DEVELOPMENT OF A GIS-BASED APPLICATION FOR FIRE MODELLING IN THE PROCESS INDUSTRIES

by

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CERTIFICATION OF APPROVAL

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Approved by,

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

The major hazards with which the chemical industry is concerned are fire, explosion and toxic release. Of these three, fire is the most common. In assessing the damage potential and causes or errors which have led to these disasters, an analysis has to be done. The impacts of fires in the process industries may be predicted by the application of mathematical models. However, the applications of these models require competency in mathematics and computer programming. Therefore, the objective of this project is to develop an application called the Fire Simulation Tool (FiST), which is able to study the impact of fire in the process industry. The scope of work for this project is confined to fire cases only, which are: flash fire, jet fire, pool fire and fireball.

The FiST application is developed using Visual Basic (VB) programming language with integration of GIS tools. The mathematical models of the four types of fire are simulated and the results are integrated to GIS for better visualization. The development is done by customizing MapObjects using VB. With MapObjects user can incorporate mapping capabilities in their application.

The methodology of the project includes utilizing established models in order to calculate the impact of fire. The development of this software has been divided into five different stages, which are planning the application, building the graphical user interface (GUI), writing the computer programme, software validation and verification and lastly, integrating the results from the tool with GIS application to present the simulation outcome as buffer zones around the centre of the accident.

The results from FiST software is verified and validated with other risk assessment softwares such as: FRED (developed by Shell Global company, 2004), BIS (developed by ThermDyne Technologies Ltd, 2003) and SCIA (developed by El-Harbawi, 2006) and with established data. The software is capable to estimate the thermal radiation and the impacts from the fire scenarios which include the probability of first, second and third degree of burns for the human skin. The FiST application is useful and feasible because it is user-friendly, able to function as a stand-alone application and it is compatible with all windows operating system. Furthermore, the cost of developing the software is cheap and the application incorporates the risk tolerability limit for Malaysia.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF STUDY

One of the most important factors in chemical process plants is safety. All operations and processes must be carried out under safe conditions in order to protect the life and environment. Fire and explosions are among the commonly occurring major accidents in chemical process plants.

The use of computers for rapidly and easily estimating the effects from explosion, fire and smoke events has grown tremendously in the last several years (Nolan, 1996). Software product or services are readily available in conducting mathematical consequence modelling of most hydrocarbon adverse events.

Mathematical models can be used to estimate the effects of accidents. They consist of sets of equations which require some assumed data on the source of release for a material. These assumptions are from the input data which is then inserted into the mathematical equations. The first step when trying to predict these phenomena is to estimate the amount of material involved in the accident and the rate at which it is spilled or released. This is done by applying source term models. Source term models are based on fluid dynamics and heat transfer and require the exact or estimated values of the temperature and pressure of the material involved. This often constitutes a factor of uncertainty, as these conditions may depend on the evolution of the situation. Consequently, models commonly apply simplifying assumptions and assume standard initiating events.

A number of models have been developed and published that describe fires, atmospheric dispersion and the effects of explosions. Their degree of complexity varies significantly: some are very simple, some are more complex and some are very complex. Overly simplistic models are easy to use but they can sometimes lead to significant errors. In theory, complex models should provide good results but in practice they often require information and data which are unavailable (Casal, 2008).

The risk from industrial hazards can be calculated in two ways; with calculation models or with the aid of computer programs. The two methods should be combined in order to minimise failures. The complex development of accident scenarios can be achieved by using consequence modelling combining with computer software (El-Harbawi, 2006).

Since the evolution of Geographic Information Systems (GIS), it has become a useful tool in investigating the consequences of chemical hazards. GIS provides powerful tools for visualization and spatial analysis functions. Hence, the integration of GIS and simulation models, together with the necessary databases and expert systems, within a common and interactive graphical user interface would provide a more powerful and user-friendly risk information systems.

1.2 PROBLEM STATEMENT

The consequence from fires in the process industries may be evaluated using mathematical models, which is referred as fire modelling. Mathematical models are extremely useful tools in simulating the consequences of any possible industrial accidents. However, it is difficult to implement manually due to the following reasons:

- A large number of these calculations are required,
- The equations involved are difficult to calculate and also time consuming,
- There are several event outcomes to follow; thus resulting in difficulty to keep track of them,
- Unable to obtain a representation of the impacts since they are only based on calculations

These mathematical models can be simulated using programming languages such as Visual Basic (VB). The GIS can be integrated with VB to create a graphic user interface (GUI) that is able to display the impact graphically. ESRI MapObjects will be used as a developer product for creating customized GIS desktop applications. With MapObjects, developers will be able to add dynamic mapping and GIS capabilities to existing applications or build their own unique mapping programs. Customizing GIS using VB enable users to assess the impacts of fires using screening and scenarios methodology, which allow users to estimate the radius of a threat zone. Hence, fire modelling can be made feasible by using computer aided technologies which not only estimate the impacts but also display them graphically through the integration of GIS and the simulation models.

1.3 OBJECTIVES OF STUDY

The main objectives of this study are:

i) To develop a stand-alone user-friendly system using Microsoft Visual Basic application to study the impact of fires in the process industry.

ii) To customize a GIS Windows-based application by integrating Visual Basic with MapObjects to assess fire with its geographical locations.

iii) To verify the validity of the results from this GIS-based application by comparing the results obtained with other results from established data, published literature, laboratory and numerical data sets and various risk assessment softwares.

iv) To incorporate Malaysian standards and regulations into the developed tool.

1.4 SCOPE OF STUDY

This study is conducted to develop a software using Visual Basic programming language which is able to study the harmful consequences of fires. Existing models and procedures are used in carrying out this project. The technique for assessing the consequences from fires is developed by integrating the models in the system with the aid of the GIS tools.

The scope of work for this project is confined to fire cases only which include the study on the basic principles, effects and experimental and theoretical research and consequence modelling techniques on the following:

- Flash fire
- Jet fire
- Pool fire
- BLEVE/Fireball

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Major accidents have been defined as "an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances" (Casal, 2008). Major accidents involve the release – instantaneous or over a relatively short period – of significant amounts of energy or of one or more hazardous materials.

A major accident is always originated by a loss of containment. This can be due to the collapse or the explosion of a tank, the failure of a pipe, a leak trough a hole, etc. After the initial release, the incident can follow different ways and diverse accidental scenarios can be reached depending on the circumstances and on the physical state of the released substance. If it is a liquid, a pool can be formed. If the substance is flammable and is ignited, there will be a pool fire; if it is not immediately ignited, the evaporation can give rise to a toxic or a flammable cloud which, if ignited, will lead to a flash fire and possibly to an explosion. If a two phase mixture is released, a cloud can occur (depending on the meteorological conditions). If a gas is released, a cloud can exist in low speed releases; at high (usually sonic) speed, the substance will probably be quickly dispersed, but a jet fire is possible. In any case, the final scenario will be a fire, an explosion, a toxic cloud or no outcome (Planas and Casal, 2009).

Among the four most cited industrial accidents that occurred during the years are Flixborough, England (1974); Seveso, Italy (1976); Bhopal, India (1984); and Pasadena, Texas (1989) and are tabulated in Table 2.1. All these accidents had a significant impact on public perceptions and the chemical engineering profession that added new emphasis and standards in the practice of safety. (Crowl and Louvar, 2002). Table 2.2 on the other hand, shows a summary of the major incidents in the chemical process industries from 1943 to 2009 related to fire cases only.

Table 2.1: List of four most major industrial incidents (Hyatt, 2003).

Location	**Flixborough**	**Seveso**	**Bhopal**	**Pasadena**
Date	June 1974	July 1976	December 1984	October 1989
Hazardous material released	Cyclohexane	2,3,7,8 tetrachlorodibenzoparadioxin, simply known as TCDD or dioxin	Methyl isocyanate (MIC)	Isobutane, Ethylene and Catalyst carrier
Event	Massive failure of 20-inch bypass around a cyclohexane reactor, releasing about 40 tonne of cyclohexane. Approximately 22 tonne were in the explosive range. Most likely, the ignition source would have been fired heater. Piping most likely failed at the expansion bellows from a temporary dog-leg connection joining two reactors.	A bursting disc fitted in the vent line of the reactor producing 2,3,5 trichlorophenol (TCP) ruptured because of internal overpressure. The bursting disc discharged a cloud of about two tonnes of hot chemicals directly into the open air.	2,000 lb. of water entered a storage tank containing MIC. Some MIC boiled off. The vent scrubber was shut down for maintenance so that the vapor could not be neutralized and highly toxic MIC vapor escaped from a 33 m high vent line. The refrigeration system, designed to keep the stored MIC cool, was out of commission. The flare tower was not available since a corroded section of line had not been replaced. The water curtain was not designed for 33 m in height.	During routine maintenance of a fluff settling leg on a high-density polyethylene reactor, the entire reactor contents were discharged to the atmosphere. The cloud ignited one minute after release.
Type of incident	Vapor cloud explosion equivalent to 15 tonne of TNT	Toxic vapor cloud	Toxic vapor cloud	Vapor cloud explosion equivalent to 10 tonne of TNT
Damage	Total destruction of plant. Destruction of control room, located inside the facility. $48 millions direct damage to plant.	No damage to plant itself	No damage to plant itself	Two complete units were destroyed. Approximately $750 millions damage.
Deaths	28 people killed (18 in control room) and 36 injured	None	2,000 to 15,000 killed & 200,000 to 300,000 injured due to there being a shanty town surrounding the facility.	23 killed, 130 injured

Table 2.2: List of major accidents in chemical process industries for fires (Khan and Abbasi, 1999 a; BBC, 2001 – 2005); (The New Straits Times Press (Malaysia) Berhad, 2008); (Maykuth, 2009).

Year	Location	Chemical	Event	Death/Injury
1943	Los Angeles, CA	Butane	Fire	5/ > 25
1944	Denison, TX	Butane	Fire	10/45
1949	Perth, NJ	Hydrocarbons	Fire	4/26
1954	Bitburg, Germany	Kerosene	Fire	32/16
1958	Signal Hills, CA	Oil forth	Fire	2/34
1962	Ras Taruna, Saudi Arabia	Propane	Fire	1/111
1966	Larsoe, LA	NGL	Fire	7/20
1969	Teeside, UK	Cyclohexane	Fire	2/23
1972	Lynchburg, VA	Propane	Fire	2/3
1973	Kingman, AZ	Propane	Fire	13/89
1973	Austin, TX	NGL	Fire	6/21
1973	Staten Island, NY	LNG	Fire	40
1975	Eagle Pass, TX	Propane	Fire	16/7
1976	Los Angeles, CA	Gasoline	Fire	6/35
1976	Gadsden, AL	Gasoline	Fire	3/24
1977	Umm Said, Qatar	LPG	Fire	7/87
1978	Santa Cruz, Mexico	Propylene	Fire	52/88
1978	Texas City, TX	Butane	Fire	7/11
1986	Mont Belyieu, TX	Propane	Fire	18/56
1986	Pascagoula, MS	Aniline	Fire	7/119
1988	Maharastra, India	Naphtha	Fire	15/21
1990	Channeiview, TX	Waste oil	Fire	23/130
1994	Dronka, Egypt	Fuel	Fire	3/25
1995	Ukhta, Russia	Gas	Fire	410/500
1996	Bombay, India	Hydrocarbon	Fire	12/20
1997	Chennai, India	LPG	Fire	2/45
2004	Snoqualmie, USA	Propane	Fire	0/0
2005	Shively, KY	Fuel	Fire	0/2
2008	Tanjung Langsat, Malaysia	Petrol	Fire	0/0
2009	Sunoco, Philadelphia	Hydrogen Fluoride	Fire	0/13

2.2 FIRE

2.2.1 The Combustion Process

Fire, or combustion, is a chemical reaction in which a substance combines with oxygen and heat is released. Usually fire occurs when a source of heat comes into contact with a combustible material. There are three conditions essential for a fire: fuel, oxygen and heat. If one of the conditions is missing, fire does not occur and if one of them is removed, fire is extinguished (Mannan, 2005).

Fuel in liquid and gaseous form is much easier to be ignited. Combustion always occurs in the vapour phase, therefore liquid are volatized and solids are decomposed into vapour before combustion can take place.

Usually, the heat needed for ignition is initially supplied by an external source and then provided by the combustion process itself. The amount of heat required to cause ignition depends on the form of the substance. A gas or vapour mixture may be ignited by a spark or small flame, whereas a solid may require a more intense heat source.

One important aspect of fire is that not all range of fuel-oxidizer mixture is ignitable. Only fuel-oxidizer mixture is ignitable. Only fuel-oxidizer mixer within the range of lower flammable limit (LFL) and Upper Flammable Limit (UFL) are ignitable. Mixture below the range of LFL is too lean (fuel) to be ignited. On the other hand, mixture beyond the value of UFL is too rich (fuel) for ignition (DOE, 2004).

2.2.2 Fire Growth and Spread

Fire normally grows and spread by direct burning; resulting from impingement of the flame on combustible materials, by heat transfer or by travel of the burning material. The three main modes of heat transfer are conduction, convection and radiation, which are significant in heat transfer from fires. They are further elaborated in Table 2.3:

Table 2.3: Modes of heat transfer (Dutta, 2006).

Modes of Heat Transfer	**Description**
Conduction	The energy transfer from more energetic molecules to less energetic molecules. Heat is transferred via two mechanisms: (i) vibration between molecules in solid and (ii) collision between molecules as the result in the increase of kinetic energy particularly in liquid and gas.
Convection	The transport of heat energy by way of displacement of fluid elements from one point to another point at a different temperature and only occurs in liquids and gases. There are of two types: (i) natural convection – no external force is used and (ii) forced convection – external force is used such as stirrer.
Radiation	Electromagnetic waves emitted by a body as a result of its temperature. The heat is transferred from a body through vacuum or space.

2.3 FIRE IN PROCESS PLANT

The first of the major hazards in a process plant is fire. Fire in the process industries causes more serious accidents than explosion or toxic release, although the accidents in which the greatest loss of life and damage occur are generally caused by explosion (Mannan, 2005). Diverse historical analyses have demonstrated that fires are the most frequent type of accident, followed by explosions and gas clouds. Darbra *et al.*, (2004) found that, if only accidents leading to fire, explosions or gas clouds are considered 59.5% are for fire, 34.5% for explosions and 6% for gas clouds.

Within the petrochemical industries, many flammable gases are stored as liquid under pressure. Flammable gases are usually very easily ignited if mixed with air. Flammable gases are often stored under pressure, in some cases as a liquid, whereby even a small leak of a liquefied flammable gas from relatively large quantities of gas, which is ready for combustion (DOW, 1993).

In the process plant, fire normally results from a leakage or spillage of fluid. Larger leaks may occur from vessel, pipe or pump failures meanwhile smaller ones from flanges, sample and drain points and other small bore connections. There are several types of fire accidents, depending on the circumstances and on the substances involved. Figure 2.1 is a simplified scheme of the diverse possibilities.

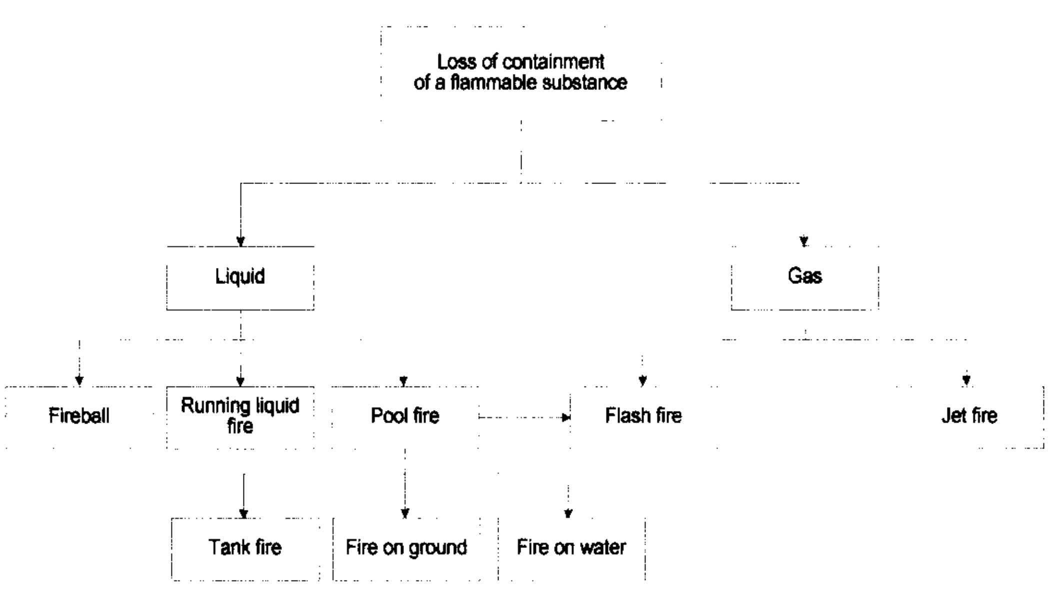

Figure 2.1: Types of fire accidents (Casal, 2008).

A pool fire occurs when a spill of liquid fuel is ignited. The size of the pool will be determined by the ground features, by the eventual existence of a confining bund or by the balance between the release rate and the evaporation rate. After a first step, the flames size and shape remain approximately constant, with large fluctuations. The combustion is rather bad and large amounts of smoke are produced. A significant part of the flames surface is covered by non-luminous black smoke. The thermal intensity decreases quickly as the distance from the flames increases. A similar scenario can occur when there is a fire in a tank storing a flammable liquid; in this case, large inventories can imply large fires, very difficult to be extinguished (BMIIB, 2008).

A jet fire would appear as a long narrow flame produced. Jet fires occur when there is a release and ignition of a flammable gas or two-phase flow through a hole, a flange, etc., at a relatively high speed. The combustion is much better than in pool fires; thermal effects can be locally very intense, especially if there is flame impingement, but their size is usually relatively reduced as compared to pool fires.

When a flammable cloud, usually due to a liquid spill or a two-phase release is ignited, the flames propagate through the flammable mixture and a flash fire occurs. A flash fire is a quick and short phenomenon which can be accompanied by mechanical effects (blast).

The fireball is generally far more serious than the other fires (ILO, 1993). It is usually related to the sudden loss of containment of a pressurized liquefied fuel, typically LPG. The two-phase cloud can burn only on its outer surface as inside there is no oxygen. This phenomenon has a short duration, but the thermal radiation intensity is very strong.

Generally, the effects of a fire are limited to relatively short distances as compared to explosions or toxic clouds. However, in process or storage plants fires can affect other equipments, especially if there is flame impingement, thus increasing the scale of the accidental scenario through the domino effect. Therefore, in consequence modelling, the estimation of fire effects and consequences can be very important.

This project focuses mainly on flash fire, jet fire, pool fire and fireball. The primary impact from fire is due to its thermal radiation. The intensity of the thermal radiation depends on the size of the fire, type of fuel, and the receptor's distance from the fire.

2.3.1 Flash Fire

A flash fire is a non-explosive combustion of an unconfined vapour cloud resulting from a release of flammable fuel into the atmosphere, which, after mixing with air, ignites. On ignition, the fire propagates through the vapour cloud and burns as a flash fire. The major hazard of flash fires is the heat effect from thermal radiation affecting objects in the nearby vicinity of the flash fire or in the path of the flash fire whether on land or water (Ashe and Rew, 2003). A flash fire occurs if ignition takes place within the flammable region of a gas cloud, generally at a point remote from the source (Rew *et al.,* 1996).

Flash fire is modelled by considering dispersion of the vapour cloud and its ignition. One of the first such models was by Eisenberg *et al.*, (1975) in which the vapour cloud was assumed to be half ellipsoid. A semi-empirical model is proposed by Raj and Emmons, (1975) to estimate the height of the flames. Furthermore, the speed of the flame propagating through the vapour cloud is taken into account. Additional experimental work on flash fires was performed as part of a Joint Industry Project (CERC, 2001). Butler and Royle, (2001) characterised the flash fires from turbulent, two-phase jet releases of propane (up to 4.9 kg/s).

The presence of obstructions in the path of the vapour cloud was found to alter the concentration of LPG vapour in the cloud dramatically with, in this case, significant decreases in the vapour concentration downwind of the fence. The concentration of gas in the vapour clouds formed was generally low and the vapour cloud fires produced were relatively lean. The flames were therefore often invisible. Ignition of the cloud was observed at concentrations below the Lower Flammability Limit (LFL) of 2.2 vol.%. This is thought to be due to localised pockets of high concentration of gas at locations where the average concentration is measured as being below the LFL. In some cases, the cloud was ignited, but the flame did not propagate throughout the cloud, resulting in the formation of isolated pockets of ignition. In no cases were fireballs observed (HSE, 2009).

It would appear that flash fires are generally not well defined within the incident reviews which have been undertaken, with the distinction between flash fires and VCEs being blurred. In many cases, detailed characteristics of flash fire events have not been recorded because of their less damaging effects. In addition, due to its sudden and quick occurrence, it is extremely difficult to obtain characteristics of the flash fire event such as estimates of flame propagation speeds. However, the review of incidents illustrates both the direct effect of flash fires in terms of fatalities and their importance in the escalation to other categories of process plant fires, resulting in a more significant threat to personnel which tends to produce severe effects in terms of material damage to the plant (Rew *et al.*, 1996).

2.3.2 Jet Fire

A jet fire occurs when flammable gas emitting from a pipe or equipment then ignited and burns on the orifice (Mannan, 2005). A jet fire may result from a high-pressure leakage of gas from process plants or storage tanks. Storage tanks or process vessels containing, for example LPG which is exposed to an enveloping fire, after a very short period of time vent their contents though a relief valve. If the released gas is ignited, a jet fire may occur (Andreassen *et al.*, 1992).

Jet flames can occur in chemical process industries, either by design or by accident. They occur intentionally in burners and flares. Ejection of flammable fluid from a vessel, pipe or pipe flange can give rise to a jet flame if the material ignites. An intermediate situation, and one which particularly concerns the designer, is where the jet flame results from ignition of flammable material vented from a pressure relief valve.

Scenarios involving jet flames are not easy to handle, since a large jet flame may have a substantial 'reach', sometimes up to 50 meters or more. Jet fires scenarios are results of an accidental release of gas. Similar fire may also occur in the case of intentional disposal of unwanted gas in flares. Jet fires have been involved in a number of accidents. Perhaps the most dramatic were the large jet fires from the gas riser on the Piper Alpha oil platform in 1988. In other cases jet fires from pressure relief valves have caused adjacent vessels to overheat and burst, giving rise to a BLEVE, such was the case at Mexico City in 1985 (Mannan, 2005).

Jet fire modelling incorporates many mechanisms, similar to those considered for pool fires. Hawthorne *et al.*, (1949) worked with vertical flames up to 1 m in length; the expression proposed by these authors to calculate the flames length is still used. Classical studies concerning flares under the action of wind were published by Kalghatgi, (1983) and Chamberlain, (1987). Sonju and Hustad, (1986) worked with methane and propane subsonic jet fires up to 8 m in length. Johnson *et al.*, (1994) obtained experimental results with large horizontal natural gas jet fires. Vertical sonic and subsonic propane jet fires have been studied by Sugawa and Sakai, (1997) (7 – 8 m length) and Palacios *et al.*, (2009) (up to 10 m length). Hydrogen sonic flames up to 1.4 m in length have been studied by Mogi and Horiguchi, (2009).

2.3.3 Pool Fire

Pool fire occurs when a flammable liquid spills onto the ground and is ignited. A pool fire begins typically with the release of flammable material from process equipment or storage. If the material is a liquid, stored at a temperature below its normal boiling point, the liquid will collect in a pool. The geometry of the pool is dictated by the surroundings. If the liquid is stored under pressure above its normal boiling point, then a fraction of the liquid will flash into vapour, with a portion of the unflashed liquid remaining to form a pool in the vicinity of the release (AIChE, 2003).

There are many experimental works done related to pool fire in the last century. Most work of pool fire deals with circular pools. A particular type of circular pool fires is the storage tank fire (Mannan, 2005). Much of the early work was done on relatively small diameter pool fire. Subsequent studies indicate that the effect of pool diameter is important and that it is preferable to carry out studies on large pool fires. This initial works appeared to focus and concentrate on determining the liquid burning rate of heat transfer to the liquid surface and of the fraction of heat radiated. Experimental studies on these aspects were conducted by Rasbash *et al.*, (1956) and by Blinov and Khudiakov, (1957). This work covered a wide range of pool diameters. Hottel, (1958) analysed their data to show that, as the diameter of pool fire is increased, there is progression from a laminar to a transition and finally to a turbulent regime.

Burgess and Zabetakis, (1964) carried out experiments on small pool fires to determine the liquid burning rate and fraction of heat radiated. Yumoto, (1971) has done experiments to study the relative contribution of radiation and convection to heat transfer to the liquid surface in large pool fires. Large scale tests on pool fires from LNG have been undertaken in the American Gas Association (AGA) project as described by Brown *et al.*, (1975), who give correlations for the liquid burning rate and the heat radiated.

The theoretical treatment for pool fire is correspondingly complex. It is appropriate, therefore to describe first some of the empirical features of pool fires. A pool fire burns with a flame which is often taken to be a cylinder with a height, twice the pool diameter. In still air the flame is vertical, but in wind it tilts. Wind also causes the base of the flame to extend beyond the downwind edge of the pool, thus exhibiting flame drag. With some pool fires blow out can occur at a wind speed of about 5 m/s. The characteristics of a pool fire depend on the pool diameter. The liquid burning, rate increases with diameter until for large diameters and it reaches a fixed value. The heat radiated from the flame behaves similarly (Mannan, 2005).

Experimental data obtained with different fuels (crude oil, kerosene, heptane, etc.) have been published by Koseki, (2000). Hayasaka *et al.*, (1992) measured the emissivity for heptane pools with a diameter of 3 m. Planas *et al.*, (2003) measured also the emissivity from hydrocarbon pool fires by using infrared thermography. The main features of gasoline and diesel oil pool fires of up to 6 m diameter have been studied by Chatris *et al.*, (2001) and Muñoz *et al.*, (2004).

The modelling of pool fires covers the following aspects: (i) flame geometry, (ii) liquid burning rate, (iii) flame characteristics (iv) heat radiated and (v) view factor. Reviews of pool fire models have been presented by several authors, including de Ris, (1979); Mudan, (1984) and Crocker and Napier, (1988); Andreassen *et al.*, (1992), Rew and Hulbert, (1996); Cuchi and Casal, (1998) and Kashef *et al.*, (2002).

2.3.4 Fireball

If a liquid with a vapour pressure greater than atmosphere pressure is released, some rapid flash evaporation of the liquid will occur and a rapidly expanding cloud of vapour with some entrained liquid droplets will form. The higher the vapour pressure, the higher the fraction of the liquid mass flash-evaporated or entrained, until effectively all of the liquid is formed into an expanding cloud. The ignition of such cloud leads to a fireball (Roberts, 1982).

A fireball in such a situation generally develops according to the following stages, for a release at ground level: an expanding hemispherical ball of flame is formed at ground level; the fireball transforms into a near spherical shape and lifts off from the ground and it then rises as a rapidly cooling ball of combustion products. Hasegawa and Sato, (1977, 1978) have reported that when the theoretical percentage of flash evaporation exceeds 35%, the released liquid burns virtually entirely as a fireball. This roughly indicates that the mass of liquid entrained is about twice the mass of the vapour produced by flash evaporation.

Experimental work has been restricted to few experiments performed at rather small scale. No experimental work has been performed with large scale fireballs. However, some accidents have been analyzed and expressions allowing the estimation of fireball size, elevation and duration have been obtained (for example, see Satyanarayana *et al.*, (1991) for a review and Martinsen and Marx, (1999) for the estimation of surface emissive power).

The modelling of fireballs covers the following aspects: (i) the fireball regime, (ii) the mass of fuel in the fireball, (iii) the fireball development and timescale, (iv) the fireball diameter and duration, (v) the heat radiated and (vi) the view factor.

The treatment of the heat radiated from a fireball is a good illustration of the different approaches which may be taken to the modelling of fires in process plants. There are three ways to determine the heat radiated. One is to assume that it is a given fraction of the heat released. Another is to assume a given value for the heat radiated from the flame surface, or surface emissive power. The third is to estimate the heat radiated from the flame properties, such as flame temperature and emissivity (Mannan, 2005).

Generally, fireballs are of short duration, but have very high thermal radiation flux. A fireball resulting from a BLEVE may be up to several hundred feet in diameter. Table 2.4 shows a summary of previous studies conducted on fireballs.

Table 2.4: Some studies of fireballs (Mannan, 2005).

Experimental study on fireballs or propellants	Gayle and Bransford, (1965)
Theoretical study of fireballs of rocket propellants	R.W. High, (1968)
Theoretical study of fireballs of propellants	Bader, Donaldson and Hardee, (1971)
Theoretical study of fireballs from bursting vessels	Hardee and Lee, (1973, 1975)
Experimental and theoretical study of fireballs from a stationary vapour cloud	Fay and Lewis, (1977) Fay, Desgroseilliers and Lewis, (1979)
Theoretical study of LNG fireballs	Hardee, Lee and Benedick, (1978)
Experimental and theoretical study of fireballs following liquid-flash-off	Hasegawa and Sato, (1977, 1978)
Experimental and theoretical study of fireballs from bursting vessels	Maurer *et al.*, (1977) Giesbrecht *et al.*, (1980)
Review of experimental and theoretical work on fireballs and of case histories and assessment hazard	Marshall, (1977a, 1987) A.Baker, (1979)
Experimental study on fireballs Review of experimental and theoretical work on fireballs and correlation of principal features of fireball behaviour	Roberts, (1981/82, 1982) Lihou and Maund, (1982)
Experimental and theoretical study of fireballs Review of experimental and theoretical work on fireballs	Moorhouse and Pritchard, (1982)
Theoretical study of fireballs	Jaggers *et al.*, (1986); Roper *et al.*, (1986)
Experimental study of BLEVEs, including fireballs	Johnson and Pritchard, (1991)

2.4 COMPUTER-AIDED FOR RISK ASSESSMENT

The risk from industrial hazards can be calculated in two ways, handy with simple calculation models or with the aid of computer programs. The two methods should be combined in order to minimize failures. The complex development of accident scenarios can be achieved by using consequence modelling combining with computer software (El-Harbawi, 2006).

Several computer languages have been used in the past to develop the risk assessment software such as, C++, Visual Basic, Fortran, Delphi, and Pascal (or any other program which can run under the Microsoft Windows operating system) and can be connected to other computer tools to provide an attractive user-friendly "front-end platform".

2.4.1 Simulation Applications for Industrial Accidents

Several computer programs and softwares have been developed to evaluate the consequences of the accidental releases. Typically, the risk assessment technique such as HAZOP (Hazard and Operability Study) is one of the most common tools to accomplish hazard assessment qualitatively. It was developed in the early 1970s at Imperial Chemical Industries (ICI), U.K. The basic principle of HAZOP study is that hazards arise in a plant due to deviations from normal behaviour. ALOHA (Areal Locations of Hazardous Atmospheres) is a computer program designed particularly for use by people responding to chemical accidents. PHAST (Process Hazard Analysis Software Tool) by Det Norske Veritas (DNV) is designed for fire, explosion and dispersion accidents. FRED (Fire, Release, Explosion and Dispersion) software created by Shell company, it is used to calculate effects such as blast waves from high-pressure-vessel failure, blowdown of two-phase pipelines and subsea gas releases. The SAFETI package (Safety Abroad First-Educational Travel Information) was developed by Technica for the risk assessment of chemical process industry facilities (Pitblado and Napanis, 1989).

2.5 GEOGRAPHIC INFORMATION SYSTEMS (GIS)

GIS can be defined as "an information system that is designed to work with data referenced by spatial or geographic coordinates. In other words, a GIS is both a database system with specific capabilities for spatially-referenced data, as well as a set of operations for working with the data" (Star and Estes, 1990).

As compared with maps, GIS has the inherent advantage that data storage and data presentation is separate. As a result, data may be presented and viewed in various ways enabling a wide variety of products to be created from the same basic data. Once they are stored in a computer, we can zoom into or out of a map, display selected areas, make calculations of the distance between places, present tables giving details of features shown on the map and superimpose the map on other information.

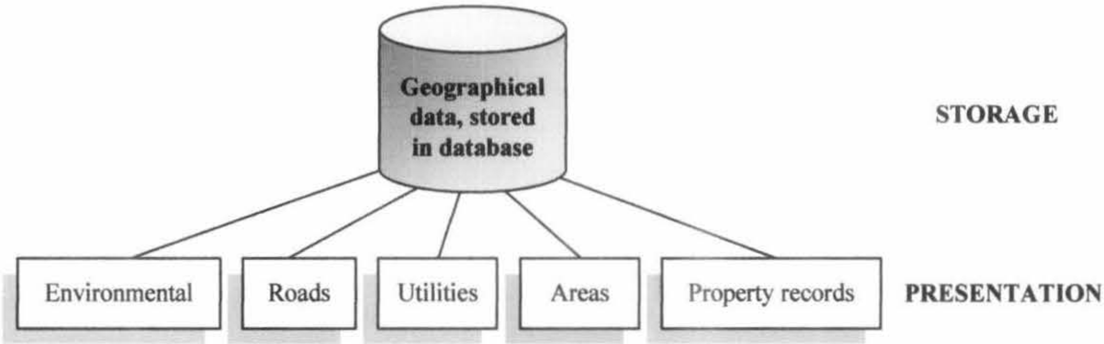

Figure 2.2: A map as a presentation medium and storage medium.

For many years, GIS has been considered to be too difficult, expensive and proprietary. The advent of the graphical user interface (GUI), powerful and affordable hardware and software and public digital has broadened the range of GIS applications and brought GIS to mainstream use in the 1990s (Chang, 2003).

According to a published survey (Crockett, 1997); ESRI Inc. and Intergraph Corp. have dominated the market for GIS software. The main software product from ESRI Inc. is ArcGIS, a scalable system with ArcView, ArcEditor and ArcInfo. All three versions of the system operate on the Windows platforms and share the same applications and extensions, but they differ in their capabilities.

2.5.1 GIS-based Software Applications for Environment Risk Assessment

Several computer programs and softwares have been developed for the evaluation of the consequences of accidental releases. GIS can provide tools for spatial and customized interface of risk assessment, and visual presentation of modelling results and site conditions. The integration of the risk assessment results with spatial land-use information will be helpful for identifying and assessing hazard impacts on specific receptors through various exposure pathways, where map can be valuable for risk analysis. Table 2.5 represents a summary of GIS-based softwares, which have been developed to evaluate fire hazards in the process industries:

Table 2.5: GIS-based softwares in fire hazards assessment (El-Harbawi, 2006).

Name of software	Name of establishment	Hardware requirement	Website address/Reference
BREEZE	Trinity consultants	WINDOWS 95/98/NT	www.breezesoftware.com
RISK WIT	VVT automation		www.vtt.fi/aut/rm/riskana/indexe.htm
PHAST	DNV		www2.dnv.com/software/Products /Risk_Management/phast.htm
TRACE	SAFER	WINDOWS 95/98/NT	www.safersystem.com/trace2.htm
SEVEX	ATM PRO		www.atm-pro.com/new
TOXFLAM & EXPSYS	ENVIROWARE	LINUX	www.enviroware.it

2.5.2 ESRI MapObjects

GIS programmers working in a Windows environment have several choices of programming environments. Using the New Technology operating system, choices include ArcInfo, ArcView or MapObjects. The Windows 95 operating system offers GIS programmers ArcView and MapObjects. Most GIS developers are familiar with ArcInfo and ArcView, but perhaps less familiar with MapObjects (Lombard, 1997).

MapObjects is a set of mapping and GIS components for application developers. MapObjects consists of an Object Linking and Embedding (OLE) Control and a collection of programmable OLE Automation objects. MapObjects can operate within any programming environment that supports OLE controls. MapObjects is an ideal for those wishing to work within a "visual" programming environment such as Visual C++ or Visual Basic (Lombard, 1997).

CHAPTER 3
METHODOLOGY

3.1 PROJECT WORKFLOW

Prior in developing the Fire Simulation Tool (FiST), which enables the user to study the impacts of fires; namely flash fire, jet fire, pool fire and fireball, the parameters and calculation models for the four different fire scenarios are gathered. As it is difficult to calculate the outcome of fires and interpret them graphically, a stand-alone user-friendly software package using Visual Basic is developed to simulate fire scenarios in which the parameters such as flame height, flame diameter and thermal effects are calculated. Please refer to Appendix A for the Gantt chart for this project.

Once the interfaces are completed, the results from the tool will be linked to GIS to display the impact graphically. This report describes the development of flash fire, jet fire, pool fire and BLEVE/fireball modelling and simulation. The project workflow is divided into two stages as shown in Figure 3.1.

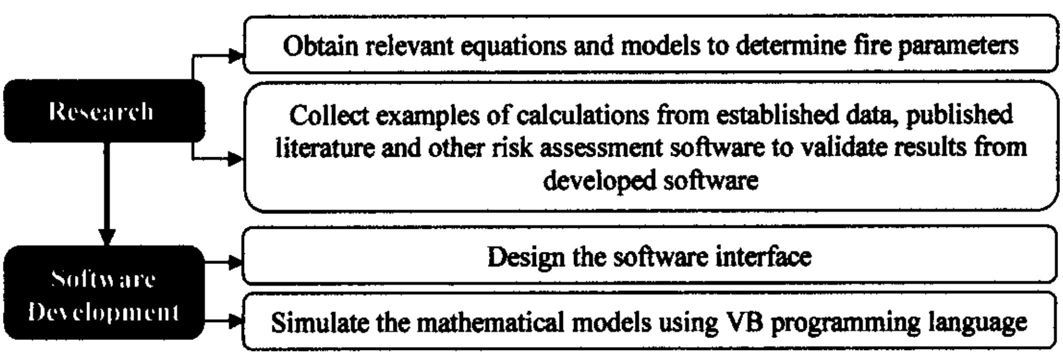

Figure 3.1: The methodology flow diagram.

3.2 FIRE MODELLING

Fire can be classified into different categories depending on the type of fuel (gas or liquid), physical properties of the fuel, and how it is released into the atmosphere. Based on these considerations, fire may be categorized as flash fire, jet fire, pool fire or fireball (DOE, 2004). The parameters for these fire scenarios are obtained from literature review and are shown in the following figures in terms of logic diagrams. The logic diagram acts as a guideline during the calculation phase of the project using the mathematical models.

3.2.1 Flash Fire

For flash fire models, the important parameters are the flame shape, heat transfer assessment and duration (Andreassen *et al.,* 1992). The calculation models for these parameters are presented in Appendix B (section B.1). The logic diagram for calculating these parameters is as shown in Figure 3.2.

Flash Fire

↓

Estimate flame shape

$$V_r = \frac{2\pi}{3}\sigma_x\sigma_y\sigma_z\left(r_l^3 - r_u^3\right) \qquad \text{(Eq.3.1)}$$

$$A_r = \frac{2\pi}{3}\left(\sigma_x^2 + \sigma_y^2 + \sigma_z^2\right)\left(r_l^3 + r_u^3\right) \qquad \text{(Eq.3.2)}$$

↓

Estimate source view factor

$$F_h = \frac{1}{\pi}\left\{\tan^{-1}\sqrt{\frac{x_r+1}{x_r-1}} - \frac{x_r^2 - 1 + h_r^2}{\sqrt{AB}}\tan^{-1}\sqrt{\frac{(x_r-1)A}{(x_r+1)B}}\right\} \qquad \text{(Eq.3.3)}$$

$$F_v = \frac{1}{\pi}\left\{\frac{1}{x_r}\tan^{-1}\left(\frac{h_r}{\sqrt{x_r^2-1}}\right) + \frac{h_r(A-2x_r)}{x_r\sqrt{AB}}\tan^{-1}\sqrt{\frac{(x_r-1)A}{(x_r+1)B}} - \frac{h_r}{x_r}\tan^{-1}\sqrt{\frac{x_r-1}{x_r+1}}\right\} \qquad \text{(Eq.3.4)}$$

↓

Estimate heat transfer

$$Q_f = A_r\sigma\left(\varepsilon_g T_g^4 - \varepsilon_a T_a^4\right) \qquad \text{(Eq.3.5)}$$

↓

Estimate the duration

$$t = \frac{1}{2kT_a^3}\left\{\left[\tan^{-1}\left(\frac{T_g}{T_a}\right) - 0.5\ln\left(\frac{T_g - T_a}{T_g + T_a}\right)\right] - \left[\tan^{-1}\left(\frac{T_{gi}}{T_a}\right) - 0.5\ln\left(\frac{T_g - T_a}{T_{gi} + T_a}\right)\right]\right\} \qquad \text{(Eq.3.6)}$$

$$t_{1/2} = \frac{1}{2kT_a^3}\left\{\left[\tan^{-1}\left(\frac{\beta+1}{2}\right) - \tan^{-1}\beta - 0.5\ln\left(\frac{\beta+1}{\beta+3}\right)\right]\right\} \qquad \text{(Eq.3.7)}$$

$$t_{eff} = 3 \times t_{1/2} \qquad \text{(Eq.3.8)}$$

↓

Estimate thermal effects

$$Q_n = F\sigma\left(T_g^4 - T_a^4\right) \qquad \text{(Eq.3.9)}$$

Figure 3.2: Logic diagram for calculation of flash fire radiation effect (Andreassen *et al.,* 1992).

3.2.2 Jet Fire

The important calculations for jet fire modelling are flame shape, flame tilt, flame dimensions and heat transfer assessment (Andreassen *et al.*, 1992). The calculation models for estimating these parameters are given in Appendix B (section B.2) and the logic diagram for calculating these parameters is shown in Figure 3.3.

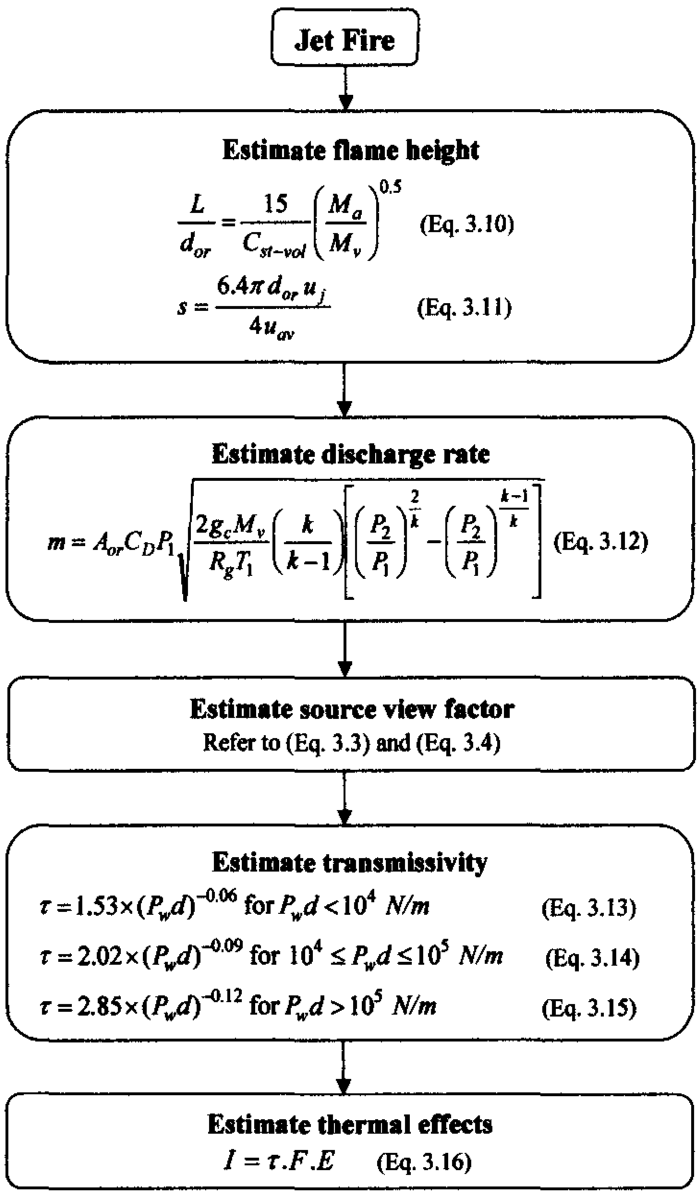

Figure 3.3: Logic diagram for calculation of jet fire radiation effect (Andreassen *et al.*, 1992).

3.2.3 Pool Fire

Pool fire models have been applied to a large variety of combustible and flammable materials. Pool fire models are composed of several component submodels. A selection of these is briefly reviewed below (CCPS, 1994):

- Burning rate
- Pool size
- Flame surface emitted power
- Geometric view factor
- Atmospheric transmissivity
- Heat transfer

These parameters are described in detail in Appendix B (section B.3). Figure 3.4 shows the logic diagram for calculating these parameters.

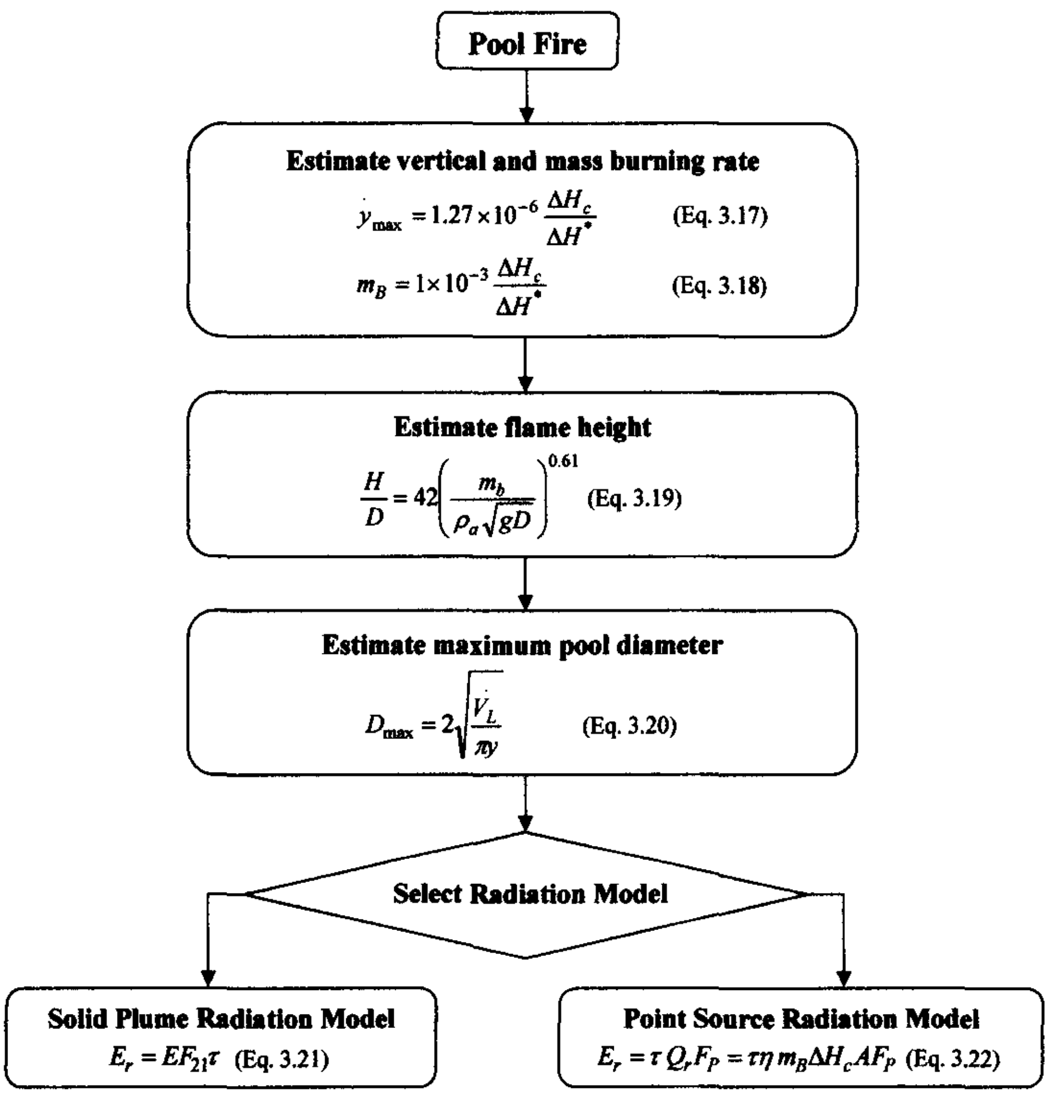

Figure 3.4: Logic diagram for calculation of pool fire radiation effect (CCPS, 2000).

3.2.4 BLEVE/Fireball

The calculation models for estimating the parameters for fireball can be found in Appendix B (section B.4). The logic diagram showing the calculation procedures is given in Figure 3.5.

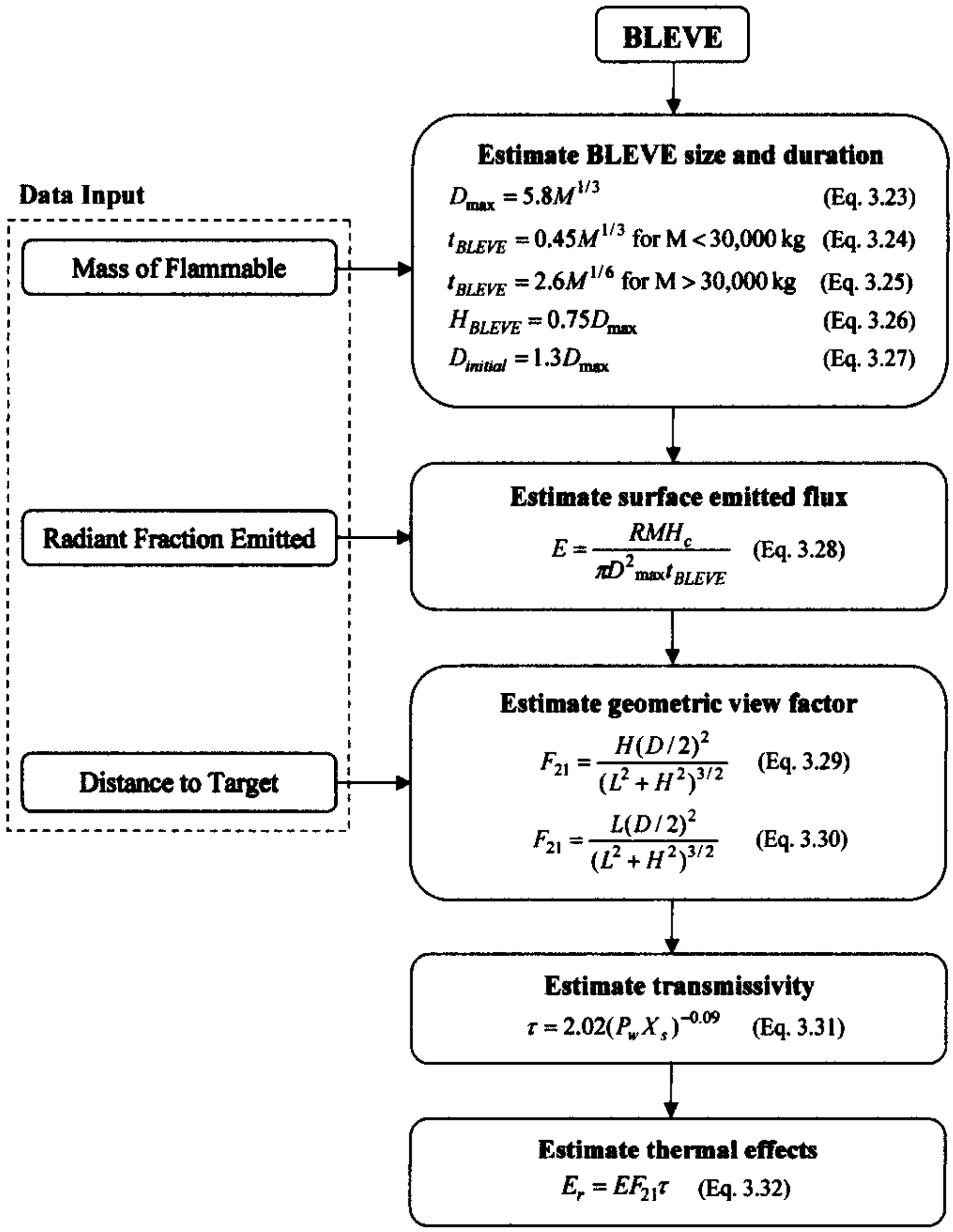

Figure 3.5: Logic diagram for calculation of BLEVE radiation effect (CCPS, 2000).

3.3 EFFECTS OF ACCIDENT IMPACTS ON PEOPLE AND STRUCTURES

A function that relates the magnitude of an action – for example, thermal radiation from a fire – to the degree of damage it causes, is required to estimate the consequences of an accident on people. The most frequesntly applied method is the probit analysis, which relates the probit (from probability unit) variable to the probability (Casal, 2008).

Probit equations are available for a variety of exposures, including exposures to toxic materials, heat, pressure, radiation, impact, and sound, to name a few. For toxic exposures, the causative variable is based on the concentration; for explosions, the causative variable is based on the explosive overpressure or impulse, depending on the type of injury or damage. For fire exposure, the causative variable is based on the duration and intensity of the radiative exposure. Probit equations can also be applied to estimate structural damage, glass breakage, and other types of damage (CCPS, 2000).

3.3.1 Thermal Radiation Effects on People and Structures

The estimation of the effects of thermal radiation on people and structures is a key step in the assessment of hazard for installation where flammable liquids or gases are stored. Heat from thermal radiation can cause various harms to the human body (El-Harbawi, 2006).

The main effects of thermal radiation on people are burns to the skin, the severity of which depends on the intensity of the radiation and on the dose received. The injury caused to the skin by the heat radiation are commonly classified as: first, second or third-degree burn. This determines to what extent and to which depth the skin has been damaged. First-degree burns are superficial injuries and is characterized by a red, dry and painful skin. Second-degree burns are deeper injuries whereby the skin becomes wet and red with formation of blisters. Third-degree burns penetrate more deeply into the skin in which victims lose all sensation in the burned area, and the skin will have been destroyed and be white, yellow or black in colour.

The probit equations are used to estimate the probability of an impact (e.g. fatality, injury) for a specified harm dose. The dose is a function of the intensity and duration of the harmful effects. Eisenberg, (1975) has suggested various probit equations to estimate the probability of injuries or death due to high thermal radiation. The probit models for injury by thermal radiation (TNO, 1992) are shown below:

First-degree burns:

$$Y = -39.83 + 3.0186\ \ln(Q^{4/3}t) \qquad \text{(Eq. 3.33)}$$

Second-degree burns:

$$Y = -43.14 + 3.0186\ \ln(Q^{4/3}t) \qquad \text{(Eq. 3.34)}$$

Lethality:

$$Y = -36.38 + 2.56\ \ln(Q^{4/3}t) \qquad \text{(Eq. 3.35)}$$

where

Y is the probit variable (-)

Q is the radiation intensity (W/m^2)

t is the exposure time (sec)

The effects of thermal radiation on structures depends on whether they are combustible or not, and the nature and duration of the exposure. All structural materials classified as combustible or non combustible, inherently possess a degree of fire resistance. Wooden materials will fail due to combustion, whereas steel will fail due to thermal lowering of the yield stress. The degree of damage may vary with the basic material and building configuration. The building materials and the design of the details of construction have always played an important role in building firesafety. High radiation from fires, such as BLEVE fireballs may arise a considerable distance above the ground and this makes them relatively difficult to be protected from (El-Harbawi, 2006). Table 3.1 provides a summary, in an approximate way, on the effects of thermal radiation.

Table 3.1: Thermal radiation effects (DOW, 1993).

Heat Flux (kW/m^2)	Observed Effect
35-37.5	Sufficient to cause damage to process equipment. Cellulosic material will pilot ignite within one minute's exposure.
23-25	Spontaneous ignition of wood after long exposure. Unprotected steel will reach thermal stress temperatures which can cause failures. Pressure vessel needs to be relieved or failure will occur.
12.6	Thin steel with insulation on the side away from the fire may reach a thermal stress level high enough to cause structural failure.
9.5	Minimum energy required for piloted ignition of wood, melting of plastic tubing.
4.0	Pain threshold reached after 8 sec; second-degree burns after 20 sec. Sufficient to cause pain to personnel if unable to reach cover within 20 sec; however blistering of the skin (second-degree burns) is likely; 0% lethality.
1.6	Will cause no discomfort for long exposure.

3.3.2 Risk Assessment

Risk assessment is the process of gathering data and synthesizing information to develop an understanding of the risk of a particular installation. The effort needed to evaluate the risk posed by a particular hazardous installation will vary depending upon the foundation of information available to understand the significance of potential accidents that could occur (DOE, 2004).

In understanding the risk posed by an installation, the information required is answers to these questions:

(i) What can go wrong?
(ii) How likely is it?
(iii) What are the impacts?

Answers to the first question are obtained during hazard identification. Information gathered from the second question is during the probability or frequency analysis phase and from the third question during consequences analysis phase. Risk can therefore be considered to be a function of the existence of a hazard, the frequency of occurrence of an incident associated with the hazard and the consequence or impact of the incident should it occur, or in functional equation form:

$$\text{Risk} = f\,(\textit{incident, frequency, consequence}) \qquad \text{(Eq. 3.36)}$$

3.4 SOFTWARE DEVELOPMENT STAGES

The application used in developing the Fire Simulation Tool (FiST) is Microsoft Visual Basic 6.0. Visual Basic (VB) is relatively simple to learn and use programming language due to its graphical development features.

FiST is a software package for estimating the impacts of fires in the process industries. The codings for FiST are built using VB language, which consists of a graphic user interface (GUI) as front end and mathematical models as back end (source code). The results of calculations using the codes can be presented in tabulated or graphical forms, can be saved and exported to the GIS software for risk presentation.

The development of this software has been divided into five different stages, which are:

- Planning the application
- Building the graphical user interface (GUI)
- Writing the computer program
- Software validation and verification
- Integrating the results from the tool with GIS application

3.4.1 Application Planning

The first step in application planning is identifying the various tasks that the application needs to perform. The second step is to determine how these tasks are logically related and to identify objects to which each task will be assigned. The following step is to classify the events needed to trigger an object into executing its assigned tasks. Lastly, a sketch of the graphical user interface is prepared. The application should be able to compute the impacts of fires in the process industries.

3.4.2 Building the Graphical User Interface (GUI)

The application designed is based on object-orientated programming. It has been designed using multiple Graphical user interfaces (GUIs). The computation of the mathematical models for flash fire, jet fire, pool fire and fireball is written in VB programme, following the flowchart given in Figure 3.6. GUI is easy to use and the users can perform the fire modeling simulations by a few clicks on the buttons.

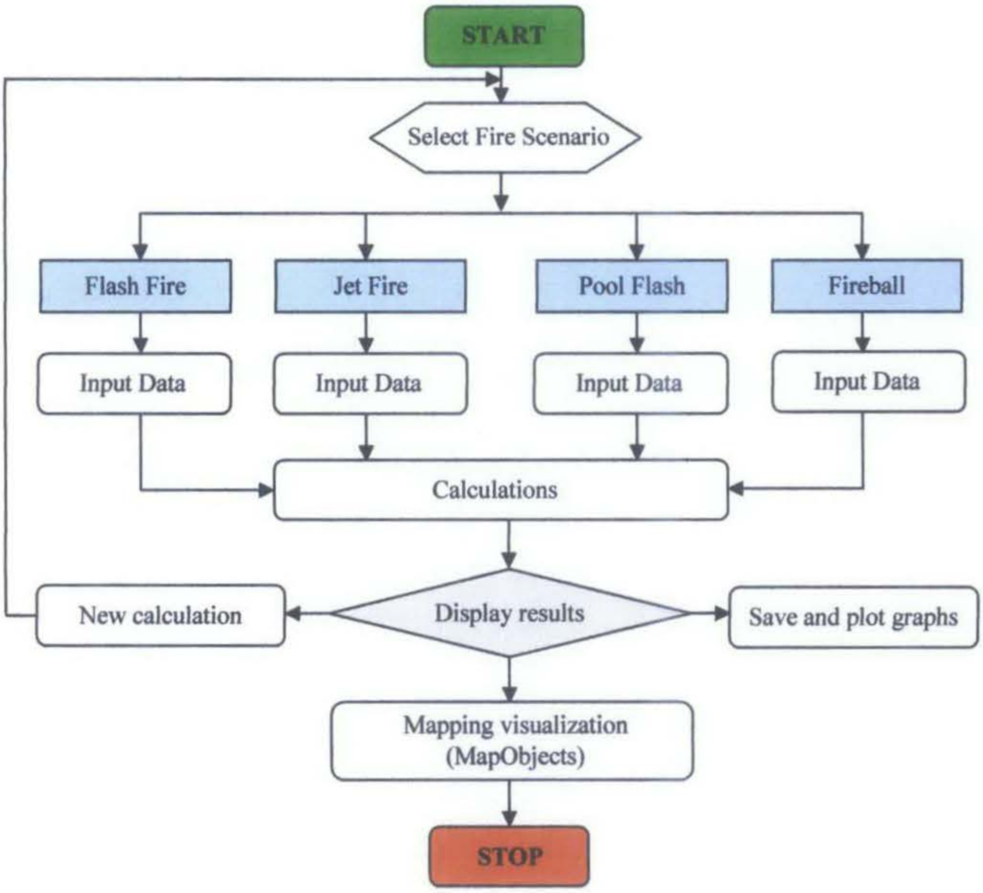

Figure 3.6: Flowchart of FiST.

3.4.3 Writing the Computer Programme

The application is written in standard Microsoft Visual Basic 6.0 and distributed in object format with the source code. After creating the interface for the FiST application, it is necessary to write the code that defines the applications behaviour. VB is used to develop the application as front-end (GUI) and simulate the mathematical models for the impacts of fires in the back-end (codes).

3.4.4 FiST Validation and Verification

Verification and validation of computational simulations is the most important step to build confidence and quantify results. Verification assesses the accuracy of a solution to a computational model. Validation on the other hand, is the assessment of the accuracy of a computational simulation by comparison with experimental data.

The validation process confirms that a correct system is being made (i.e., the system requirements are correct, complete, consistent, operationally and technically feasible, and verifiable). The verification process ensures that the design solution has met the systems requirement and that the system is ready for use in the operational environment for which it is intended.

3.4.5 Integrating the Results from the Tool with GIS Application

GIS tools can be integrated into an application having available data for calculations in non-GIS components by using MapObjects. Using MapObjects, FiST allows users to utilize GIS and mapping technology to solve their problems. The technique has been done by using VB to customize the MapObjects. Figure 3.7 shows the simple diagram how to customize MapObjects using VB to create a GUI.

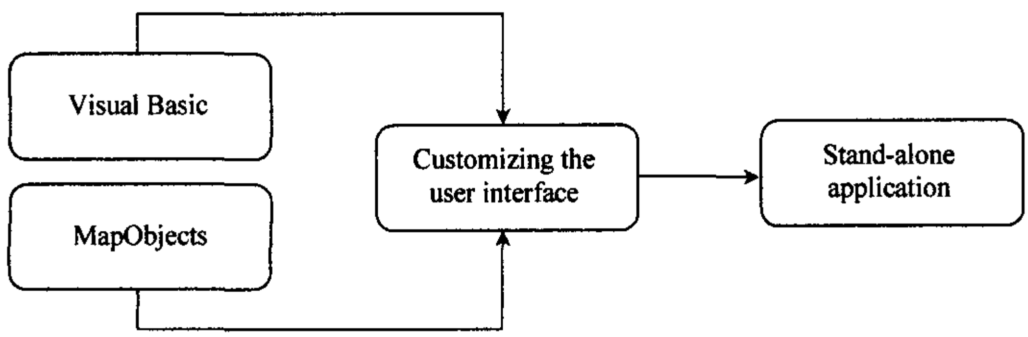

Figure 3.7: Customizing MapObjects using VB to create a GUI.

- **Loading the MapObjects**

A GIS mapping application can be developed by user by adding a map component to the application. The MapObjects can be embedded into an existing application to add additional mapping capability and can be used to create a new stand-alone application. The MapObjects can be loaded from the Visual Basic (VB) environment by displaying the VB components dialog box, where the MapObjects can be added by selecting it in the controls tab. Figure 3.8 shows the MapObjects control inside the VB component dialog box. After MapObjects is selected from the dialog box, the MapObjects control will appear in the VB control toolbox (Figure 3.9).

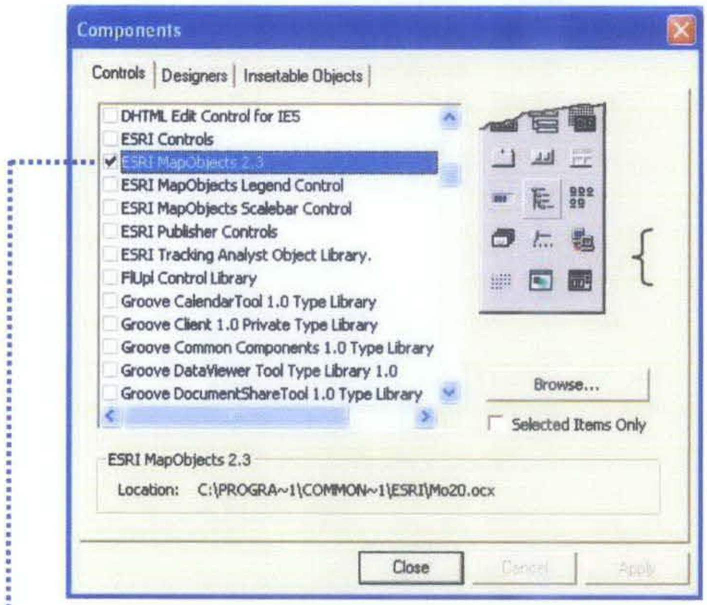

Figure 3.8: VB component dialog box.

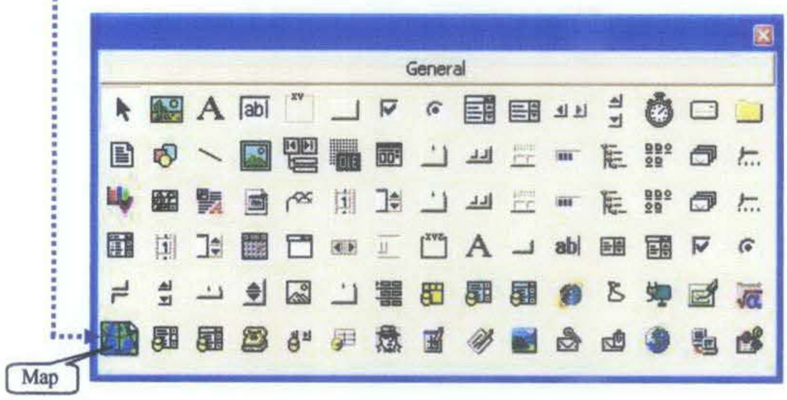

Figure 3.9: VB control toolbox.

CHAPTER 4
RESULTS AND DISCUSSION

This chapter explains and discusses the results obtained from the current research in the context with the findings of earlier studies. The FiST software has been successfully developed and implemented in an interactive Visual Basic (VB) environment. The software is designed to be user-friendly to simulate fire scenarios: flash fire, jet fire, pool fire and BLEVE/fireball. It is developed using VB language whose state of art consists of a graphic user interface (GUI) as front end and mathematical models as back end (source code). The results of calculations using the codes can be presented in tabulated or graphical forms. The GIS is integrated with VB, which enables the software to display the hazard zones graphically.

4.1 SOFTWARE INTRODUCTION INTERFACE

After accessing the sofware, the interface shown below (Figure 4.1) would appear on the screen and is visible for about 5 seconds before proceeding automatically to the main general interface (Figure 4.2).

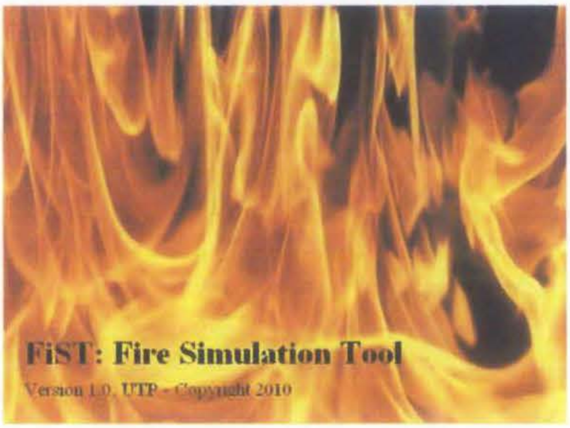

Figure 4.1: FiST introduction interface.

4.2 GENERAL INTERFACE

The general interface is used to obtain selections in order to perform the general commands required by the user. Figure 4.2 represents the main general interface of the software.

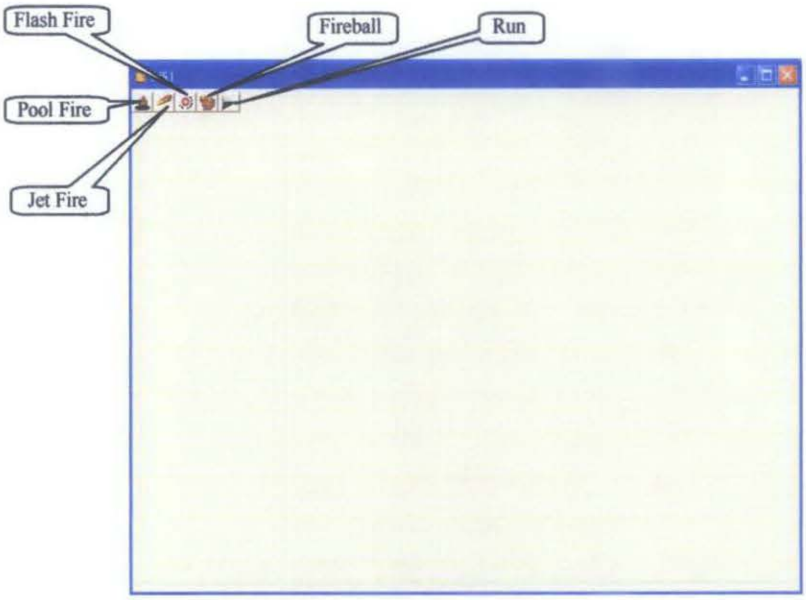

Figure 4.2: FiST main general interface

User may either click on the run button or select any one of the fire scenarios given, which will lead directly to the chosen scenario interface. The run button allows user to start the application, whereby the following selection of fire scenarios commands, appear on the interface (Figure 4.3).

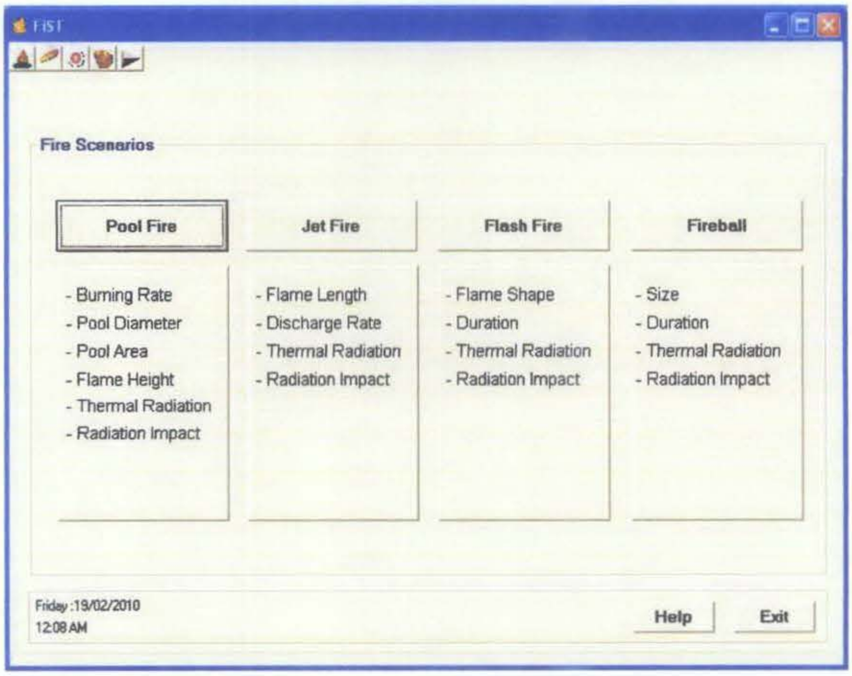

Figure 4.3: FiST main general interface after running application.

4.2.1 Help Command

The help interface is generated when the "Help" command is selected, which is shown by the following (Figure 4.4).

Figure 4.4: About FiST interface.

4.2.2 Exit Command

The "Exit" command terminates the FiST application, allowing user to exit the interface.

4.3 FIRE SCENARIOS INTERFACE

The fire scenarios interface is designed to calculate the four types of fires; Pool Fire, Jet Fire, Flash Fire and Fireball. Each of these fires has its own interface and the interface is capable of estimating different parameters. This report explains the development of the pool fire interface in detail. If user clicks on the pool fire command button, the application will gain access to the pool fire interface and display it. Figure 4.5 shows how the two interfaces are linked.

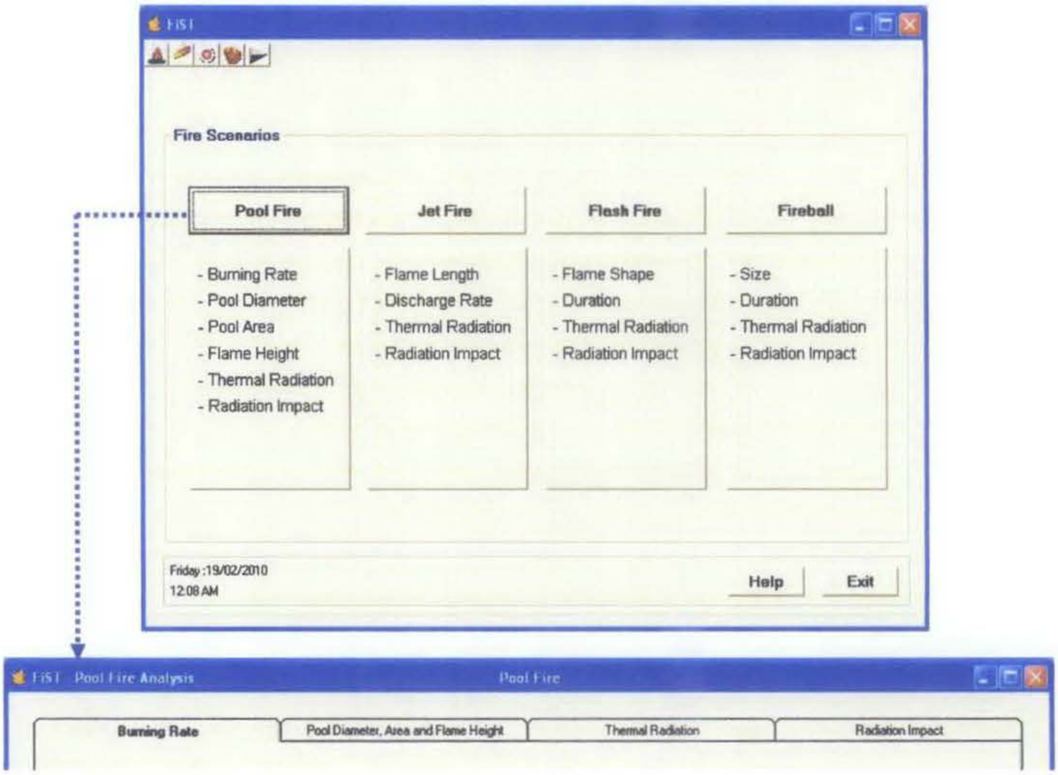

Figure 4.5: Fire Scenario interface (Pool Fire interface).

The text boxes which are located below the command button for the four types of fires consists of their parameters which act as a link, where by if user clicks on it, the user is directly linked to the tab at which the parameter is calculated.

The pool fire interface is designed using tabs control at which the calculation stages have been divided accordingly to simplify user's input and output data process. As shown in Figure 4.5, the pool fire interface consist of four tabs; burning rate; pool diameter, area and flame height; thermal radiation and radiation impact.

4.3.1 Burning Rate Tab

This page allows the user to calculate the burning rate of a pool fire, which has been divided into two sections, namely; vertical burning rate and mass burning rate (Figure 4.6). In obtaining the values for these parameters, the user is required to key in the input data first.

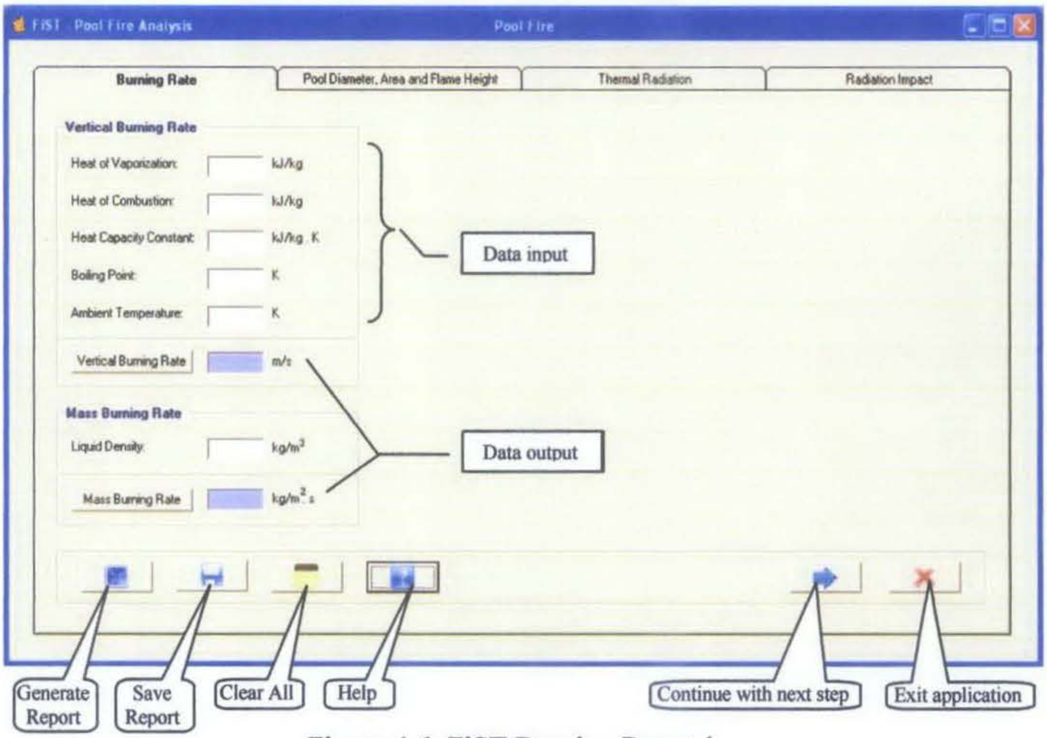

Figure 4.6: FiST Burning Rate tab.

The user is required to fill in all the fields and must not leave any empty in order to obtain the results and must perform the calculations from top to bottom and left to right in a sequential manner. For example, if the user wants to calculate the mass burning rate, the vertical burning rate must be calculated first. Prior to calculating the vertical burning rate, all the inputs for this parameter must be keyed in by the user. If the user failed to do so, an error message will be generated by the software to alert the user about the missing field(s) which has not been keyed in (Figure 4.7).

The burning rate interface allocates one section on the right hand side of the page to allow the user to generate a report after the simulation is successfully done. To generate a report, user can simply click on the generate report command button, whereby a white box will appear, showing a summary of the input and output data (Figure 4.8).

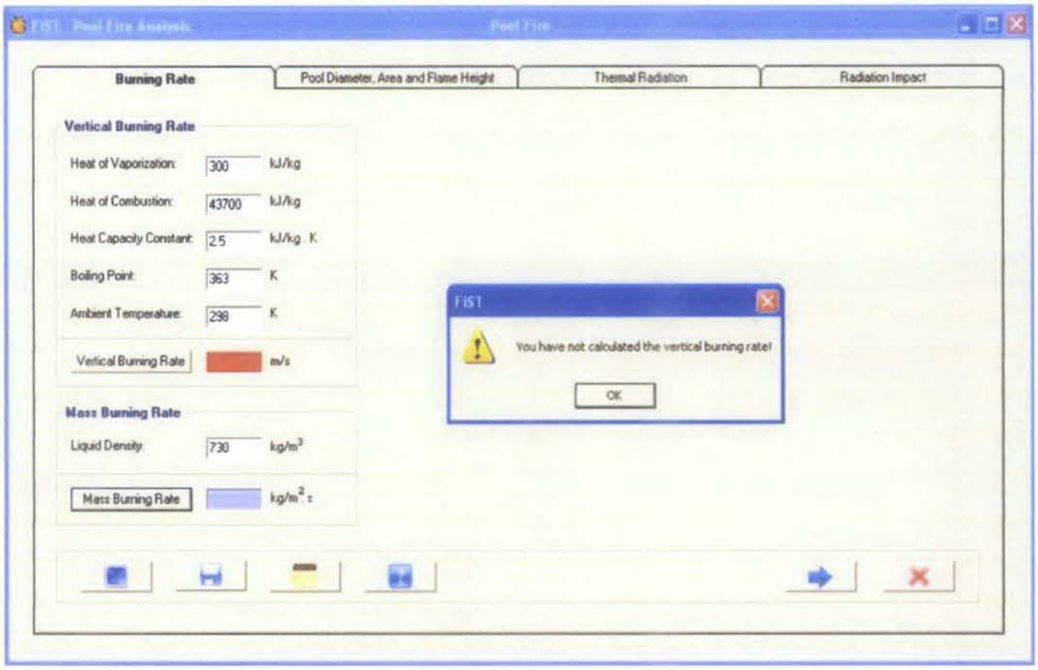

Figure 4.7: Error message generated by FiST.

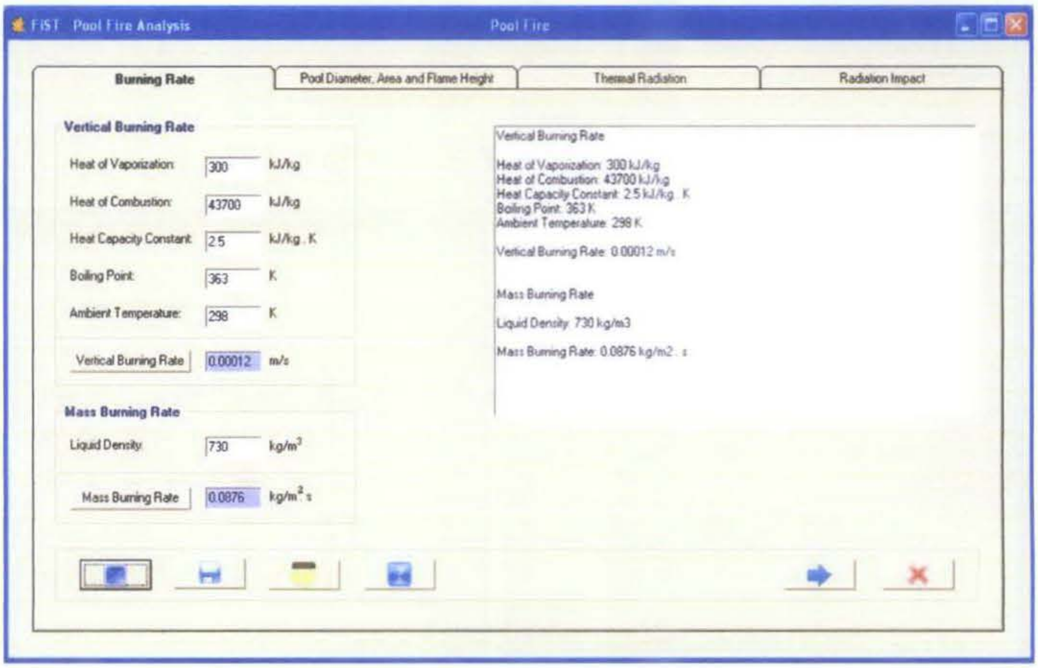

Figure 4.8: Generate report after simulation.

4.3.2 Pool Diameter, Area and Flame Height Tab

Figure 4.11 shows the pool diameter, area and flame height interface at which it has also been divided into two sections. The first section allows user to calculate the diameter and area of a pool fire whereas the second part is flame height. Like the burning rate tab, the same applies here whereby the calculations are required to perform in an orderly manner.

On the right hand side of the interface is a labelled picture/sketch of the pool fire at which as the user fills in the input data and generates the output, the responding values automatically appear at respective parameters in the picture/sketch (i.e. diameter and height). If user wishes to save image, a save image command button is available for that purpose (Figure 4.11).

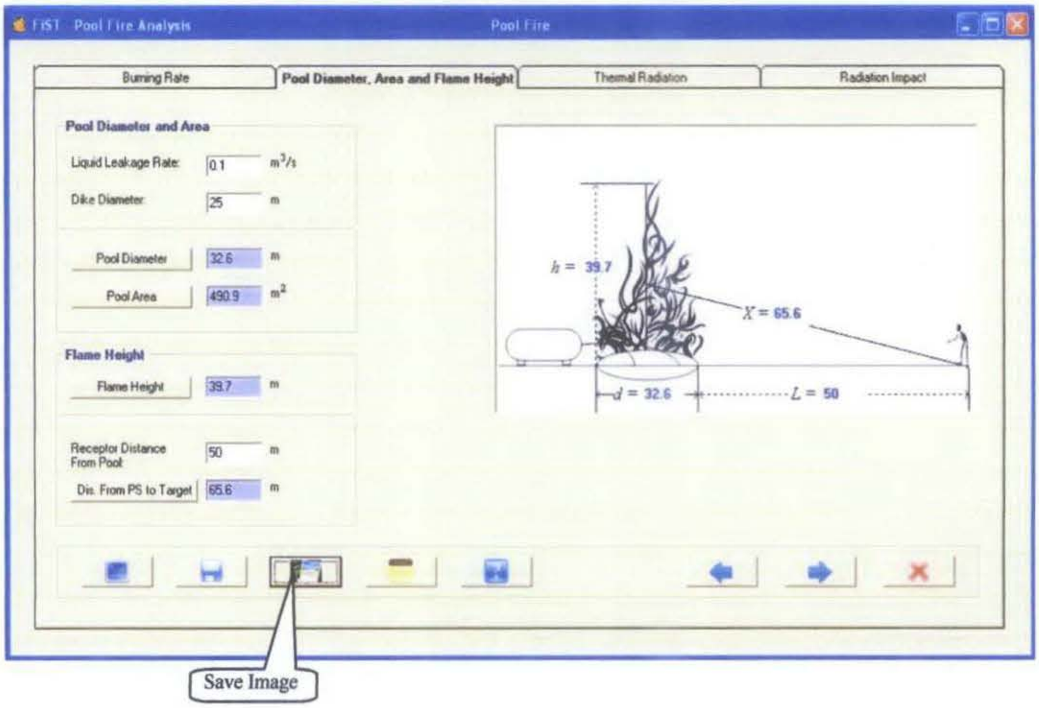

Figure 4.11: FiST Pool Diameter, Area and Flame Height tab.

4.3.3 Thermal Radiation Tab

This interface enables the user to calculate the thermal radiation of a pool fire, whereby only two inputs are required, which is the relative humidity and radiation efficiency (Figure 4.12). User may also generate a report for this tab, which will be displayed in the white blank box after clicking on the generate report command button.

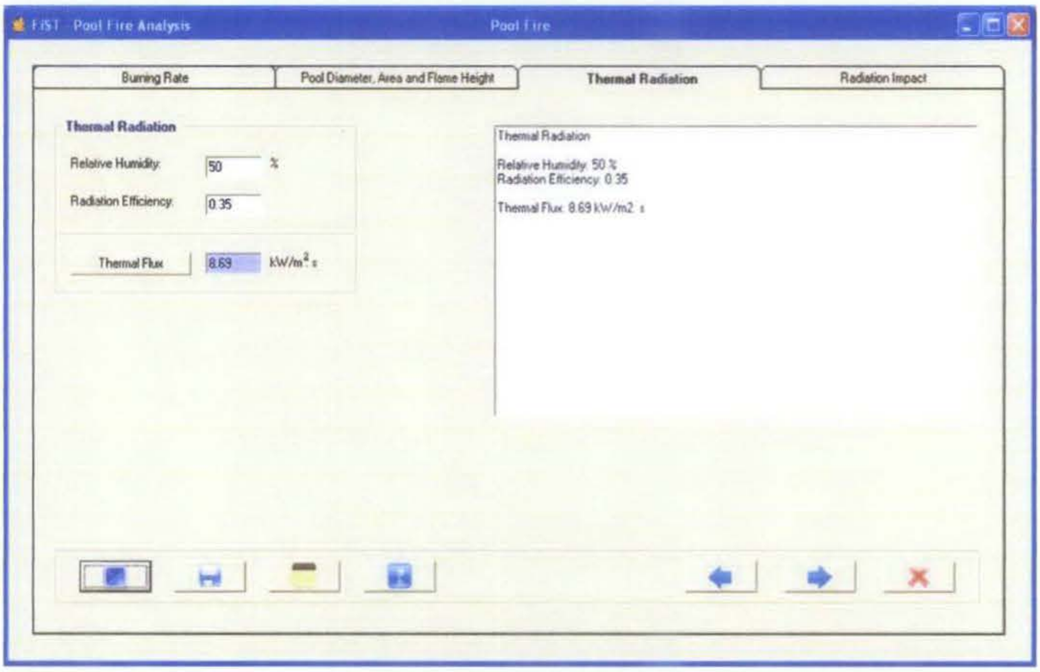

Figure 4.12: FiST Thermal Radiation tab.

4.3.4 Radiation Impact Tab

This tab allows user to determine the radiation impacts from the fire to personnel and also to structures. The results of computation for the radiation impact to personnel are presented in the interface shown in Figure 4.13 whereas for impact to structures, is shown in Figure 4.14. The impacts of the pool fire in terms of degree of burns is shown in a simplified representation whereby user is required to click on the respective values from the list box for it to appear in the image (Figure 4.13).

The input values are in a form of a text box and the results are displayed as a list box. The codes retrieve the information from the previous tabs, process it, and present the results as GUI, or text file, then display it through VB or Microsoft Excel for plotting or GIS for mapping visualization. Figure 4.15 and Figure 4.16 represent the graphs plotted using VB and Microsoft Excel.

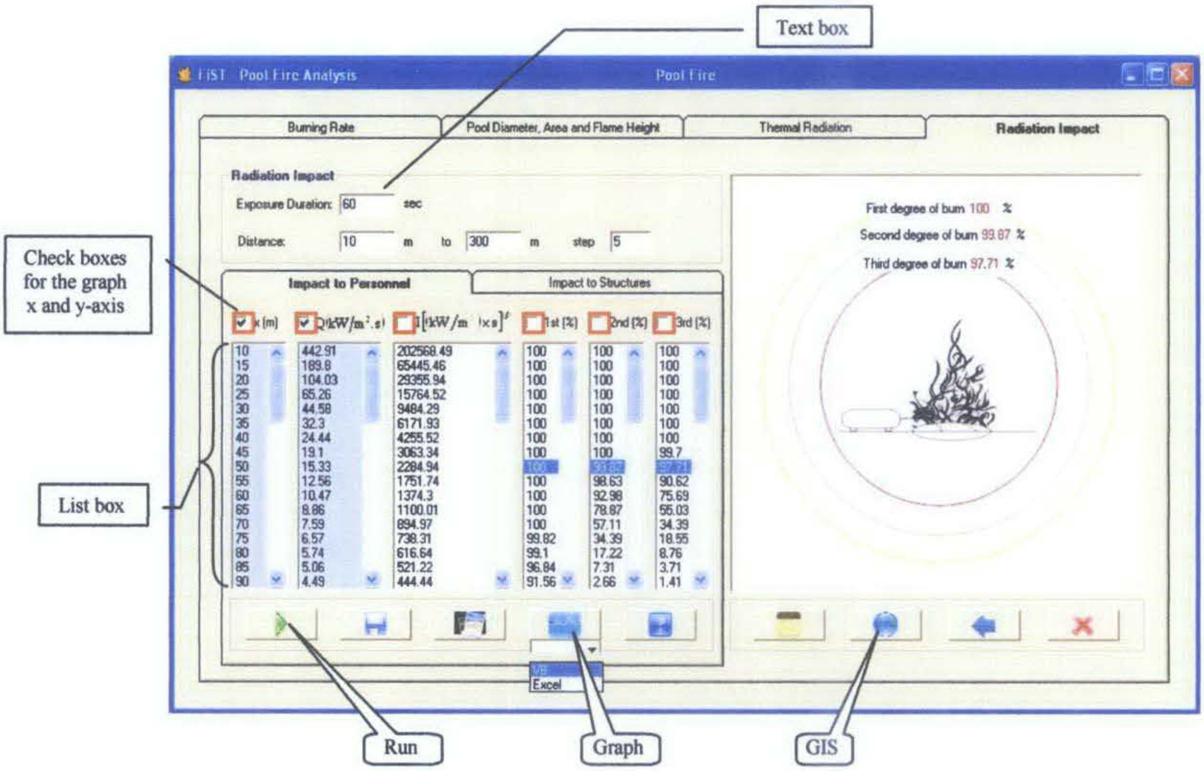

Figure 4.13: FiST Radiation Impact tab – Impact to Personnel.

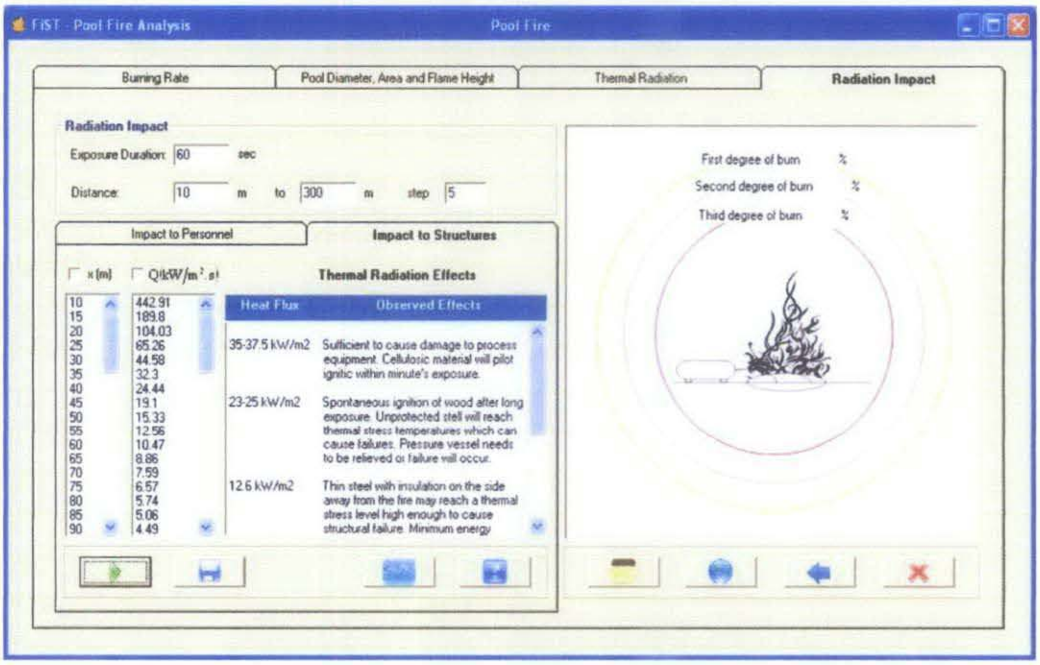

Figure 4.14: FiST Radiation Impact tab – Impact to Structures.

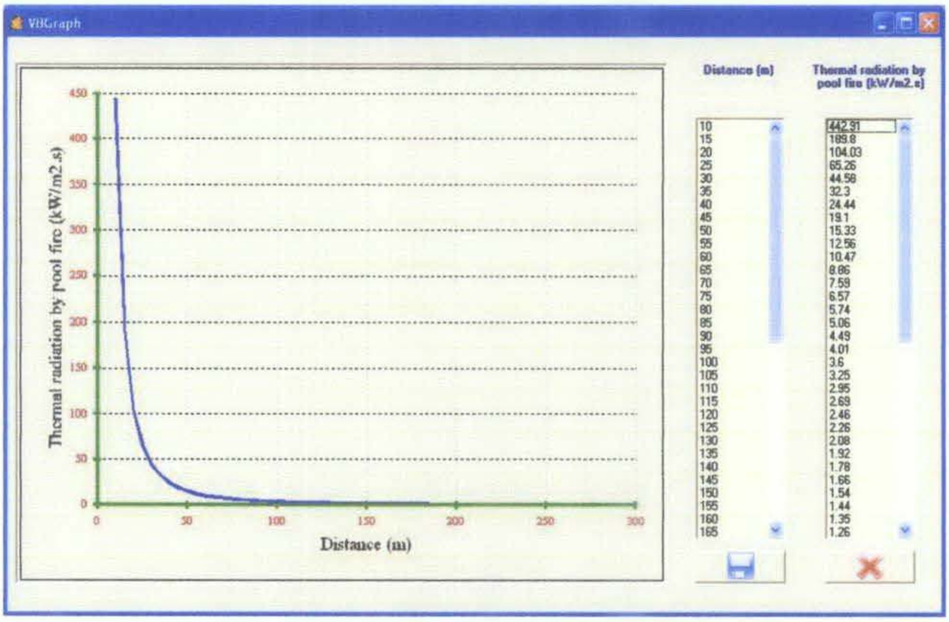

Figure 4.15: Thermal Radiation by Pool Fire (kW/m^2 s) vs. Distance (m) plotted using Visual Basic.

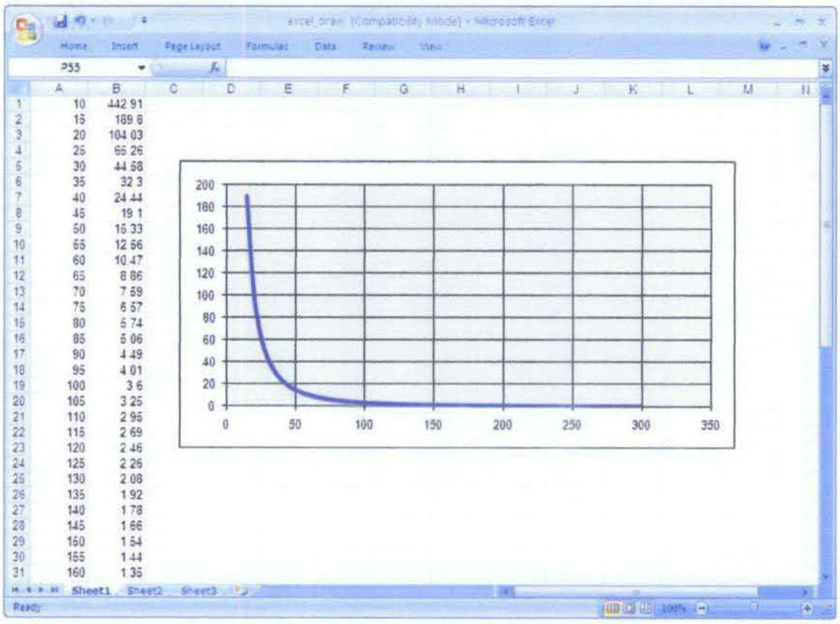

Figure 4.16: Thermal Radiation by Pool Fire (kW/m^2 s) vs. Distance (m) plotted using Microsoft Excel.

The interfaces development for flash fire, jet fire and fireball follow the same methodology as the pool fire described throughtout this report. Each fire scenario possesses different mathematical models and parameters whereby, the interfaces are built based on them accordingly.

4.3.5 Risk Tolerability Limit

Usually, the outcome from risk assessment is compared to some criteria so that decision can be made whether the risk is broadly acceptable or tolerable or if it is unacceptable. Based on the risk tolerability limits for Malaysia, risk levels of less than 1 x 10^{-6} per person per year may be used as involuntary risk level posed by industrial activities (DOE, 2004).

In incorporating Malaysian standards and regulations into the developed tool, the risk tolerability limit interface allows user to determine the tolerated risk from the fire impacts and compare it to Malaysia's risk tolerability limit. The probability of degree of burns field is automatically retrieved from the radiation impact tab by double clicking on the desired value from the list box. User is only required to key in the frequency/year value (Figure 4.17 and Figure 4.18).

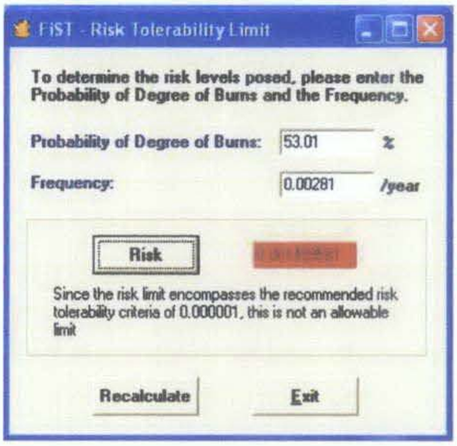

Figure 4.17: FiST risk tolerability limit interface – exceeding recommended risk.

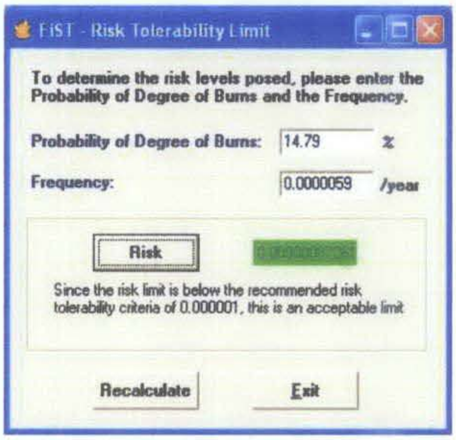

Figure 4.18: FiST risk tolerability limit interface – below recommended risk.

4.4 GEOGRAPHIC INFORMATION SYSTEMS (GIS) INTERFACE

The GIS interface provides options such as zoom in and out, navigation controls, determining radius covered from impact release point, create buffer zones, select map and print map. This interface is designed by adding the MapObjects component into VB (Figure 4.19 and Figure 4.20). The results of the worst-case consequence modelling calculations from the fire's thermal radiation impact can be presented on the map in a graphical form. The possible public exposure to the hazard region is presented as a circle around the point of release from the source.

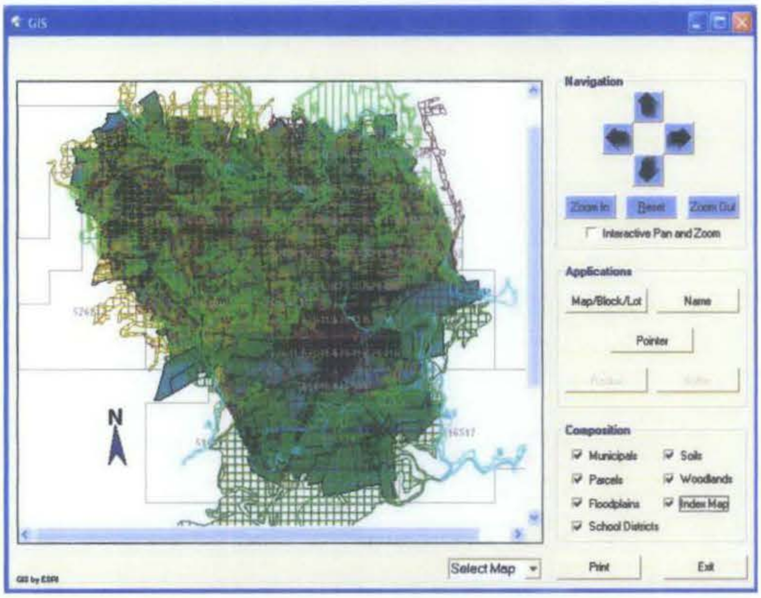

Figure 4.19: GIS interface – default map.

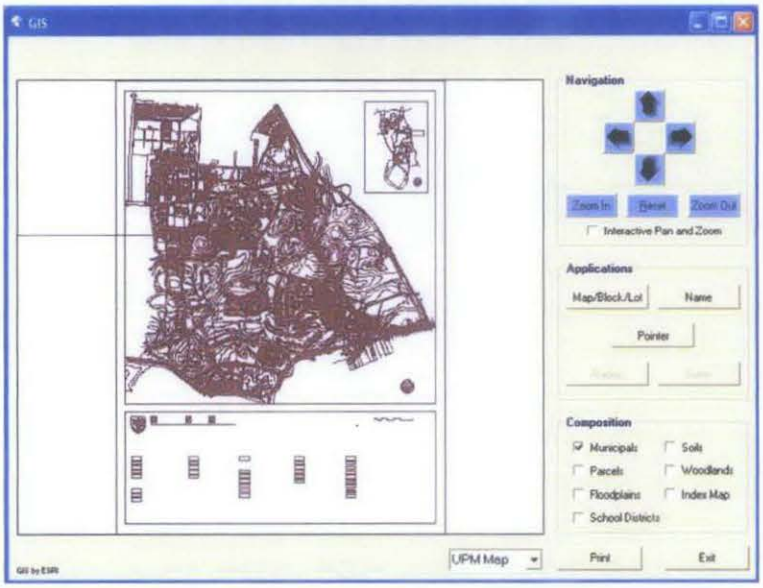

Figure 4.20: GIS interface – UPM map.

4.4 GEOGRAPHIC INFORMATION SYSTEMS (GIS) INTERFACE

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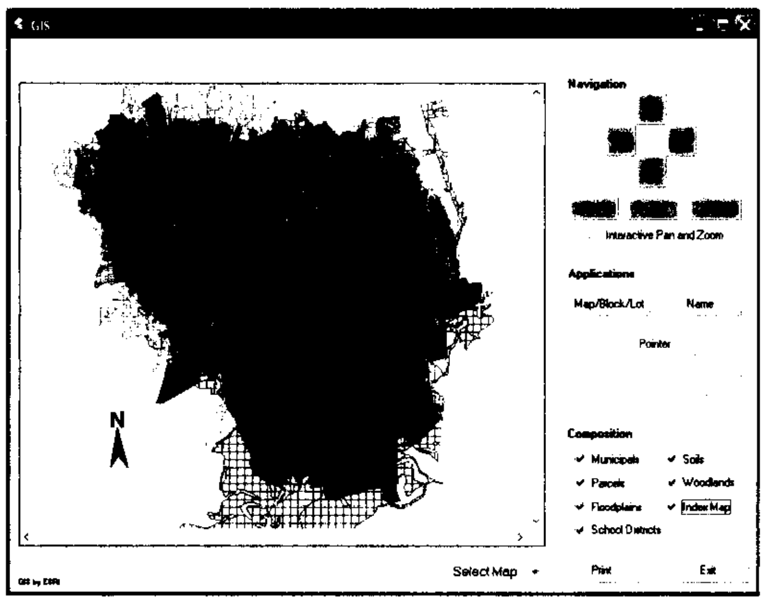

Figure 4.19: GIS interface – default map.

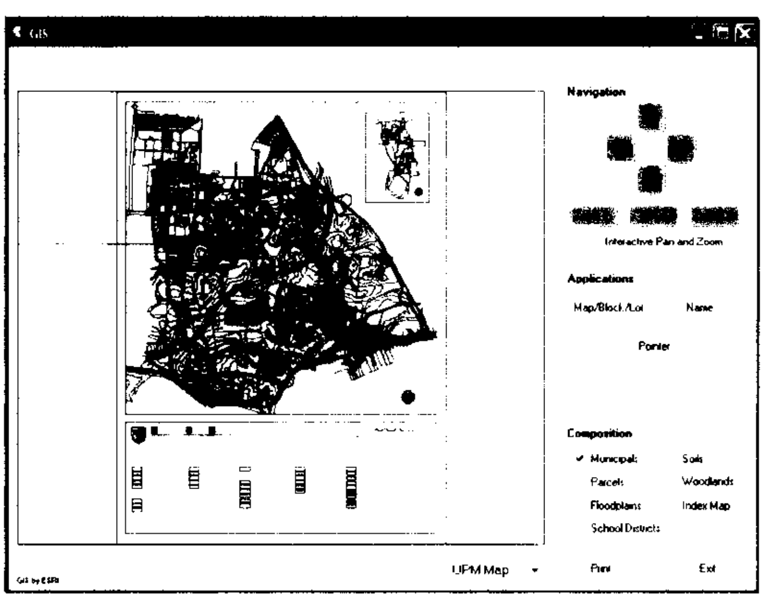

Figure 4.20: GIS interface – UPM map.

4.5 SOFTWARE VERIFICATION AND VALIDATION

Verification is the assessment of the accuracy of the solution to a computational model. The results generated by the application (i.e. for flash fire, jet fire, pool fire and fireball) were performed by referring to Andreassen *et al.*, (1992); Casal, (2008) and CCPS, (2000). Appendix C shows the sample of the calculations from the mentioned references above.

Validation on the other hand is the assessment of the accuracy of the model used and program developed by comparison with case study or other softwares. To confirm the validity of the FiST software, the results have been tested using established data and compared with results from published literature and a few risk assessment softwares.

4.5.1 Case Studies

The application of the FiST software for predicting the impact of fire requires the investigation of several accident scenarios. Therefore, three case studies that have been considered by other authors and softwares are compared with FiST. The descriptions for these studies are as follows:

Case study 1: BLEVE Incident Simulator (BIS)

BIS is a simulation software for LPG and propane BLEVE incidents. The BIS software was developed by ThermDyne Technologies Ltd with the help of Professor Birk Queen's University, a leading expert on BLEVEs and their consequences. This simulation software is intended as a basic training simulator for responding to BLEVE incidents. BIS studied various accident scenarios for 9119 kg propane tank incident.

Case study 2: Simulation of Chemical Industrial Accidents (SCIA)

The risk assessment study for 10,000 kg methane gas release has been carried out using SCIA software developed by El-Harbawi, (2006). It is capable of handling multiple and alternative accident scenarios, complex terrain dispersion and uncertain quantification (including parameter and model uncertainty). With the SCIA software, users can estimate the quantity of the substance(s) that could be released, the extension of the hazard zone created due to the release, and the number of casualties.

Case study 3: Mexico City

The risk assessment study has been carried out using FiST software to study the consequences from Mexico City disaster. In November, 1984, an enormous disaster involving an LPG installation occurred in Mexico City and resulted in the deaths of over 500 people. The LPG-facilities consisted of 6 spherical storage tanks (4 with a volume of 1600 m^3 and 2 with a volume of 2400 m^3). The facilities comprise additional 48 horizontal cylindrical bullet tanks of different sizes. The overall storage capacity is about 16,000 m^3.

4.5.1 Flash Fire

The results obtained from the FiST software are verified and validated with results from published literature and also from another software, which is available in Table 4.1. In estimating the flash fire hazards, it is found that the results obtained from FiST differs slightly with the results of Andreassen *et al*., (1992) due to the difference in decimal places. As for the comparison between the two softwares, it can be concluded that FiST has a good agreement with the results obtained from SCIA to estimate the flash fire hazards. The flash fire outputs from FiST for release of 10,000 kg methane are presented in Table D.1.

Table 4.1: Comparison on flash fire output results between FiST and Andreassen *et al.*, (1992).

Flash Fire Parameters	Results		
	From published literature	From other software	From current software
	Andreassen *et al.*, (1992)	SCIA, (2006)	FiST
Volume of flash fire (m^3)	833.40	834.98	835.40
Area of flash fire (m^2)	423.50	423.36	422.23
Life time (sec)	–	5702.93	6139.41
Half-life time (sec)	–	8.67	8.67
Effective duration time (sec)	24.50	26.01	26.01
Thermal radiation (kW/m^2) at 50 m	140.00	142.09	144.12

4.5.2 Jet Fire

The comparison between the FiST software results and results from Casal, (2008) to estimate the jet fire hazards is shown in Table 4.2. The two results show a good agreement regardless the variation of the results, which is mainly due to the difference in the decimal places. The results from the simulation have also been validated with other published literature. The comparisons in Table 4.3 are made between the results from FiST and CCPS, (2000) for the release of methane gas from a hole (25 mm diameter). It is noted for the two sets of results that the flame length and discharge rate show reasonable conformity. However, the thermal radiation intensity value varies significantly due to their difference in calculation methods. The solid flame model is applied in FiST for the calculation of thermal intensity whereby CCPS uses the point source model. Table D.2 shows the jet fire outputs from FiST for the release of butane gas.

Table 4.2: Comparison on jet fire output results between FiST and Casal, (2008).

Jet Fire Parameters	Results	
	Casal, (2008)	FiST
Flame length (m)	8.4	8.47
Lift-off distance (m)	0.3	0.31
Diameter of jet fire (m)	1.00	1.03
Flame area (m^2)	–	29.07
Discharge rate (kg/s)	0.447	0.445
Average emissive power (kW/m^2)	215	209.87
Thermal radiation intensity (kW/m^2)	4.5	4.64

Table 4.3: Comparison on jet fire output results between FiST and CCPS, (2000).

Jet Fire Parameters	Results	
	CCPS, (2000)	FiST
Flame length (m)	5.0	5.31
Discharge rate (kg/s)	8.37	6.754
Thermal radiation intensity (kW/m^2)	22.0	33.41

4.5.3 Pool Fire

The results obtained from FiST verify with the results obtained from the spreadsheet developed by CCPS, (2000). The comparison between the results is available in Table 4.4. However, the two parameters which shows a significant deviation is the distance from point source to target and thermal flux due to miscalculations in computing the distance from the center of the pool to the receptor. The dike's radius and the receptor distance from pool should be summed up (since point source is located at center of pool). CCPS on the other hand accounted for the dike's diameter instead. This variation of result directly affects the result obtained for the themal flux. The pool fire outputs from FiST for release of a hydrocarbon liquid is shown in Table D.3.

Table 4.4: Comparison on pool fire output results between FiST and CCPS, (2000).

Pool Fire Parameters	Results	
	CCPS, (2000)	FiST
Vertical burning rate (m/s)	0.00012	0.00012
Mass burning rate (kg/m^2 s)	0.0876	0.0876
Pool diameter (m)	32.57	32.57
Pool area (m^2)	490.87	490.87
Flame height (m)	39.72	39.72
Distance from point source to target (m)	77.58	65.579
Thermal flux (kW/m^2 s)	6.12	8.695

Table 4.5 is related to an example from TNO, (1992) by FiST software for the release of 28.3 m^3 of benzene. By applying an input of release rate (28.3 m^3) in the pool fire assessment using the FiST software, it is estimated that the flame height is equal to 69.80 m, the pool fire diameter is equal to 42.45 m, the area of the circular shaped pool is 1412 m^2 and the thermal flux (5.46 kW/m^2 s). In order to calculate the received heat flux at the target from the flame at a given location, the FiST software utilizes a point source model for assessing the impact of radiation from pool fire at which the received thermal flux is determined from the total energy rate from the combustion process.

Table 4.5: Comparison on pool fire output results between FiST and TNO, (1992).

Pool Fire Parameters	Results	
	TNO, (1992)	FiST
Material: Benzene		
Vertical burning rate (m/s)	–	0.00011
Mass burning rate (kg/m^2 s)	0.0850	0.0928
Pool diameter (m)	42.45	42.45
Pool area (m^2)	1415	1412
Flame height (m)	46.77	69.80
Distance from point source to target (m)	–	126.10
Thermal flux (kW/m^2 s)	4.58	5.46

Thermal radiation load is estimated based on the exposure time of 60 seconds for the release of 28.3 m^3 of benzene. Thermal dose unit is then converted to a first degree of burn, second degree of burn and third degree of burn by means of probit type relationships. The extent to which people are injured by exposure to thermal radiation depends on both the thermal flux and the exposure time. Figures 4.21, 4.22 and 4.23 show the probability of first degree burn, the probability of second degree burn and the probability of fatality, respectively.

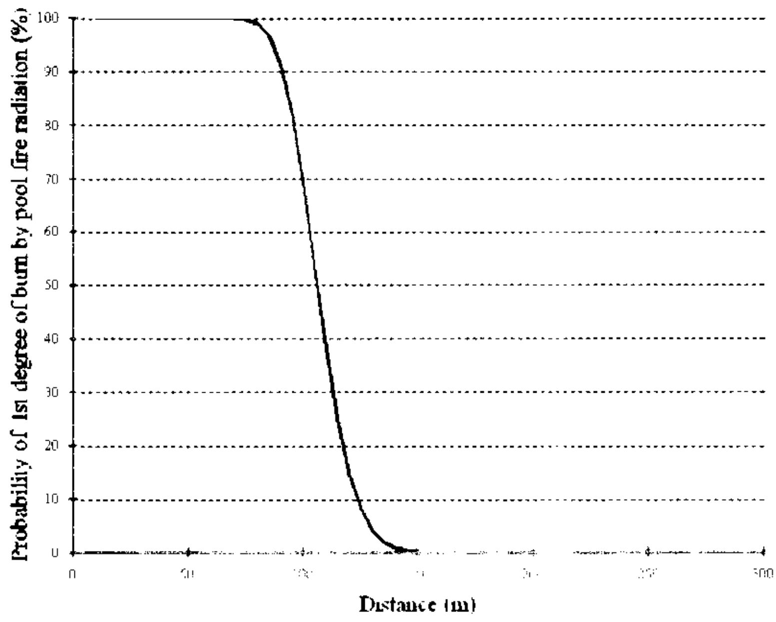

Figure 4.21: Probability of first degree of burn by thermal radiation from pool fire [predicted by the FiST software for release of 28.3 m^3 of benzene].

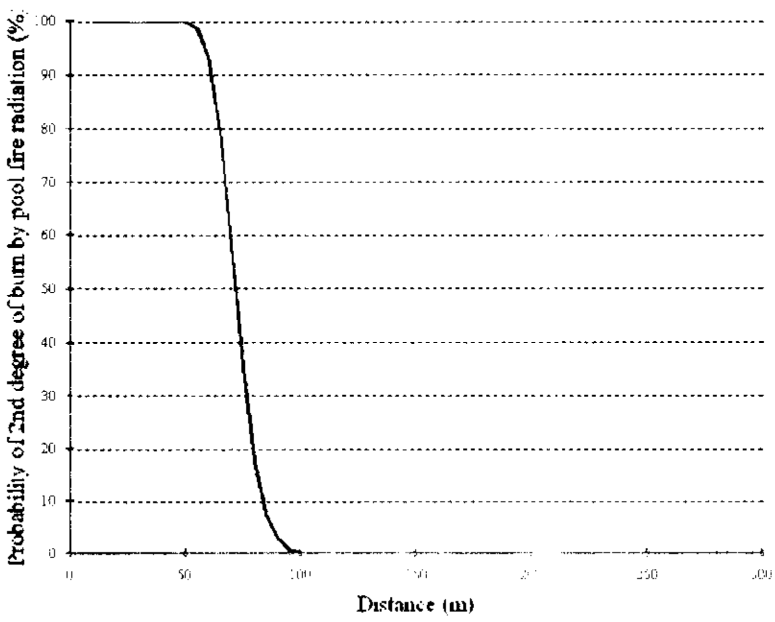

Figure 4.22: Probability of second degree of burn by thermal radiation from pool fire [predicted by the FiST software for release of 28.3 m^3 of benzene].

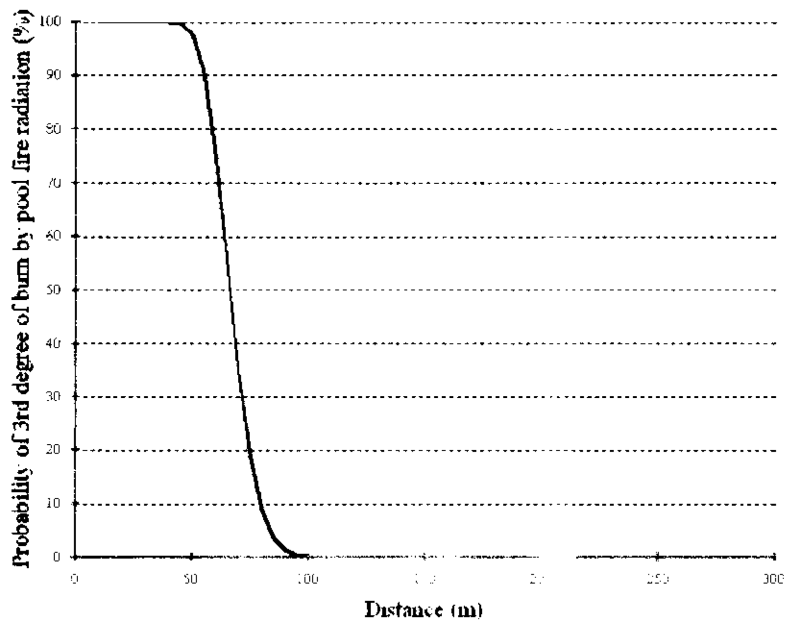

Figure 4.23: Probability of third degree of burn by thermal radiation from pool fire [predicted by the FiST software for release of 28.3 m^3 of benzene].

Eisenberg *et al.,* (1975) shows that the exposure time for the second degree of burn can be as low as 10 sec for a heat flux of 10 kW/m^2. Where the flux is only 5 kW/m^2, 10 sec exposure only results in the onset of pain. Mannan, (2005) considers a thermal dose of 3.5×10^4 $(kW/m^2)^{4/3} \times s$ for a 5 sec of exposure. It can be concluded from the release of 28.3 m^3 of benzene, that the 100% probability of first degree burn can appear at a distance of 70 m (Figure 4.21), and the 100% probability of second degree burn will appear at a distance of 45 m (Figure 4.22), while, the 100 % probability of third degree burn will appear at a distance of 40 m (Figure 4.23).

4.5.4 Fireball

Table 4.6 shows the comparison between the FiST software results and results from the spreadsheet developed by CCPS, (2000) to estimate the fireball hazards. It can be concluded that the results obtained from FiST has a good agreement with the results of CCPS, (2000). Table D.4 shows the fireball outputs from FiST for release of 100,000 kg propane.

Table 4.6: Comparison on fireball output results between FiST and CCPS (2000).

Fireball Parameters	Results	
	CCPS, (2000)	FiST
Maximum fireball diameter (m)	269	269
Fireball height (m)	202	201.8
Path length (m)	150	149.6
Combustion duration (sec)	17.7	17.7
Surface emitted flux (kW/m^2)	345	345.6
Received thermal flux for vertically oriented target (kW/m^2)	34.3	34.4
Received thermal flux for horizontal oriented target (kW/m^2)	–	34.6

FiST software has been validated using the fireball physical parameter results obtained from different software or with data from real accidents (Table 4.7). According to FiST, the maximum fireball radius estimated for a BLEVE of the 735,000 kg LPG is approximately 523 m and the fireball height and duration are 392.30 m and 24.70 sec respectively. These results are compared with FRED software and also from an accident which took place in Mexico City in 1985. A fireball diameter of 522.50 m is given by FRED software whereby a range of 200 – 300 m is reported to be seen from the real accident. The diameter of a fireball increases as the mass of fuel involved in the fireball increases. The values predicted by Figure 4.24 are almost equivalent to the others predicted by the experimental methods from work of High, (1968); Hardee *et al.,* (1978); Hasegawa and Sato (1978) and Satyanarayana *et al.,* (1991). Out of the four experimental methods, FiST shows the best agreement with Satyanarayana *et al.,* (1991).

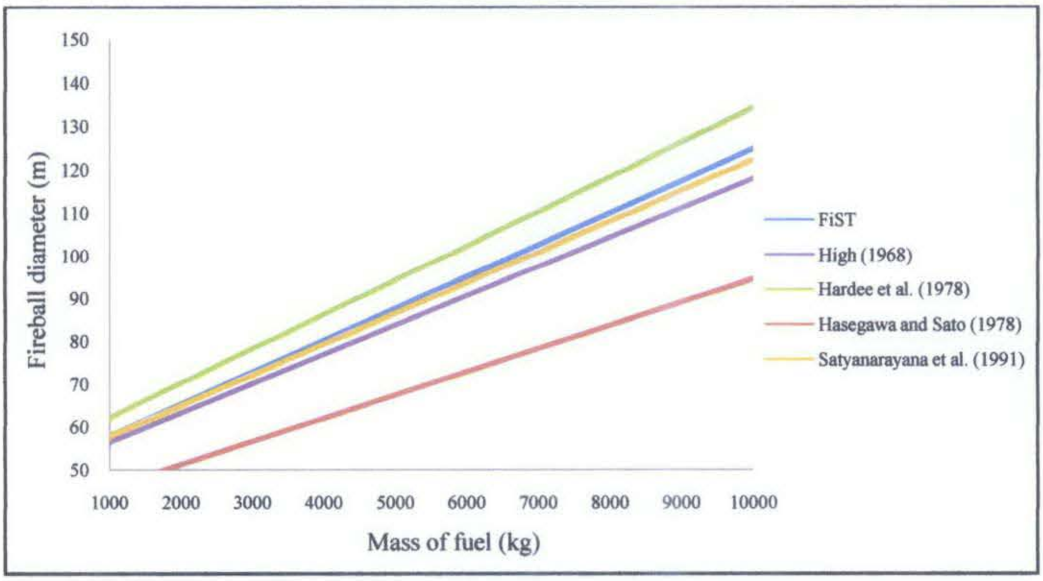

Figure 4.24: Experimental and calculated relationships between maximum fireball diameter and fuel mass.

Table 4.7: Comparison on fireball parameters between FiST with other softwares and reported data.

Fireball parameters	Results				
	From other softwares		**From previous accident**		**From current software**
	BIS, (2003)	**FRED, (2004)**	**Mexico City (1984)**		**FiST**
Chemical: **Propylene**					
Quantity stored (kg): 120,000					
Fireball diameter (m)		253.60			286.00
Fireball height (m)					214.50
Fireball duration (sec)		25.61			18.30
Chemical: **Propane**					
Quantity stored (kg): 9119					
Fireball diameter (m)	120	109.40			121.00
Fireball height (m)					90.80
Fireball duration (sec)	9.00	20.68			9.40
Chemical: **LPG**					
Quantity stored (kg): 70,000					
Fireball diameter (m)		243.40			239.00
Fireball height (m)					179.30
Fireball duration (sec)		15.49			16.7
Chemical: **LPG**					
Quantity stored (kg): 735,000			Reported	Calculated	
Fireball diameter (m)		522.50	200-300	520	523.00
Fireball height (m)			300		392.30
Fireball duration (sec)		28.55	20	29	24.70

FiST has considered the point source model for evaluating the thermal radiation from fireball hazard. Table 4.8 shows the thermal radiation results from FiST and the results are compared with other softwares. According to FiST, the radiation heat flux estimated for 9119 kg propane is approximately 21.40 kW/m^2 and for 70,000 kg LPG is 9.00 kW/m^2.

Table 4.8: Comparison on thermal radiation between FiST with other softwares.

Fireball parameters	Results		
	From other softwares		**From current software**
	FRED, (2004)	**SCIA, (2006)**	**FiST**
Chemical: **Propane**			
Quantity stored (kg): 9119			
Receptor distance (m): 138.2			
Radiation heat flux (kW/m^2)	25.74	24.00	21.40
Chemical: **LPG**			
Quantity stored (kg): 70,000			
Receptor distance (m): 500			
Radiation heat flux (kW/m^2)	8.72	9.33	9.00

4.6 HAZARD MAPPING

Geographic information systems (GIS) allow spatial relationships between populations and hazards to be examined and it can be useful for hazard identification and exposure assessment phases of risk assessment (El-Harbawi, 2006). The FiST software allows users to identify potential chemical hazards around the residential areas. To begin the scenario assessment, the GIS interface is accessed by clicking on the GIS icon in the thermal radiation tab.

Taking an example of a release of a hydrocarbon liquid from a tank, which has the potential of a pool fire accident, the hazard zone in Figure 4.25 would cover an area with a diameter of 90 m in the vicinity of the tank with a fatality of 99%. The details of the case study for pool fire hazards have been discussed in section 4.5.3.

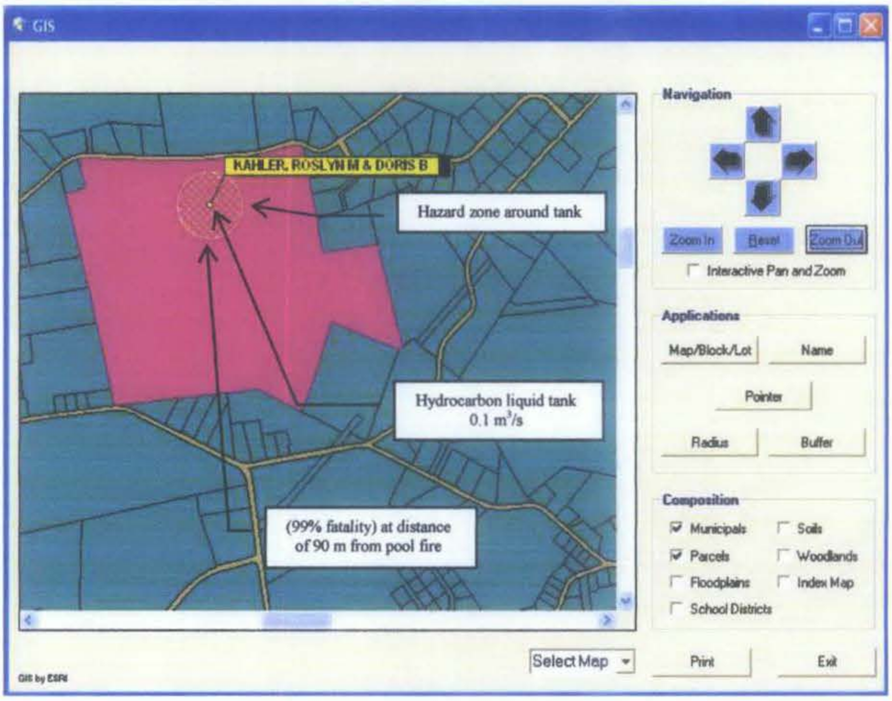

Figure 4.25: Potential hazard zone from pool fire around the accident center.

The hazard zone in Figure 4.26 illustrates the hazard footprint that would be expected when the rupture of a 9119 kg propane tank occurs. Within a range of 1410 m, humans receive 99% fatal burns from the thermal radiation 2599.69 $(kW/m^2)^{4/3} \times s$. The case study for fireball was assessed and discussed in section 4.5.4.

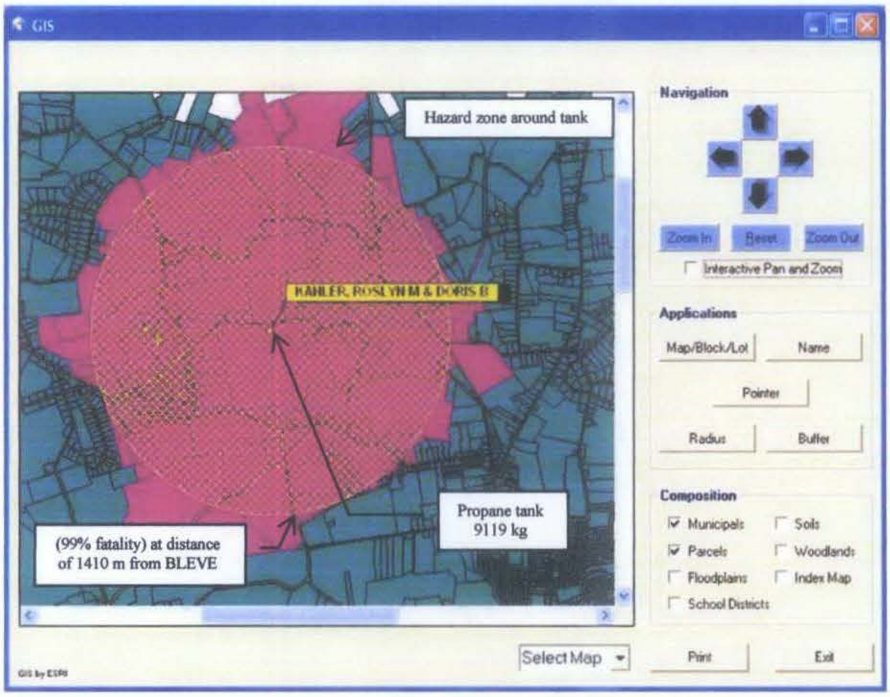

Figure 4.26: Potential hazard zone from BLEVE around the accident center.

CHAPTER 5
CONCLUSION

Consequence modelling plays an important role in assessing hazards for process industries. With the aid of mathematical models, the consequences of leakage resulting to fires may be obtained. However, the mathematical models are difficult to apply manually mainly because of the following reasons: (i) a large number of these calculations are required, (ii) the calculations involved are complicated and time consuming (iii) there are various event outcomes making it difficult to keep track of them, and (iv) unable to obtain the impacts representation since they are solely based on calculations. For these reasons, the estimation is best carried out by using a developed software.

This report describes the stages of the software's development. The application is called Fire Simulation Tool (FiST) and was developed using Visual Basic (VB) programming language to study the impact of fires in the process industry. FiST allows users to estimate the consequences from fire accidents, which includes the impacts of flash fire, jet fire, pool fire and fireball. Several different mathematical models were used for these fire scenarios. The results from these methods are verified and validated with other risk assessment softwares such as FRED (developed by Shell Global company, 2004), BIS (developed by ThermDyne Technologies Ltd, 2003), SCIA (developed by El-Harbawi, 2006) and with established data. The results from FiST are proven to be consistent with no significant deviation arising for all trials.

FiST is practical and feasible because it is user-friendly, able to function as a stand-alone application and it is compatible with all windows operating system. Furthermore, the application is integrated with GIS, which enables users to get better visualization on the impacts of fire through the mapping capabilities provided. By customizing MapObjects using VB, FiST acts as an effective graphical tool. In addition, Malaysian standards and regulations are incorporated into the developed tool for risk evaluation, whereby users are able to compare their results to the risk tolerability limit for Malaysia.

CHAPTER 6

RECOMMENDATIONS

1. Develop a chemical database containing the required information for input data (e.g. heat of capacity, heat of vaporization, etc.) at which user may add, delete and update them if necessary.
2. Link the results from the thermal radiation tab to the GIS form. By doing so, user is not required to key in the value into the GIS interface manually.
3. Enable user to upload and select map with different formats (e.g. JPEG, AutoCAD, etc.).

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APPENDICES

APPENDIX A

Table A.1: Gantt Chart for the First Semester of 2 – Semester Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14
1	Selection of Project Topic	■	■	■							Mid-Semester Break					
2	Preliminary Research Work		■	■	■											
3	Submission of Preliminary Report				●											
4	Project Work					■	■	■	■	■						
5	Submission of Preliminary Report									●						
6	Seminar (compulsory)									●						
7	Project Work Continues											■	■	■	■	■
8	Submission of Interim Report															●
9	Oral Presentation															●

● Suggested milestone
■ Process

Table A.2: Gantt Chart for the Second Semester of 2 – Semester Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	16	17	18	19	20
1	Project Work Continues	■	■	■	■				Mid-Semester Break													
2	Submission of Progress Report I					●																
3	Project Work Continues					■	■	■		■	■	■										
4	Submission of Progress Report II												●									
5	Poster Presentation/Pre-EDX/Seminar												■									
6	Submission of Dissertation (soft bound)														●							
7	Final Oral Presentation																			●	●	
8	Submission of Dissertation (hard bound)																					●

● Suggested milestone
■ Process

APPENDIX B

B.1 Flash Fire

B.1.1 Flame Shape

Eisenberg *et al.*, (1975) have proposed a model which assumes the flash fire to be a half ellipsoid. In this model the volume V_r and area of radiation A_r of a flash fire are given by the following equations:

$$V_r = \frac{2\pi}{3}\sigma_x\sigma_y\sigma_z\left(r_l^3 - r_u^3\right) \tag{B.1}$$

$$A_r = \frac{2\pi}{3}\left(\sigma_x^2 + \sigma_y^2 + \sigma_z^2\right)\left(r_l^3 + r_u^3\right) \tag{B.2}$$

with:

$$r_l = \left[2\ln\left(\frac{2\dot{m}}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z C_l}\right)\right]^{0.5} \tag{B.3}$$

$$r_u = \left[2\ln\left(\frac{2\dot{m}}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z C_u}\right)\right]^{0.5} \tag{B.4}$$

where

C_l is the concentration at lower explosion limit (kg/m^3)

C_u is the concentration at upper explosion limit (kg/m^3)

m is the total mass of gas (kg)

r_l is a parameter of gas cloud at lower explosion limit (-)

r_u is a parameter of gas cloud at upper explosion limit (-)

σ_x is the dispersion coefficient in the downwind direction (m)

σ_y is the dispersion coefficient in the crosswind direction (m)

σ_z is the dispersion coefficient in the vertical direction (m)

B.1.2 Heat Transfer Assessment

The net heat loss from a flash fire, Q (kW) is mainly by radiation which is given, according to Eisenberg *et al.* (1975), by the following equation:

$$Q_f = A_r\sigma\left(\varepsilon_g T_g^4 - \varepsilon_a T_a^4\right) \tag{B.5}$$

where

ε_g is the emissivity of the burning gas cloud (-)

T_g is the effective radiation temperature of the flash fire (K)

ε_a is the emissivity of the environment (-)

T_a is the ambient temperature (K)

σ is the Stefan Boltzmann's constant = 56.7 X 10^{-12} (kW/m^2 K^4)

Since the emissivity of both the burning gas cloud and the environment can be set to unity, Eq. (B.5) will be simplified to the following equation:

$$Q_f = A_r\sigma\left(T_g^4 - T_a^4\right) \tag{B.6}$$

The net effective thermal radiation heat flux, Q_n (kW/m^2) to a target at some distance from the flash fire is given by:

$$Q_n = F\sigma\left(T_g^4 - T_a^4\right) \tag{B.7}$$

where:

F is the view factor between the flash fire and the target (for close target, the view factor can be set equal to unity. Otherwise, the solid flame model will be used as presented below (TNO, 1992):

The view-factor for a cylindrical radiator

It can be assumed the plane of the receiver is oriented in such a manner that the normal to this plane and the centre line of the cylinder are located in one (vertical) plane (Figure B.1). The view factor is then dependent (beside h and x) on the orientation angle θ.

It can be defined:

$$h_r = \frac{h}{r} \tag{B.8}$$

$$x_r = \frac{x}{r} \tag{B.9}$$

$$A = (x_r + 1)^2 + h_r^2 \tag{B.10}$$

$$B = (x_r - 1)^2 + h_r^2 \tag{B.11}$$

Then, for a horizontal plane at ground-level $\left(\theta = \frac{\pi}{2}\right)$:

$$F_h = \frac{1}{\pi}\left\{\tan^{-1}\sqrt{\frac{x_r+1}{x_r-1}} - \frac{x_r^2 - 1 + h_r^2}{\sqrt{AB}}\tan^{-1}\sqrt{\frac{(x_r-1)A}{(x_r+1)B}}\right\} \tag{B.12}$$

And for a vertical plane at ground-level ($\theta = 0$):

$$F_v = \frac{1}{\pi}\left\{\frac{1}{x_r}\tan^{-1}\left(\frac{h_r}{\sqrt{x_r^2-1}}\right) + \frac{h_r(A-2x_r)}{x_r\sqrt{AB}}\tan^{-1}\sqrt{\frac{(x_r-1)A}{(x_r+1)B}} - \frac{h_r}{x_r}\tan^{-1}\sqrt{\frac{x_r-1}{x_r+1}}\right\} \quad \text{(B.13)}$$

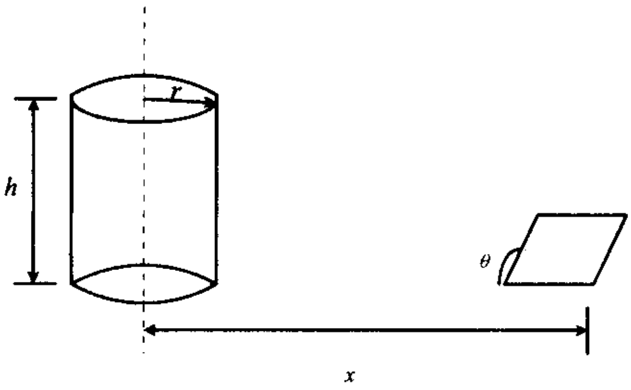

Figure B.1: Coordinate system for calculating a view factor for a vertical cylindrical radiator

B.1.3 Duration

The duration of flash fire can be found from the following Equation (Eisenberg *et al.*, 1975):

$$t = \frac{1}{2kT_a^3}\left\{\left[\tan^{-1}\left(\frac{T_g}{T_a}\right) - 0.5\ln\left(\frac{T_g-T_a}{T_g+T_a}\right)\right] - \left[\tan^{-1}\left(\frac{T_{gi}}{T_a}\right) - 0.5\ln\left(\frac{T_g-T_a}{T_{gi}+T_a}\right)\right]\right\} \quad \text{(B.14)}$$

where $k = A_r\sigma/\rho_b V_r$ and the subscript i means the initial value. The initial temperature of the hot gases, T_{gi}, is by Eisenberg et al., (1975) given to be the adiabatic flame temperature.

Eq. (B.14) may be rewritten in terms of the half-life time, $t_{1/2}$ (sec), of the flash fire,

$$t_{1/2} = \frac{1}{2kT_a^3}\left\{\left[\tan^{-1}\left(\frac{\beta+1}{2}\right) - \tan^{-1}\beta - 0.5\ln\left(\frac{\beta+1}{\beta+3}\right)\right]\right\} \quad \text{(B.15)}$$

where $\beta = T_{gi}/T_a$

The effective duration of the flash fire, t_{eff} (sec), is by Eisenberg, *et al.* (1975) given to be:

$$t_{eff} = 3 \times t_{1/2} \quad \text{(B.16)}$$

B.2 Jet Fire

B.2.1 Flame Height

There are various sets of equations proposed by different authors for predicting the shape and size of a jet fire, with significant scattering in the results. (i.e. for calm situations and the presence of wind). In a calm wind situation, the length of the flames in a jet fire can be estimated in a simple way (Hawthorne *et al.,* 1949).

Mudan and Croce (1988) provide a more detailed and recent review of jet flame modelling. The method begins with the calculation of the height of the flame. If we define the break point for the jet as the point at the bottom of the flame, above the nozzle, where the turbulent flame begins, then the flame height is given for turbulent gas jets burning in still air by

$$\frac{L}{d_{or}} = \frac{5.3}{c_{st-vol}}\left[\frac{T_{ad}}{\alpha_{st}T_{cont}}\left(c_{st} + (1-c_{st})\frac{M_a}{M_v}\right)\right]^{0.5} \tag{B.17}$$

where

L is the length of the visible flame, from the lift-off distance to the tip (m)

d_{or} is the orifice or exit diameter (m)

$c_{st\text{-}vol}$ is the mole fraction of fuel in stoichiometric fuel-air mixture (-)

T_{ad} is the adiabatic flame temperature (K)

T_{cont} is the jet fluid temperature (K)

M_a is the molecular weight of air = 29 (kg/kmol), and

M_v is the molecular weight of fuel (kg/kmol)

α_{st} is the ratio of the number of moles of reactants to moles of product for a stoichiometric fuel-air mixture (-)

For most fuels, $c_{st\text{-}vol}$ is typically much less than 1, α_{st} is approximately 1, and the ratio T_{ad}, T_{cont} varies between 7 and 9. These assumptions are applied to Eq. (B.17) resulting in the following simplified equation,

$$\frac{L}{d_{or}} = \frac{15}{C_{st-vol}}\left(\frac{M_a}{M_v}\right)^{0.5} \tag{B.18}$$

Mudan and Croce (1988) also provide expressions for the flame height considering the effects of crosswind.

The lift-off distance, s (m) can be estimated using the following expression given by Hawthorne *et al.*, (1949):

$$s = \frac{6.4\pi d_{or} u_j}{4u_{av}} \tag{B.19}$$

where

u_j is the exit velocity (m/s)

u_{av} is the average jet velocity (m/s) = $0.4u_j$

Finally, the diameter of the jet fire can be estimated as a function of its length using the following expression:

$$D_j = 0.29x\left[\ln\left(\frac{L+s}{x}\right)\right]^{0.5} \tag{B.20}$$

where

x is the axial distance from the orifice (m)

s is the lift-off distance (m)

B.2.2 Discharge Rate

$$m = A_{or}C_D P_1 \sqrt{\frac{2g_c M_v}{R_g T_1}\left(\frac{k}{k-1}\right)\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{k}} - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right]} \tag{B.21}$$

where

m is mass flow rate of gas through the hole (kg/s)

C_D is the discharge coefficient (-)

A_{or} is the area of the hole (m^2)

P_1 is the pressure upstream of the hole (N/m^2)

g_c is the gravitational constant (kg m/N s^2)

M_v is the molecular weight of the gas (mass/mole)

k is the heat capacity ratio, C_P/C_V (-)

R_g is the ideal gas constant (J/kmol)

T_1 is the initial upstream temperature of the gas (K)

P_2 is the downstream pressure (N/m^2)

As the upstream pressure P_1 decreases (or downstream pressure P_2 decreases), a maximum is found in Eq. (B.21). This maximum occurs when the velocity of the discharging gas reaches the sonic velocity. At this point, the flow becomes independent of the downstream pressure and is dependent only on the upstream pressure. The equation representing the sonic or choked case is:

$$m_{hole} = A_{or} C_D P_1 \sqrt{k \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \frac{M_v}{T_1 R_g 10^3}} \tag{B.22}$$

The pressure ratio required to achieve choking is given by

$$\frac{P_{choked}}{P_1} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{B.23}$$

The average surface emissive power, E (kW/m^2) may also be calculated according to the following equation (Andreassen *et. al.*, 1992):

$$E = \frac{\eta_{rad}\, m \Delta H_c}{A} \tag{B.24}$$

where

η_{rad} is the fraction radiated of total energy released (-)

B.2.3 Geometric View Factor

The view factor is one of the most important quantities to estimate accurately since the heat intensity experienced by an object is highly dependent on the distance and orientation of the object (DOW, 1993). The view factors are dependant on the position and on the orientation of the receiver with respect to the radiator. The calculations for the view factor of a vertical cylindrical radiator (for solid flame model) has been mentioned in part B.1.2.

B.2.4 Atmospheric Transmissivity

The atmospheric transmissivity accounts for the absorption of the thermal radiation by the atmosphere, essentially by carbon dioxide and water vapour. This attenuates the radiation that finally reaches the target surface. The atmospheric transmissivity depends on the distance between the flames and the target. While the carbon dioxide content in the atmosphere is essentially constant, the water vapour content depends on the temperature and the atmospheric humidity (Casal, 2008).

$$\tau = 1.53 \times (P_w d)^{-0.06} \quad \text{for} \quad P_w d < 10^4 N/m \tag{B.25}$$

$$\tau = 2.02 \times (P_w d)^{-0.09} \quad \text{for} \quad 10^4 \le P_w d \le 10^5 N/m \tag{B.26}$$

$$\tau = 2.85 \times (P_w d)^{-0.12} \quad \text{for} \quad P_w d > 10^5 N/m \tag{B.27}$$

where

P_w is the water partial pressure (N/m^2)

d is the distance between the surface of the flame and the target (m)

P_w can be estimated by the following expression:

$$P_w = P_{wa} \frac{H_R}{100} \tag{B.28}$$

where

P_{wa} is the saturated water vapour pressure at atmospheric temperature (N/m^2)

H_R is the relative humidity of the atmosphere (%)

P_{wa} can be obtained from the prevailing temperature of the atmosphere (K) given by Reid *et al.*, (1977):

$$\ln P_{wa} = 23.18986 - \frac{3816.42}{(T - 46.13)} \tag{B.29}$$

B.2.5 Heat Transfer

The solid flame model is applied for this case whereby the fire is assumed to be still, grey body encompassing the entire visible volume of the flames, which emits thermal radiation from its surface. The irradiance of the smoke (non visible flame) plume above the fire is partly taken into account. Most models apply the maximum length of the flame rather than the average one, and this includes some of the smoke volume above the flame (Casal, 2008). The thermal radiation intensity, I (kW/m^2) reaching a given target is

$$I = \tau . F . E \tag{B.30}$$

where

τ is the atmospheric transmissivity (-)

F is the view factor (-)

E is the average emissive power of the flames (kW/m^2)

The calculations for the view factor of a vertical cylindrical radiator has been mentioned in part B.1.2.

B.3 Pool Fire

B.3.1 Burning Rate

Large pool fires burn at a constant vertical rate, characteristic for the materials. Knowledge of the burning rate allows the heat output per unit area and the duration of the fire to be estimated (CCPS, 2000).

$$y_{\max} = 1.27 \times 10^{-6} \frac{\Delta H_c}{\Delta H^*} \tag{B.31}$$

where

y_{max} is the vertical rate of liquid level decrease (m/s)

ΔH_c is the net heat of combustion (kJ/kg)

ΔH^* is the modified heat of vaporization at the boiling point of the liquid given by Eq. (B.32) (kJ/kg)

Typical vertical rates are 0.7 x 10^{-4} m/s (gasoline) to 2 x 10^{-4} m/s (LPG).

The modified heat of vaporization includes the heat of vaporization, plus an adjustment for heating the liquid from the ambient temperature, T_a to the boiling point temperature of the liquid, T_{BP}.

$$\Delta H^* = \Delta H_v + \int_{T_a}^{T_{BP}} C_p dT \tag{B.32}$$

where

ΔH_v is the heat of vaporization of the liquid at ambient temperature (kJ/kg)

C_p is the heat capacity of the liquid (kJ/kg°C)

The equation above can be modified for mixtures, or for liquids such as gasoline which are composed of a number of materials (Mudan and Croce, 1988).

The mass burning rate of the pool fire, m_B (kg/m^2 s), given by CCPS (2000) is:

$$m_B = 1 \times 10^{-3} \frac{\Delta H_c}{\Delta H^*} \tag{B.33}$$

B.3.2 Flame Height

Bagster (1986) summarizes rules of thumb for H/D ratios: Parker (1973) suggests a value of 3 and Lees (1994) lists a value of 2. The flame height equation is given as:

$$\frac{H}{D} = 42 \left(\frac{m_b}{\rho_a \sqrt{gD}} \right)^{0.61} \tag{B.34}$$

where

H is the visible flame height (m)

D is the equivalent pool diameter (m)

m_B is the mass burning rate (kg/m^2 s)

ρ_a is the air density (1.2 kg/m3 at 20°C and 1 atm.)

g is the acceleration of gravity (9.81 m/s^2)

B.3.3 Pool Diameter

In most cases, pool size is fixed by the size of the release and by local physical barriers (e.g., dikes, sloped drainage areas). For a continuous leak, on an infinite flat plane, the maximum diameter is reached when the product of burning rate and surface area equals the leakage rate.

$$D_{max} = 2\sqrt{\frac{\dot{V}_L}{\pi y}} \quad \text{(B.35)}$$

where

D_{max} is the equilibrium diameter of the pool (m)

V_L is the volumetric liquid spill rate (m^3/s), and y is the liquid burning rate (m/s)

Eq. (B.35) assumes that the burning rate is constant and that heat transfer is from the flame. More detailed pool burning geometry models are available (Mudan and Croce, 1988).

B.3.4 Geometric View Factor

The calculations for the view factor of a vertical cylindrical radiator (for solid flame model) has been mentioned in part B.1.2.

Eq. (B.36) on the other hand assumes that all radiation arises from a single point and is received by an object perpendicular to this. This view factor must only be applied to the total heat output, not to the flux. Other view factors based on specific shapes (i.e., cylinders) require the use of thermal flux and are dimensionless. The point source view factor provides a reasonable estimate of received flux at distances far from the flame. At closer distances, more rigorous formulas or tables are given by Hamilton and Morgan (1952), Crocker and Napier (1986), and TNO (1979).

$$F_P = \frac{1}{4\pi x^2} \quad \text{(B.36)}$$

where

F_p is the point source view factor (m^{-2})

x is the distance from the point source to the target (m)

The path length and distance from the flame surface to the target is (CCPS, 2000):

$$x = \left[H^2 + [(D/2) + L]^2\right]^{0.5} \qquad \text{(B.37)}$$

where

L is the receptor distance from pool (m)

B.3.5 Atmospheric Transmissivity

The atmospheric transmissivity is an important factor. Thermal radiation is absorbed and scatted by the atmospheric. (Pietersen and Huerta, 1984), recommend a correlation formula that accounted for humidity:

$$\tau = 2.02(P_w X_s)^{-0.09} \qquad \text{(B.38)}$$

where

P_w is water partial pressure (N/m^2), and

X_s is distance from flame axis to receptor length (m)

B.3.6 Heat Transfer

The computation of the received thermal flux is dependent on the radiation model selected. There are two basic types of thermal radiation models, namely, the point source model and the plume fire model (Mudan *et al.*, 1995). If the point source model is selected, then the received thermal flux is determined from the total energy rate from the combustion process. If the solid plume radiation model is selected, the received flux is based on correlations of the surface emitted flux:

Point Source Radiation Model

The model overestimates the intensity of thermal radiation at locations close to the fire because in the near field, the radiation is greatly influenced by the flame size, shape, tilt and orientation of the observer.

The total energy rate from the combustion, Q_r (kJ/s) may be expressed in the following way:

$$Q_r = \eta m_B \Delta H_c A \qquad \text{(B.39)}$$

where

n is the fraction of the combustion energy radiated, typically 0.15 to 0.35

m_B is the mass burning rate (kg/m^2 s)

ΔH_c is the heat of combustion for the burning liquid (kJ/kg)

A is the total area of the pool (m^2)

Therefore the thermal flux received at the target, E_r (kW/m^2) is given by:

$$E_r = \tau Q_r F_P = \tau \eta m_B \Delta H_c A F_P \qquad \text{(B.40)}$$

where

τ is the atmospheric transmissivity (-)

Q_r is the total energy rate from the combustion (kJ/s)

F_P is the point source view factor (m^{-2})

The Solid Flame Model

The solid flame model is the most usual method used and which yields the most accurate results, both in the near and far field of any fire. This model considers the flame as a body which emits thermal radiation. The shape or geometry of this body may be idealized as a cylinder or a cone for all fires expects the fireball scenario which may be idealized as a sphere.

The surface emitted power or radiated heat flux maybe computed from the Stefan-Boltzman equation. This is very sensitive to the assumed flame temperature, as radiation varies with temperature to the fourth power. Further, the obscuring effect of smoke substantially reduces the total emitted radiation integrated over the whole flame surface (CCPS, 2000).

The surface emissive power depends on the fuel type and the pool diameter. The correlation of the following form is given by Mudan and Croce (1988):

$$E = E_{max} \exp(-sD) + E_g [1 - \exp(-sD)] \qquad \text{(B.41)}$$

where

E_{max} is the maximum emissive power of luminous spots (approx 140 kW/m^2)

E_g is the emissive power of smoke ((approx. 20 kW/m^2), Hagglund and Perssonnm (1976))

s = 0.12m^{-1} = experimentally determined parameter

The radiative flux onto a target is given by:

$$E_r = E\,F_{21}\,\tau \qquad (B.42)$$

where

E is the surface emissive power (kW/m^2)

F_{21} is the solid plume view factor (-)

τ is the atmospheric transmissivity (-)

B.4 Fireball

The catastrophic release of a substantial amount of flammable liquid will give rise, upon ignition, to a particular fire which goes under the name of fireball, and the major consequences of such a phenomenon are due to thermal radiation (CCPS, 2000).

B.4.1 BLEVE Size and Duration

Maximum fireball diameter (m): $D_{max} = 5.8M^{1/3}$ (B.43)

Fireball combustion duration (sec):

$$t_{BLEVE} = 0.45M^{1/3} \text{ for } M < 30{,}000 \text{ kg} \qquad (B.44)$$

$$t_{BLEVE} = 2.6M^{1/6} \text{ for } M > 30{,}000 \text{ kg} \qquad (B.45)$$

Center height of fireball (m): $H_{BLEVE} = 0.75D_{max}$ (B.46)

Initial ground level hemisphere diameter (m): $D_{initial} = 1.3D_{max}$ (B.47)

where

M is the initial mass of flammable liquid (kg)

B.4.2 Surface Emitted Flux

The four parameters used to find a fireball's thermal radiation hazard are mass of fuel, fireball's diameter, duration, and thermal emissive power.

$$E = \frac{RMH_c}{\pi D^2_{max} t_{BLEVE}} \qquad (B.48)$$

where

E is the radiative emissive flux (kW/m^2)

R is the radiative fraction of the heat of combustion (-)

M is the initial mass of fuel in the fireball (kg)

H_c is the net heat of combustion per unit mass (kJ/kg)

D_{max} is the maximum diameter of the fireball (m)

t_{BLEVE} is the duration of the fireball (sec)

Hymes (1983) suggests the following values for R:

- 0.3 for fireballs from vessels bursting below the relief set pressure
- 0.4 for fireballs from vessels bursting at or above the relief set pressure.

B.4.3 Geometric View Factor

As the effects of a BLEVE mainly relate to human injury, a geometric view factor for a sphere to a receptor is required. In the general situation, a fireball center has a height, H, above the ground. The distance L is measured from a point at the ground directly beneath the center of the fireball to the receptor at ground level. For a horizontal surface, the view factor is given by

$$F_{21} = \frac{H(D/2)^2}{(L^2 + H^2)^{3/2}} \tag{B.49}$$

where D is the diameter of the fireball. When the distance, L, is greater than the radius of the fireball, the view factor for a vertical surface is calculated from

$$F_{21} = \frac{L(D/2)^2}{(L^2 + H^2)^{3/2}} \tag{B.50}$$

B.4.4 Atmospheric Transmissivity

The atmospheric transmissivity accounts for the fact that the emitted radiation is partly absorbed by the air present between the radiator and the radiated object (TNO, 1992). It is an important factor, as typically 20-30% of the heat flux may be absorbed or scattered by the atmosphere over a distance of 100 m under typical conditions. Some thermal radiation models ignore this effect. For longer path lengths (over 20 m), where absorption could be 20-40 %, this well result in a substantial overestimate for received radiation (CCPS, 1995).

The calculation for the atmospheric transmissivity has been mentioned in part B.3.5. The path length and distance from the flame surface to the target is (CCPS, 2000):

$$X_s = \left[H_{BLEVE}^2 + L^2\right]^{0.5} - \left[0.5D_{max}\right] \tag{B.51}$$

B.4.5 Received Thermal Flux

The radiation received by a receptor (for the duration of the BLEVE incident) is given by:

$$E_r = \tau E F_{21} \qquad \text{(B.52)}$$

where

E_r is the surface emissive power (kW/m^2)

F_{21} is the view factor (-)

τ is the atmospheric transmissivity (-)

APPENDIX C

C.1 Example Problem for Flash Fire, Andreassen *et. al* (1992)

6.2.7 Example

A total mass of 10000 kg of LNG is released into the atmosphere: The vapour cloud of LNG is formed. The cloud encounters an ignition source approximately 100 m from the release point. The volume and area of radiation of the resulting flash fire shall be predicted as well as its effective duration and average radiation intensity on the ground just below the flash fire.

Solution:

1. Define necessary input data:

- concentration at lower explosion limit:	3.5 kg/m^3
- concentration at upper explosion limit:	12.4 kg/m^3
- adiabatic flame temperature (Methane):	1950 °C = 2223 K
- ambient temperature:	10 °C = 283 K
- density of hot gas layer (air at T_g = 1500 K):	0.25 kg/m^3
- downwind dispersion coefficient:	5.6 m
- crosswind dispersion coefficient:	4.0 m
- dispersion coefficient in the vertical direction:	3.8 m

2. Prediction of volume and area of radiation:

Eq. (6.3) predicts r_l = 1.70 and Eq. (6.4) predicts r_u = 0.61. Thus, from Eq. (6.2) the area of radiation of the flash fire is predicted to: <u>423.5 m^2</u>
and Eq. (6.1) predicts a volume of the flash fire of: <u>833.4 m^3</u>

3. Effective duration of the flash fire:

From Eq. (6.13) combined with Eq. (6.14), the effective duration of the flash fire can be predicted to: <u>24.5 sec.</u>

4. Radiation intensity to a target just below the flash fire:

In this case the flash fire is rather close to the target and the view factor can be taken equal to unity. For an average flash fire temperature of (1950 + 10)/2 = 980°C, the incident radiation intensity will be according to Eq. (H.11) when assuming an emissivity of the burning vapour cloud of unity: <u>140 kW/m^2</u>

Human beings with no protective clothing will achieve full blister within a second. A heat flux of that level will be lethal within a very short time.

C.2 Example Problem for Jet Fire, Casal (2008)

Example 3-6

A cylindrical tank containing butane has been heated to 51 °C. Gas is vented upwards from a release device (outlet internal diameter: 0.025 m) located on the top of the tank, 4 m above ground (Fig. 3-11). There is no wind. Estimate the maximum thermal radiation on the wall of a tank located at a horizontal distance of 9 m from the jet axis, at a height of 4.5 m above the ground.

ΔH_c = 45700 kJ kg^{-1}, γ = 1.11. Constants in the Antoine equation for butane: A = 4.35576, B = 1175.58, C = -2.071. Ambient temperature = 18 °C. Relative humidity = 50%.

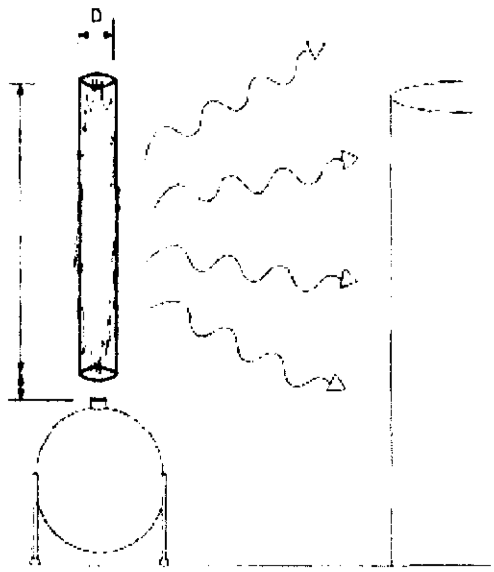

Fig. 3-11. Jet fire in a calm situation.

Solution

The combustion reaction is:

$$C_4H_{10} + \frac{13}{2} O_2 \rightarrow 4CO_2 + 5H_2O$$

$$c_{st-mf} = \frac{1}{1 + \frac{13}{2}\frac{1}{0.21}} = 0.0313$$

Estimation of the length of the flame using Eq. (3-58):

$$L = 0.025 \frac{15}{0.0313}\left(\frac{29}{58}\right)^{1/2} = 8.4 \text{ m}$$

Estimation of the lift-off distance using Eq. (3-59):

$$s = \frac{6.4\ \pi\ 0.025\ u_j}{4 \cdot 0.4\ u_j} = 0.3 \text{ m}$$

Pressure inside the vessel:

$$\log P = 4.35576 - \frac{1175.58}{324 - 2.071} \; ; P = 5 \text{ bar.}$$

Calculation of the mass flow rate of fuel using Eq. (2-19):

$$m' = \pi \frac{0.025^2}{4} 0.62 \cdot 5 \cdot 10^5 \sqrt{1.11 \left(\frac{2}{1.11+1} \right)^{\frac{1.11+1}{1.11-1}} \frac{58}{324 \cdot 8.314 \cdot 10^3}} = 0.447 \text{ kg s}^{-1}$$

For butane jet fires, Brzustowski [35] obtained the following value for the radiant heat fraction: $\eta_{rad} = 0.3$. If the jet fire is assumed to be a cylinder, from Eq. (3-60) an average diameter $D \approx 1$ m is obtained.
Estimation of the average emissive power using Eq. (3-27):

$$E = \frac{0.3 \cdot 0.447 \cdot 45{,}700}{\pi \cdot 1 \cdot 8.4 + 2\pi \frac{1^2}{4}} = 215 \text{ kW m}^{-2}$$

Estimation of the view factor from Table (3-4): $F_v = 0.0238$. For a relative humidity of 50% and $l = 9$ m, $\tau = 0.88$. Therefore, the thermal radiation intensity (Eq. (3-20)) is:

$$I = 0.0238 \cdot 215 \cdot 0.89 = 4.5 \text{ kW m}^{-2}$$

C.3 Example Problem for Pool Fire, CCPS (2000)

2.2.6.3. EXAMPLE PROBLEM

Example 2.30: Radiation from a Burning Pool. A high molecular weight hydrocarbon liquid escapes from a pipe leak at a volumetric rate of 0.1 m^3/s. A circular dike with a 25 m diameter contains the leak. If the liquid catches on fire, estimate the thermal flux at a receiver 50 m away from the edge of the diked area. Assume a windless day with 50% relative humidity. Estimate the thermal flux using the point source and the solid plume radiation models.

Additional Data:

Heat of combustion of the liquid:	43,700 kJ/kg
Heat of vaporization of the liquid:	300 kJ/kg
Boiling point of the liquid:	363 K
Ambient temperature:	298 K
Liquid density:	730 kg/m^3
Heat capacity of liquid (constant):	2.5 kJ/kg-K

Solution: Since the fuel is a high molecular weight material, a sooty flame is expected. Equations (2.2.51) and (2.2.53) are used to determine the vertical burning rates and the mass burning rates, respectively. These equations require the modified heat of vaporization, which can be calculated using Eq. (2.2.52):

$$\Delta H^* = \Delta H_v + \int_{T_a}^{T_{BP}} C_p \, dT$$

$$= 300 \text{ kJ/kg} + (2.5 \text{ kJ/kg K})(363 \text{ K} - 298 \text{ K}) = 462 \text{ kJ/kg}$$

The vertical burning rate is determined from Eq. (2.2.51):

$$\dot{y}_{max} = 1.27 \times 10^{-6} \frac{\Delta H_C}{\Delta H^*} = (1.27 \times 10^{-6})\left(\frac{43{,}700 \text{ kJ/kg}}{462 \text{ kJ/kg}}\right) = 1.20 \times 10^{-4} \text{ m/s}$$

The mass burning rate is determined by multiplying the vertical burning rate by the density of the liquid:

$$m_B = \rho \dot{y}_{max} = (730 \text{ kg/m}^3)(1.20 \times 10^{-4} \text{ m/s}) = 0.0876 \text{ kg/m}^2 \text{ s}$$

The maximum, steady state pool diameter is given by Eq. (2.2.54),

$$D_{max} = 2\sqrt{\frac{\dot{V}_L}{\pi \dot{y}}} = 2\sqrt{\frac{(0.10 \text{ m}^3\text{/s})}{(3.14)(1.20 \times 10^{-4} \text{ m/s})}} = 32.6 \text{ m}$$

Since this is larger than the diameter of the diked area, the pool will be constrained by the dike with a diameter of 25 m. The area of the pool is

$$A = \frac{\pi D^2}{4} = \frac{(3.14)(25 \text{ m})^2}{4} = 491 \text{ m}^2$$

The flame height is given by Eq. (2.2.55),

$$\frac{H}{D} = 42\left(\frac{m_B}{\rho_a \sqrt{gD}}\right)^{0.61} = 42\left[\frac{(0.0876 \text{ kg/m}^2 \text{ s})}{(1.2 \text{ kg/m}^3)\sqrt{(9.81 \text{ m/s}^2)(25 \text{ m})}}\right]^{0.61} = 1.59$$

Thus, $H = (1.59)(25 \text{ m}) = 39.7 \text{ m}$

Point Source Model. This approach is based on representing the total heat release as a point source. The received thermal flux for the point source model is given by Eq. (2.2.61). The calculation requires values for the atmospheric transmissivity and the view factor. The view factor is given by Eq. (2.2.60), based on the geometry shown in Figure 2.80. The point source is located at the center of the pool, at a height equal to half the height of the flame. This height is (39.7 m)/2 = 19.9 m. From the right triangle formed,

$$x^2 = (19.9 \text{ m})^2 + (25 + 50 \text{ m})^2 = 6020 \text{ m}^2$$

$$x = 77.6 \text{ m}$$

This represents the beam length from the point source to the receiver. The view factor is determined using Eq. (2.2.60)

$$F_p = \frac{1}{4\pi x^2} = \frac{1}{(4)(3.14)(77.6 \text{ m})^2} = 1.32 \times 10^{-5} \text{ m}^{-2}$$

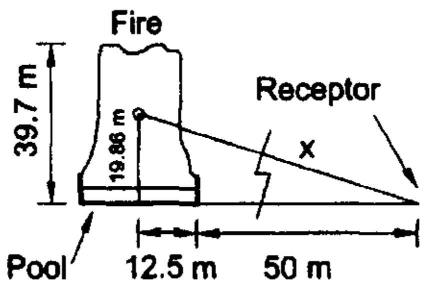

FIGURE 2.80. Geometry of Example 2.30: Radiation from a burning pool.

The transmissivity is given by Eq. (2.2.42) with the partial pressure of water given by Eq. (2.2.43). The results are

$$P_w = \frac{RH}{100}\exp\left[14.4114 - \frac{5328}{T_a}\right] = 0.0156 \text{ atm} = 1580 \text{ Pa at } 298 \text{ K}$$

$$\tau_a = 2.02(P_w X_s)^{-0.09} = (2.02)[(1580 \text{ Pa})(77.6 \text{ m})]^{-0.09} = 0.704$$

The thermal flux is given by Eq. (2.2.61), assuming a conservative value of 0.35 for the fraction of the energy converted to radiation.

$$E_r = \tau_a \eta m_B \Delta H_c A F_p$$

$$E_r = (0.704)(0.35)(0.0876 \text{ kg/m}^2 \text{ s})(43{,}700 \text{ kJ/kg})(491 \text{ m}^2)(1.32 \times 10^{-5} \text{ m}^{-2})$$
$$= 6.11 \text{ kJ/m}^2 \text{ s} = 6.11 \text{ kW/m}^2$$

C.4 Example Problem for Fireball, CCPS (2000)

2.2.4.3. EXAMPLE PROBLEMS

Example 2.27: BLEVE Thermal Flux. Calculate the size and duration, and thermal flux at 200 m distance from a BLEVE of an isolated 100,000 kg (200 m³) tank of propane at 20°C, 8.2 bar abs (68°F, 120 psia). Atmospheric humidity corresponds to a water partial pressure of 2810 N/m² (0.4 psi). Assume a heat of combustion of 46,350 kJ/kg.

Solution. The geometry of the BLEVE are calculated from Eqs. (2.2.32)- (2.2.36). For an initial mass, M = 100,000 kg, the BLEVE fireball geometry is given by

$$D_{max} = 5.8\,M^{1/3} = (5.8)(100{,}000\text{ kg})^{1/3} = 269\text{ m}$$

$$t_{BLEVE} = 2.6\,M^{1/6} = (2.6)(100{,}000\text{ kg})^{1/6} = 17.7\text{ s}$$

$$H_{BLEVE} = 0.75\,D_{max} = (0.75)(269\text{ m}) = 202\text{ m}$$

$$D_{initial} = 1.3\,D_{max} = (1.3)(269\text{ m}) = 350\text{ m}$$

For the radiation fraction, R, assume a value of 0.3 (Hymes, 1983; Roberts, 1981).

The emitted flux at the surface of the fireball is determined from Eq. (2.2.40),

$$E = \frac{RMH_c}{\pi D_{max}^2 t_{BLEVE}} = \frac{(0.3)(100{,}000\text{ kg})(46{,}350\text{ kJ/kg})}{(3.14)(269\text{ m})^2(17.7\text{ s})} = 345\text{ kJ/m}^2\text{ s} = 345\text{ kW/m}^2$$

The view factor, assuming a vertically oriented target, is determined from Eq. (2.2.47).

$$F_{21} = \frac{L(D/2)^2}{(L^2 + H_{BLEVE}^2)^{3/2}} = \frac{(200\text{ m})(269\text{ m}/2)^2}{\left[(200\text{ m})^2 + (202\text{ m})^2\right]^{3/2}} = 0.157$$

The transmissivity of the atmosphere is determined from Eq. (2.2.42). This requires a value, X_s, for the path length from the surface of the fireball to the target, as shown in Figure 2.72. This path length is from the surface of the fireball to the receptor and is equal to the hypotenuse minus the radius of the BLEVE fireball.

$$\text{Path Length} = \sqrt{H_{BLEVE}^2 + L^2} - \frac{D_{max}}{2}$$

$$= [(202\text{ m})^2 + (200\text{ m})^2]^{1/2} - (0.5)(269\text{ m}) = 150\text{ m}$$

The transmissivity of the air is given by Eq. (2.2.42),

$$\tau_a = 2.02(P_w X_s)^{-0.09} = (2.02)\left[(2810\text{ Pa})(150\text{ m})\right]^{-0.09} = 0.630$$

The received flux at the receptor is calculated using Eq. (2.2.45)

$$E_r = \tau_a E F_{21} = (0.630)(345\text{ kW/m}^2)(0.158) = 34.3\text{ kW/m}^2$$

This received radiation is enough to cause blistering of bare skin after a few seconds of exposure.

An alternate approach is to use Eq. (2.2.41) or (2.2.44) to estimate the radiative energy received at the receptor. In this case X_c is the distance from the center of the fireball to the receptor. From geometry this is given by

$$X_c = \sqrt{(202\text{ m})^2 + (200\text{ m})^2} = 284.2\text{ m}$$

Substituting into Eq. (2.2.41)

$$E_r = \frac{2.2\tau_a R H_c M^{2/3}}{4\pi X_c^2} = \frac{2.2(0.630)(0.3)(46.35\times10^6\ \mathrm{J/kg})(100{,}000\ \mathrm{kg})^{2/3}}{(4)(3.14)(284.2\ \mathrm{m})^2}$$

$$= 40.9\ \mathrm{kW/m^2}$$

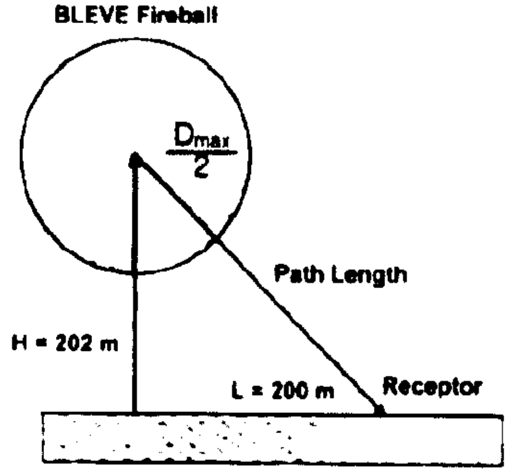

FIGURE 2.72 Geometry for Example 2.27: BLEVE thermal flux.

which is close to the previously calculated value of 34.2 kW/m^2. Using Eq. (2.2.44)

$$E_r = \frac{8.28\times10^5 M^{0.771}}{X_c^2} = \frac{(8.28\times10^5)(100{,}000\ \mathrm{kg})^{0.771}}{(284.2\ \mathrm{m})^2} = 73.4\ \mathrm{kW/m^2}$$

which is a different result, more conservative in this case.

APPENDIX D

D.1 Flash Fire

Table D.1: FiST input and output flash fire parameters from 10,000 kg methane gas release

	Value	Unit
Input parameters:		
Fuel properties: Methane		
Mass of gas release	10,000	kg
Dispersion coefficient in the downwind direction	5.60	m
Dispersion coefficient in the crosswind direction	4.00	m
Dispersion coefficient in the vertical direction	3.80	m
The concentration at lower explosion limit	3.50	kg/m^3
The concentration at upper explosion limit	12.40	kg/m^3
Density of burning gas	0.25	kg/m^3
Ambient temperature	283	K
Initial temperature of the hot gas	289	K
Effective radiation temperature of the flash fire	1253	K
Output parameters:		
Volume of flash fire	835.40	m^3
Area of flash fire	423.36	m^2
Thermal radiation at 50 m	144.12	kW/m^2
Life time	6139.41	sec
Half-life time	8.67	sec
Effective duration time	26.01	sec
Probability of 1st degree of burn by flash fire at 300 m	75.62	%
Probability of 2nd degree of burn by flash fire at 300 m	0.44	%
Fatality percentage by thermal radiation from flash fire at 300 m	0.28	%

D.2 Jet Fire

Table D.2: FiST input and output jet fire parameters for release of butane gas

	Value	Unit
Input parameters:		
Material: Butane		
Hole diameter	0.025	m
Distance from flame	9	m
Leak height above ground	4.5	m
Axial distance from hole	4	m
Ambient temperature	291	K
Flame temperature	324	K
Relative humidity	50	%
Output parameters:		
Flame length	8.47	m
Lift-off distance	0.31	m
Diameter of jet fire	1.03	m
Flame area	29.07	m^2
Discharge rate	0.445	kg/s
Average emissive power	209.87	kW/m^2
Thermal radiation intensity	4.64	kW/m^2
Probability of 1st degree of burn by pool fire at 100 m	74.26	%
Probability of 2nd degree of burn by pool fire at 100 m	0.39	%
Fatality percentage by thermal radiation from pool fire at 100 m	0.25	%

D.3 Pool Fire

Table D.3: FiST input and output pool fire parameters for release of a hydrocarbon liquid

	Value	Unit
Input parameters:		
Heat of vaporization of liquid	300	kJ/kg
Heat of combustion of liquid	43700	kJ/kg
Heat capacity constant of liquid	2.5	kJ/kg K
Boiling point of liquid	363	K
Ambient temperature	298	K
Liquid density	730	kg/m^3
Liquid leakage rate	0.1	m^3/s
Dike diameter	25	m
Receptor distance from pool	50	m
Relative humidity	50	%
Radiation efficiency	0.35	–
Output parameters:		
Vertical burning rate	0.00012	m/s
Mass burning rate	0.0876	kg/m^2 s
Maximum pool diameter	32.57	m
Pool area	490.87	m^2
Flame height	39.72	m
Distance to receptor	65.579	m
Thermal flux	8.695	kW/m^2 s
Probability of 1st degree of burn by pool fire at 100 m	68.69	%
Probability of 2nd degree of burn by pool fire at 100 m	0.24	%
Fatality percentage by thermal radiation from pool fire at 100 m	0.16	%

D.4 Fireball

Table D.4: FiST input and output fireball parameters for fireball hazard from 100,000 kg propane

	Value	Unit
Input parameters:		
Material name: Propane		
Initial flammable mass	100,000	kg
Distance from fireball center on ground	200	m
Radiation fraction	0.3	–
Heat of combustion	46350	kJ/kg
Exposure duration	15	sec
Output parameters:		
Maximum fireball diameter	269	m
Fireball height	201.8	sec
Path length	149.6	m
Combustion duration	17.7	sec
Surface emitted flux	345.6	kW/m^2
Received thermal flux for vertically oriented target	34.4	kW/m^2
Received thermal flux for horizontal oriented target	34.6	kW/m^2
Probability of 1st degree burn by fireball at 1 km	100	%
Probability of 2nd degree burn by fireball at 1 km	91.64	%
Fatality percentage by thermal radiation from fireball at 1 km	73.17	%