without damaging equipment or themselves.

8.3.4.2 Teaching enhancement

The virtual flooding and gas absorption experiment should be considered as a novel teaching method that can help students to execute and interpret 'real' experimental laboratory projects. It is not suggested that the virtual world should replace the real laboratory experiment but it can be considered as an enhancement to the teaching. Using the virtual environment the users learn by their actions and control the interaction and investigation of the knowledge contained within the world. This increases the users' capacity for critical thought and encourages them to take a 'deep' approach to learning. However that implementation is not

straightforward, and virtual reality should be used as a supplement to real experiences, and in situations where the real experience is inaccessible. Universities should encourage the development of virtual reality environments as useful tools in engineering, science, and education, initially in the areas of higher-dimensional scientific visualisation and the development of virtual accident scenarios for the reduction of laboratory accidents.

8.3.4.3 Evaluation results

The evaluation trials for the virtual flooding and gas absorption experiment produced encouraging feedback representing the suitability and effectiveness of applied virtual reality technology and concepts. They provided useful comments about incorrect and missing components and confirmed the hypotheses that virtual reality has relevance and potential in the field of chemical engineering. Trainees enjoyed the interactive nature of the virtual reality system, the acceptable realism of visuals and sounds, and the dynamic simulation of the chemical process.

8.4 Overall conclusions

The chemical process industries are dangerous environment and many aspects of safety must be taken into account during the training of employees to operate chemical engineering equipment. Virtual reality technology provides a valuable approach for training personnel in dangerous workplace environments. The ability to visualise complex and dynamic process within a virtual chemical plant environment is a potential advantage of virtual reality technology.

Four virtual reality training applications in the chemical engineering field were developed during this research study. The hardware and software chosen for the development of these applications was viable and remains valid for future chemical engineering training applications. The PC-platform provides the ideal choice for most desktop virtual reality systems. It allows flexible configurations, supports of a wide variety of input and output devices and its overall cost remains low compared to other types of virtual reality systems.

3D Studio Max provides a highly professional environment for modelling three-dimensional objects. The use of animation key-frames embedded within three-

dimensional models allow the modelling of realistic motions. The SAFE-VR virtual engine is a generalised PC-based training system that provides a graphical user interface to enable users to import CAD and other files defining the machinery or environment to which the training is related. SAFE-VR provides an effective method for creating and editing complex simulations, including fault trees and procedural simulations. These simulations contain a selection of the intuitive simulation elements combined in a simple ladder-logic combination. This feature of SAFE-VR provides a viable tool for the creation of dynamic process simulations in a real time chemical process. The implementation of such real time dynamic simulation systems in the virtual boiler plant training environment and in the virtual flooding and gas absorption experiment increases the level of realism of the virtual training systems. Using real time simulation systems in a virtual environment allows "what if" sequences to be run and the chemical process and its control strategy can be changed to test alternative concepts.

Dynamic simulated virtual training environments are pioneering and innovative tools for improved virtual training applications. Dynamic simulation is an enabling technology and one of its main benefits is the improvement of the process understanding. By understanding the process more fully, operators and engineers are able to identify, troubleshoot and correct deficiencies in the process design and its control system. Through dynamic simulated systems users are able to effectively study the process and gain better knowledge for emergency conditions and control strategies through various operating scenarios that can be constructed. The dynamic simulated, embedded, virtual reality training systems provide a new way to improve plant operations and safety training techniques without taking equipment offline or shutting down process lines and hence, they have to be carefully considered by chemical process industries.

In summary the research work concluded the following:

?? There is a large potential to develop commercially viable low-cost virtual reality training environments.
?? Virtual reality technology gives the possibility of using innovative solutions to solve existing problems.

?? Desktop virtual reality systems do not prohibit the presentation of high quality realistic virtual environments.

?? The creation of real time dynamic simulation systems, which are driving the objects within the virtual environments, increases the level of realism and the effectiveness of training.

?? Virtual reality technology is particularly suitable for use within the chemical engineering industry because environments are hazardous and extremely complicated and it is often difficult to experience them in the real world.

8.5 Recommendations

The following are some recommendations, which arise from the research work:

?? Virtual reality training environments should be introduced to the chemical engineering industry to enhance current training programs. Virtual environments can alternatively be used for extension planning and configuration changes of existing chemical process industries.

?? The development of virtual reality based learning environments for educational chemical engineering laboratories should be encouraged. Virtual reality learning systems can encourage students to think critically, develop a deep and reflective understanding of the subject and help them in developing capabilities, skills and competencies essential for further study and future employment.

?? The virtual reality chemical plant processes should be driven by fully featured, dynamic chemical process simulations in order to improve the realistic representation of the actual systems. The production of such integrated virtual chemical process environment should be undertaken by multidisciplinary teams consisting of computer programmers, chemical process engineers, training specialist, graphics artists and psychologists.

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Appendix I

Boiler model equations

Superheater	Mass balance $w_u \, ? \, w_s \, ? \, V_s \, \overset{?}{?}_s$
	Flow volume $V_s \, ? \, A_s L_s$
	Friction loss $p_u \, ? \, p_s \, ? \, f_s w_u^2 / ?_u$
	Gas tube heat balance $Q_{gs} \, ? \, Q_s \, ? \, M_s C_{st} \overset{?}{T}_{st}$
	Turbulent heat transfer-tube-steam $Q_s \, ? \, k_s w_u^{0.8} (T_{st} \, ? \, T_s)$
	Steam heat balance $Q_s \, ? \, w_u H_u \, ? \, w_s H_s \, ? \, V_s \dfrac{d}{dt}(?_s H_s)$
Steam drum	Liquid mass balance $w_e \, ? \, (1 \, ? \, x)w_r \, ? \, w_d \, ? \, w_{ec} \, ? \, \dfrac{d}{dt}(V_w ?_w)$
	Drum liquid mass $M_w \, ? \, V_w ?_w$
	Steam mass balance $w_{ec} w_r \, ? \, w_u \, ? \, w_{ec} \, ? \, \dfrac{d}{dt}(V_u \, ?_u)$
	Liquid heat balance $w_e h_e \, ? \, (1 \, ? \, x)w_r h_{wu} \, ? \, w_d / h_w \, ? \, w_{ec} H_u \, ? \, \dfrac{d}{dt}(V_w ?_w h_w)$
	Water-level displacement $? \, w_{ec} \, ? \, k_{ec}(? T_w \, ? \, ? T_u)$
Downcomer	Flow relation $p_u \, ? \, p_w \, ? \, f_d L_d w_d^2 / A_d^2 D_d g ?_w \, ? \, ?_w L_d \, ? \, w_d^2 / 2g ?_w A_d^2 \, ? \, L_d \overset{?}{w}_d / gA_d$

Risers	Mass balance $w_d \ ? \ w_r \ ? \ V_r \overset{?}{?}_r$
	Flow volume $V_r \ ? \ L_r A_r$
	Flow relation-homogeneous flow $p_w \ ? \ p_u \ ? \ f_r L_r w_r^2 / A_r^2 D_r g?_r \ ? \ ?_r L_r \ ? \ w_r^2 / 2g?_r A_r^2 \ ? \ L_r \overset{?}{w_r} / gA_r \ ? \ w_r^2 / g?_r A_r^2 \ ? \ w_d^2 / g?_w A_r^2$
	Gas-tube heat balance $Q_{gr} \ ? \ Q_r \ ? \ M_r C_{rt} \overset{?}{T_{rt}}$
	Heat transfer-tube steam water $Q_r \ ? \ k_r (T_{rt} \ ? \ T_u)^3$
	Steam and water heat balance $Q_r \ ? \ w_d h_w \ ? \ w_r h_r \ ? \ V_r \dfrac{d}{dt}(?_r h_r)$
	Mixture relation-riser drum $\dfrac{1}{?_r} \ ? \ \dfrac{x}{?_r} \ ? \ \dfrac{1 \ ? \ x}{?_w}$
	$h_r \ ? \ x H_u \ ? \ (1 \ ? \ x) h_{wu} \ ? \ x h_f \ ? \ h_{wu}$
Furnace and gas flow	Furnace $? \, T_g \ ? \ k_F \, ? \, w_F$
	Riser 1 $T_{g1} \ ? \ T_g \ ? \ Q_{gr1} / C_g (1 \ ? \ w_A / w_F) w_F$
	Superheater $T_{g2} \ ? \ T_{g1} \ ? \ Q_{gs} / C_g (1 \ ? \ w_A / w_F) w_F$
	Riser 2 $T_{g3} \ ? \ T_{g2} \ ? \ Q_{gr2} / C_g (1 \ ? \ w_A / w_F) w_F$
	Economiser $T_{g4} \ ? \ T_{g3} \ ? \ Q_{g3} / C_g (1 \ ? \ w_A / w_F) w_F$
State Equations	Superheater-state equations
	$? \, T_u \ ? \ ? T_u / ? p_u \ ?? \, p_u \ ? \ k_1 ? p_u$
	$? \, ?_u \ ? \ ?? _u / ? p_u \ ?? \, p_u \ ? \ k_2 ? p_u$
	$? \, h_{wu} \ ? \ ? h_{wu} / ? p_u \ ?? \, p_u \ ? \ k_w ? p_u$
	$? p_s \ ? \ ? p_s / ? T_s \ ?? T_s \ ? \ ? p_s / ?? _s \ ?? ?_s \ ? \ k_3 ? T_s \ ? \ k_4 ?? _s$

Appendix II

Instruction sheet for the virtual gas absorption experiment

FLOODING AND GAS ABSORPTION IN A VIRTUAL PACKED COLUMN

University of Nottingham

Nottingham

United Kingdom

2001

Flooding and gas absorption in a virtual packed column

Packed columns are used for distillation, gas absorption, and liquid-liquid extraction but are commonly employed to carry out absorption and scrubbing

operations. Usually the columns are filled with randomly oriented packing material and are characteristically operated with counter flow of the phases. Many packings are commercially available, each processing specific advantage for liquid-gas contacting from the aspects of cost, surface availability, interface generation, pressure drop, weight and corrosion resistance. The packed bed is usually formed by dumping packing elements into the column ("dumped packings") and allowing them to form a random arrangement. For the majority of application the less expensive packings are used.

A schematic diagram showing the main figure of a packed absorption column is given in the figure 1.
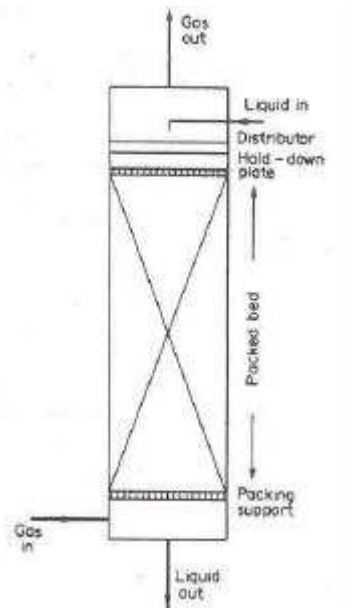

Figure 1: Schematic diagram of a packed absorption column

The virtual world based on an undergraduate laboratory experiment for the Chemical Engineering degree course at the University of Nottingham. It concerns two packed columns, which are used to absorb ammonia from an air stream. The pilot plant consists of two packed columns, which share the same ammonia; air and sulphuric acid (0.5M) supply and connected to the same air over kerosene manometer. The flow sheet of the process is shown in the figure 2.

TO VENT ON ROOF

ABSORBANT FEED TANK

DRAIN

SCRUBBED AIR EXIT

SPRAY TRAP

MANOMETER

DRAIN

TO VENT ON ROOF

SAMPLE POINT

T

SAMPLE POINT

LIQUID AMMONIA

SAMPLE POINT

DRAIN OR SAMPLE POINT

AIR SUPPLY AT 2 BAR

GAS ABSORPTION UNIT.
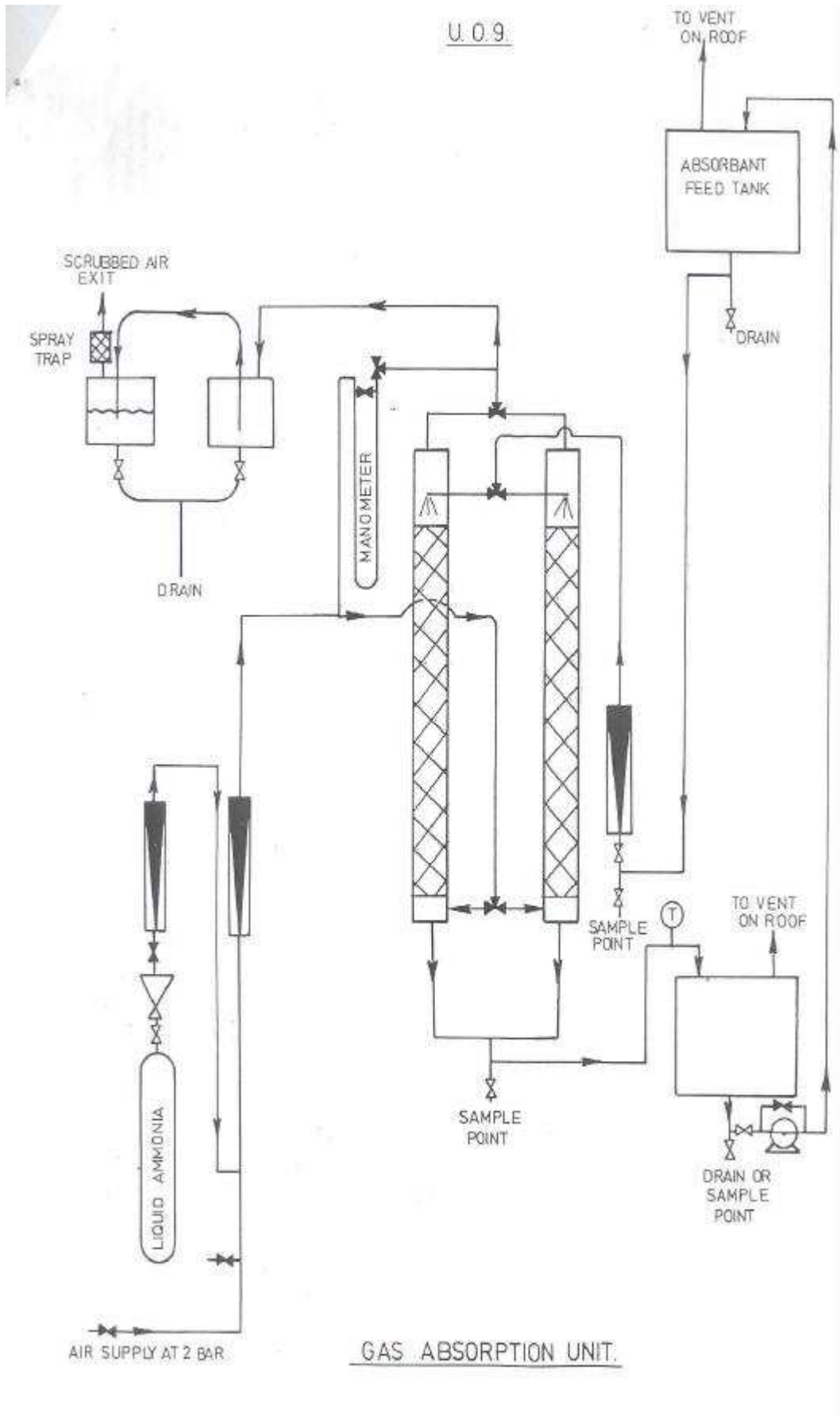
Figure 2: Flow sheet of the gas absorption unit

How to use the VR training system

At the start of the program, you should see the following scene:

Red Dot   "SPOT"   "ACTION"

(to end)   button   button

Laboratory
rig
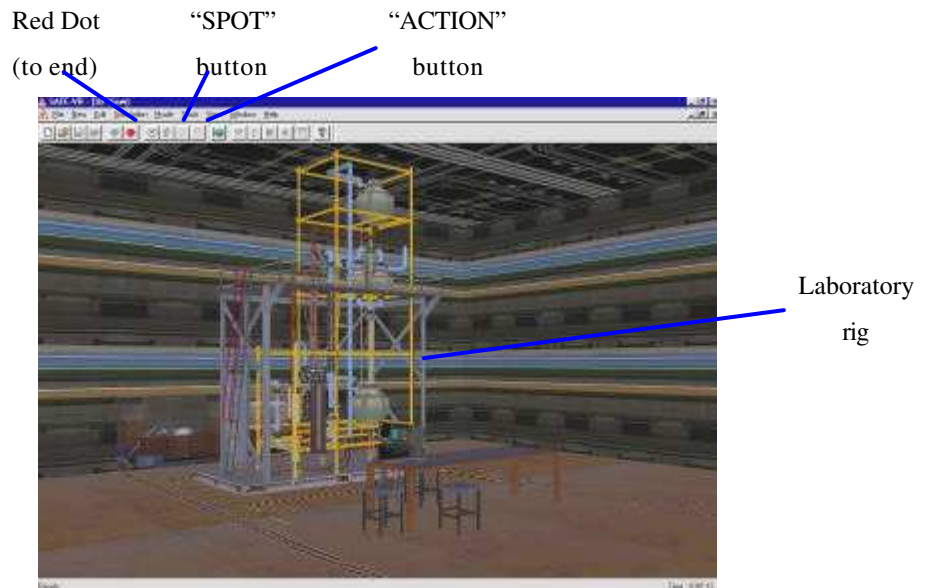
1.   Use the joystick to move around the virtual world and explore the objects

2.   To do an action:
   - i)   Use the mouse to click on the "action button" on the toolbar
   - ii)   Move the "action" cursor so that it is positioned over the object you want
   - iii)   Double click on the object to make the action

3.   Several hotkeys have been defined for easy navigation around the virtual environment. The following table is presenting them.

Hotkeys	Position
Num1	Move to manometer
Num2	Move to air rotameter
Num3	Move to liquid rotameter
Num4	Move to ammonia rotameter
Num5	Move to air inlet valve
Num6	Move to calibration graphs
Num7	Move to gas analyser
Num8	Move to ammonia valve
Num9	Move to liquid valve

By pressing the "I" button on your keyboard at any time the virtual reality training system informs you which column is running and the readings of the air, liquid and ammonia rotameters.

4.   There are several hotkeys for liquid, air and ammonia valve operation. These valves open and close in stages. The following table summarises them.

Operation	Air inlet valve	Liquid valve	Ammonia valve
Step open	"G"	"L"	"A"
Step close	"B"	"."	"Z"

5. Manometer operation

Use the valve on the top to select the column with which you have decided to connect the manometer. Using the "action button" and double click on manometer's faceplate you take the pressure drop value in cm Kerosene.

6. To determine the ammonia output concentration use the gas analyser. Pressing the "0" button on the keyboard while the analyser is running and a graph is drawn on its monitor. By double clicking on the monitor using the "action button" a message box launches with the value of output ammonia concentration in ppm. By pressing the "P" button on your keyboard the gas analyser is turned offline.

7. By double clicking on air rotameter, ammonia rotameter, liquid rotameter and manometer using the "action button" you read the indicated value of these instruments.

8. Once you feed you have finished with the virtual gas absorption experiment use the mouse to click the red dot on the toolbar. This will end your exploration of the world. By clicking the green button again you can start another training session. You may end and start as many times as necessary to familiarise yourself with the virtual environment.

Scenario

At the beginning of the training session column A is running. The liquid manometer reading is 20l/t, the air rotameter reading is 1cm and ammonia inlet valve is closed. Determine the pressure drop at various air flowrates using 20, 40, 60 and 80 l/h liquid flowrates. Fill in table 1 with the set of data that you have collected.

Switch to column B and measure the pressure drop at various air flowrates using the similar liquid flowrates as you have done with column A. Fill in the table 2 with the set of data that you have collected.

Decide the appropriate liquid, air and ammonia flowrates and take measurements for output ammonia concentration using gas analyser for both columns. Fill in the tables 3 and 4 with the values that you have measured.

Table 1

Pressure drop across Column A (glass raschig rings)

Rotameter reading (cm)	Pressure drop (cm Kerosene)			
	Liquid flowrate (l/h)			
	20	40	60	80

Table 2

Pressure drop across Column B (ceramic raschig rings)

Rotameter reading (cm)	Pressure drop (cm Kerosene)			
	Liquid flowrate (l/h)			
	20	40	60	80

Table 3

Column A (output ammonia concentration)

Liquid flowrate (l/h)	Ammonia rotameter scale (cm)	Air rotameter scale (cm)	Output ammonia conc. (ppm)

Table 4

Column B (output ammonia concentration)

Liquid flowrate (l/h)	Ammonia rotameter scale (cm)	Air rotameter scale (cm)	Output ammonia conc. (ppm)

Appendix III

Questionnaire for virtual gas absorption experiment

Name:	
Title:	
Department:	
Job title:	
Age:	

Please answer the following questions. All answers will be kept strictly confidential. Please avoid giving neutral answers unless absolutely necessary.

1. How often do you use a computer?
? Every day   ? At least twice a week   ? At least once a week
? At least once a month   ? Very rarely   ? Not at all

2. What do you use a computer for?
? Games   ? Design   ? Email
? Word processing   ? Database   ? Programming
? Spreadsheets   ? Internet   ? Maintenance-Repair

3. Have you ever been to a chemical engineering laboratory?
? Yes
? No
If yes give some brief chemical engineering examples.

_____

_____

_____

4. Have you had any experience with similar virtual reality training systems before?
? Yes
? No
If yes what type of experience?

_____

_____

5. Did you enjoy using the virtual reality program?
? Not at all   ? Not really   ? Neutral   ? A little   ? A lot

6. Did you find easy to understand and use?
? Not at all   ? Not really   ? Neutral   ? It was ok   ? Yes very easy

7. Did it help you learn?
? Not at all   ? Not really   ? Neutral   ? It was ok   ? Yes it helped a lot

_____

8. Do you think that it would help students to understand the real experiment?
? Not at all   ? Not really   ? Neutral   ? It was ok   ? Yes very much

9. Did the simulation of chemical process correspond to the real experiment?
? Not at all   ? Not really   ? Neutral   ? It was ok   ? Yes very much

10. Was enough time given for training?
? Not at all   ? Not really   ? Neutral   ? It was ok   ? Yes ample time

11. Did the system give a sense of reality "being there" in the environment?
? Not at all   ? Not really   ? Neutral   ? Yes, a little   ? Yes I felt like I
                                                        bit   was actually there

12. Was there any time that virtual world seemed more real, or as real as, the real world?
? No, did not   ? Not really   ? Neutral   ? Yes, sometimes   ? Yes it felt real
   happen at all   a
                                                       lot of time

13. Did you feel as if you were visiting the place rather than simply seeing images?
? Not at all   ? Not really   ? Neutral   ? Yes a little   ? Yes, I felt like I was
                                                            visiting the place

14. What do you think are the best features?

_____

_____

_____

_____

_____

15. What aspects of training program do you think requires improvement?

_____

_____

_____

_____

_____

_____

Additional comments?

_____

_____

_____

_____

_____

Questionnaire for virtual reality training system

Name:	CLARK
Title:	DR
Department:	SCHEME
Job title:	RESEARCH ASSOCIATE
Age:	29

Please answer the following questions. All answers will be kept strictly confidential. Please avoid giving neutral answers unless absolutely necessary.

1. How often do you use a computer?
☑ Every day   ☐ At least twice a week   ☐ At least once a week
☐ At least once a month   ☐ Very rarely   ☐ Not at all

2. What do you use a computer for?
☑ Games   ☑ Design   ☑ Email
☑ Word processing   ☑ Database   ☑ Programming
☑ Spreadsheets   ☑ Internet   ☑ Maintenance-Repair

3. Have you ever been to a chemical engineering laboratory?
☑ Yes
☐ No
If yes give some brief chemical engineering examples.
ADSORPTION MASS TRANSFER, HEAT TRANSFER, THERMODYNAMICS

4. Have you had any experience with similar virtual reality training systems before?
☐ Yes
☑ No
If yes what type of experience?

5. Did you enjoy using the virtual reality program?
☐ Not at all   ☐ Not really   ☐ Neutral   ☐ A little   ☑ A lot

6. Did you find easy to understand and use?
☐ Not at all   ☐ Not really   ☐ Neutral   ☐ It was ok   ☑ Yes very easy

7. Did it help you learn?
☐ Not at all   ☐ Not really   ☑ Neutral   ☐ It was ok   ☑ Yes it helped a lot

8. Do you think that it would help students to understand the real experiment?
☐ Not at all   ☐ Not really   ☐ Neutral   ☐ It was ok   ☑ Yes very much

Thank you for your participation

9. Did the simulation of chemical process correspond to the real experiment?

☐ Not at all   ☐ Not really   ☐ Neutral   ☐ It was ok   ☑ Yes very much

10. Was enough time given for training?

☐ Not at all   ☐ Not really   ☐ Neutral   ☐ It was ok   ☑ Yes ample time

11. Did the system give a sense of reality "being there" in the environment?

☐ Not at all   ☐ Not really   ☐ Neutral   ☐ Yes, a little bit   ☑ Yes I felt like I was actually there

12. Was there any time that virtual world seemed more real, or as real as, the real world?

☐ No, did not happen at all   ☑ Not really   ☐ Neutral   ☐ Yes, sometimes   ☐ Yes it felt real a lot of time

13. Did you feel as if you were visiting the place rather than simply seeing images?

☐ Not at all   ☐ Not really   ☐ Neutral   ☑ Yes a little   ☐ Yes, I felt like I was visiting the place

14. What do you think are the best features?

CLOSE APPROXIMATION TO REAL EXPERIMENT. EASE OF USE.

15. What aspects of training program do you think requires improvement?

Additional comments?

HAS POTENTIAL AS BOTH A SAFETY AWARENESS TOOL AND ALSO AN INTERESTING WAY FOR STUDENTS TO LEARN SIMPLE CHEMICAL ENGINEERING CONCEPTS

Thank you for your participation

Appendix IV

General comments of subjects

What do you think are its best features?

- ?? The gas analyser operation and the dynamic graph which was displayed on its monitor
- ?? The dynamic real time simulation
- ?? The animation of the rotameters' floats
- ?? The need to wait for steady state condition for taking reading gives a lifelike reality
- ?? The simulation was very sophisticated
- ?? Ability of make mistakes without damaging equipments
- ?? Hotkeys for easy navigation
- ?? Operation of valves
- ?? The navigation speed
- ?? Easy to use
- ?? Close approximation to real experiment
- ?? Enjoyable to use
- ?? Ability to move easily around the rig
- ?? Instrument operation
- ?? The details of the model
- ?? The simplicity of program being able to get a lot of data relatively quickly
- ?? The time needed to reach steady stage condition
- ?? Manometer operation
- ?? It has the potential as both a safety awareness tool and also an interesting way for students to learn simple chemical engineering concepts
- ?? Good starting point to the real lab for students.
- ?? Would be nice if undergraduate students had the opportunity to experience the VR aspect of all their laboratory experiments

What aspects of the training program do you think requires improvement?

?? More accurate model

?? Difficulties of using keyboard mouse and joystick all at once

?? Little time to practice

?? Recording the experimental data of the virtual reality experiment

?? Setting up flowrates at once without (step by step scale)

?? Hotkeys to the valves that change between columns

?? It could be easier to use the stairs

?? Hotkeys or highlights for valves

?? Texture maps

?? Navigation

?? Virtual world could become more legible if some of the details (dials, valves, etc.) were designed a little more

?? More background information, multimedia, explanation of equipments and operating process

?? Too many keys to press

?? A few of textures, maybe some extra stuff around the columns