Gas Dispersion Modeling

by

Ching Shih Gin

Dissertation submitted in partial fulfillment of

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CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2012

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 in the references and acknowledgements, and that the original work contained herein have been undertaken or done by unspecified sources or persons.

CHING SHIH GIN

ABSTRACT

Involvement of flammable or toxic materials in a process plant causes the risk of accidents. Hazard analysis and risk-based management are important to prevent escalation of dangerous event. Due to ill-defined leakage conditions, there are a few areas of uncertainty which lead to difficulty in positioning gas detectors. In industry, positioning of gas detectors has always been based on personal expertise rather than computer modeling. This method lacks of consistency and it tends to focus on locations of potential leakage but not locations of total gas accumulation. Development of gas dispersion modeling tool aids in better understanding of possible path of gas distribution and accumulation. Based on the dispersion results, possible locations of gas detector can be indicated. Gaussian plume model is being employed in this project to study dispersion of natural gas. Natural gas is a type of light gas and neutrally buoyant. Effects of meteorological parameters and gas emission rate are factors affecting dispersion pattern. After filtering the concentrations fall out of flammable range, locations where concentrations within flammable range occur are identified using top view plot and front view plot. Consequently, locations of gas detector can be determined.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Workplace safety is one of the most fundamental and important criteria in assessing a working environment. Concerns related to safety must be identified and studied in detailed prior to tragedy especially in industries that possessing risky events of toxic chemical release, fire or explosion such as oil and gas industry. Deadly incident of Bhopal in 1984 acts as alarm to process industry which emphasizes the importance of safety. In order to prevent the undesired events that will cause hazardous impacts to public health and safety from happening, studies have been carried out to understand the properties of hazardous events and hence developing methods to cope with the situation to minimize the impact or prevent them from happening at all which is even more desirable.

In an industrial process plant where flammable or toxic chemicals are being manufactured, consumed or transported, extra precautionary steps must be implemented as there are always chances of leakage or accident. Every single piece of equipment used in a process plant might become source of leakage especially when maintenance and service routines are not maintained. According to statistics done by Drager Safety, reasons of accidents can be categorized as 35% wear and tear of material and equipment, 30% human error, 30% process failure and 5% others [1]. It is clearly indicating that accident could be minimized by putting efforts to maintain equipments, standardised work to minimise human error and process error. Apart from initiative to improve management, hazard and risk analysis is playing crucial role to minimise impact of inevitable accidents. Accidental leakage and dispersion of flammable or toxic gases imply risks to people, environment and property. Studies have been conducted to correctly estimate the behavior of toxic and flammable gases dispersion resulting from accidental leakage. Studies are aimed to identify the best location to install gas detection equipments in order to detect the occurrence of gas leakage in the fastest possible time and prevent escalation of harmful events.

Methods that are generally used to study gas dispersion include integral model such as Gaussian, DEGADIS, HEGADAS, SLAB, etc, wind tunnel modeling and computational fluid dynamics (CFD) – for simulation of gas dispersion in different occasions. In this project, a simulation of gas dispersion is being modeled using Gaussian plume model in order to study the dispersion behaviour and hence investigate the best position to locate gas detector equipment. A dispersion model describes the airborne transport of gases away from the leakage source and into the surrounding. Gaussian plume model applies only to dispersion of neutrally buoyant gases.

In this project, dispersion of natural gas is being studied. Natural gas is lighter than air; when it is released to an open area, it will rise and diffuse rapidly where the dispersion path is affected by wind speed, wind direction and atmospheric stability. Natural gas is flammable in certain mixtures. Flammability limit of natural gas is between 5% and 15%. The former is known as lower flammable limit (LFL) while the latter is known as upper flammable limit (UFL). Below 5% gas in air, natural gas will not burn due to insufficient gas present to support combustion; if there is above 15% gas in air, there will be to too much gas and insufficient air to support combustion. Therefore, by finding out the probable dispersion path where concentration is within the flammable range, placement of gas detectors can be done more precisely.

1.2 Problem Statement

Any industrial process plant possesses the risk of hazardous events that could happen at any stage of the process. Toxic or flammable materials must be handled with extra care in order to prevent any unwanted tragedy. Safety precautions to tackling gas leakage or release to the environment are crucial to ensure that the working environment is safe. Therefore, simulation and modeling of gas dispersion enable hazard analysis and risk-based management to be performed in the process facilities. However, due to uncertainty in specifying process plant leakage conditions, models developed to study the unconfined spread of gas might not be accurate. Generally, gas dispersion modeling is based on the mathematical models obtained from field test data from vapor dispersion tests. In industry, gas detectors placement is based on personal expertise and experience rather than computer modeling. This method focuses on possible locations of leakage instead of locations of gas accumulations. Development of gas dispersion modeling tools allows more understanding on the behavior of gas dispersion and hence enables the positioning of gas detectors in plant to be optimized. In this project, a MATLAB-based gas dispersion modeling will be developed. From simulations of the model, possible locations of gas detector can be introduced.

In other words, problem statements of this project can be specified as:

(i) Uncertainty in specifying gas leakage conditions leads to difficulty in positioning gas detectors

(ii) Gas detectors placement is based on personal expertise rather than computer modeling

(iii) Necessity of developing gas dispersion modeling tools to aid in correct positioning of gas detectors

1.3 Project Objectives

Objective of this project is to develop a gas dispersion modeling using Gaussian plume model in order to investigate the possible locations of gas detection equipment. The model is aimed to simulate gas dispersion whenever there is gas leakage from a hole. The main objective can be divided into sub-objectives as follows:

(i) To simulate gas dispersion when gas leakage happens using Gaussian plume model
(ii) To study the possible gas dispersion path and distances where concentration is within the flammable range
(iii) To investigate the possible locations of gas detector

1.4 Scope of Project

This project mainly focuses on modeling gas dispersion in MATLAB. Algorithm that is being employed in this project is Gaussian Plume model. The basic idea of the simulation is to observe the dispersion pattern of gas released and locations where concentration of gas is within the flammable range. From the simulation results, analysis will be done to investigate the possible locations for placement of gas detectors either point detector or open path detector.

CHAPTER 2
LITERATURE REVIEW

2.1 Gas Dispersion Modeling

Over the past few years, studies of gas dispersion modeling have been conducted by researchers in order to predict the potential hazardous events in process plants. Generally, studies have been concentrated on gas dispersion in natural gas plant. If there is accidental hazardous gas release with presence of ignition source, it might lead to fire or explosion [2]. Aware of the consequences, accidental natural gas release modeling has been studied and compared using different methods to obtain the best simulation method which gives accurate results. There are three major classifications of gas dispersion modeling namely integral models, wind tunnel testing and computational fluid dynamics (CFD) models. DEGADIS, HGSYSTEM, SLAB and etc are examples of integral models.

Wind tunnel testing was initially only aimed at conducting aerodynamics research of aircrafts. It was then later developed to various areas such as automobiles and environmental studies. It is specifically designed to simulate airflow and flow velocity close to scenario concerned. There are two main types of wind tunnels which are open circuit tunnels and closed circuit tunnels. An open circuit wind tunnel has air entry open to the atmosphere. At the entry of the tunnel, a fan is located to blow air into it. This type of tunnel is simple and low in cost. However, non-uniform and turbulent flow its major drawback. On the other hand, closed circuit wind tunnel is another type of wind tunnel which is the preferable type. Air coming out from the tunnel is re-circulated into the intake end. Special vanes known as turning vanes are located at the four 90° corners in order to turn the airflow and ensure smooth flow. Closed circuit wind tunnel has more uniform airflow and air entering the test section is cleaner and hence minimizing turbulence.

Wind tunnel experiments have been conducted to model gas dispersion. In a study carried out by Ohba (2004), isothermal heavy gas and cryogenic gas were used in the wind tunnel experiments. The results were compared to field experiment results of Thorney Island Experiments and China Lake Experiments. Fluctuation in concentrations with and without a building are measured and compared to the standard deviation of fluctuation of concentrations calculated using standard deviation (STD) model. The original STD code has shown good agreement for standard deviation of concentration. Other than that, physical modeling of dense gases by fulfilling the similarity rule of Richardson number allows simulation of atmospheric stability of stable condition. Compared to results obtained from integral model, DEGADIS indicated that the wind tunnel results have good agreement with the China Lake experiment field data. However, deviation from field data had been observed at far downwind distances. This might be due to parameterization selected from plume spread used in Gaussian formula. The wind tunnel experiment results were compared to finite element method 3D (FEM3) in order to verify the accuracy of wind tunnel modeling. The calculated results showed good agreement again. FEM3 model employs the finite element method with k-ε model which takes very long computational time and excessive memory [3].

Wind tunnels have limitations in performance ability in term of parameter variations. This was found in setting up of experiment for wind tunnel study of entrainment in dense gas plume conducted by Snyder (2000) [4]. As Ohba concluded that similarity rule must be satisfied to simulate stable condition for atmospheric stability, Snyder pointed out that in order to match the Richardson number, wind tunnel is required to run at very low speed which is about or lower than $1ms^{-1}$. Problem arises from this setup is laminar flow. This will then lead to inaccuracy in simulating effects of full scale turbulences and difficulty to control the wind tunnel. When Richardson number increases, boundary layer turbulence appears to suppress to significant fractions of the boundary layer depth. Besides, mean velocities in the lower levels of plume appeared to retard and increase in the upper levels. Another finding in this study was Gaussian shape vertical concentration distribution downwind of the line source for neutral and dense gas releases. This is in contrast to the exponential distributions found in three dimensional passive gas releases.

Similarity in various fluid dynamics properties to the wind tunnel operating condition is a compulsory for wind tunnel testing. Properties include Rossby number, Richardson number, Reynolds number, Prandtl number, Eckert number, undistorted geometry, surface boundary conditions and similar approach flow characteristics.

Accurate simulations of gas releases in complex settings could be achieved by following a set of guidelines which aid in appropriate scaling parameters selection. These guidelines are based on research results done by Environmental Protection Agency and Gas Research Institute. In order to match the boundary conditions of industry site, a scale model was constructed in experiments carried out by Petersen (1997) [5]. Time-varying concentration measurement systems are usually employed to determine the peak and mean concentrations in wind tunnel experiments. Hot film sensor is used to measure and monitor the tunnel speed. In consequence analysis using wind tunnel modeling, testing under neutral stability is recommended because under stable stratification, wind tunnel simulations are not very accurate and hence not well accepted. It is difficult to simulate low wind speed and stable stratification. These are some limitations of modeling using wind tunnel experiments.

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that employs numerical methods and algorithms for fluid flow related studies. CFD code showed high agreement with data collected from a medium-scale LNG tests that were performed at the Brayton Fire Training Field (BFTF) (Cormier, Qi, Yun, Zhang & Mannan, 2009) [6]. In this study, the authors have identified some key parameters i.e. wind velocity, obstacles, released mass and sensible heat flux and their effects in LNG vapor dispersion. A generic CFD code CFX was more suitable for vapor dispersion modeling due to its high flexibility in setting up. Reynolds Averaged Navier Stokes (RANS) equations were employed in CFX code. Problem definition, solver and post processor are the three sections in CFX algorithm. In modeling of LNG vapor dispersion, air and methane are normally modeled as gas phase. It is concluded that increasing in wind velocity speed up the mixing effect with vapors and ambient air and hence reducing lower flammable limit (LFL) distance. Besides, LFL distance is affected by effects of obstacles when tested for different wind direction.

Another study conducted by Qi, Ng, Cormier & Mannan (2010), employed CFX as well. Modeling of LNG vapor dispersion to evaluate the design, sitting and layout of plants was done in ANSYS CFX [1]. Navier-Stokes equations are used again to describe the processes of heat, momentum and mass transfer. In addition to that, other chemical or physical processes such as combustion, radiation and turbulence can be described by incorporating some mathematical models together with the use of Navier-Stokes equations. Dispersion of LNG vapor in the atmosphere experiences three stages: positive buoyancy, neutral buoyancy and negative buoyancy. Each stage depends on temperature of the vapor cloud. A buoyancy model is used to capture difference in density which is caused by variation in temperature. Its status changes from negative to positive as the temperature increases. Apart from that, a wide variety of turbulence models are offered by ANSYS CFX such as k-ε model, k-ω model and shear stress transport (SST) model. Among the models, k- ε model has gained popularity due to its balance between the two most important criteria in choosing a suitable model: computational time and precision. In another study focusing on gas dispersion modeling in the presence of obstacles, it is found that realizable k-ε model can provide a more realistic results of heavy gas dispersion compared to standard k-ε model that is generally used in modeling (Tauseef, Rashtchian & Abbasi, 2011) [7]. Two main differences between these two models are a new formulation for turbulent viscosity and a new transport equation for the dissipation rate in realizable model. Another achievement of realizable k-ε model compared to its standard model is the possibility to model the concentration fluctuations which occur due to gravity slumping associated with dense gas dispersion. Predictions of peak concentrations by realizable k-ε model are non-conservative compared to the standard k-ε model. It is well known that both time and space are elements in the function of the extent of hazard posed by a dispersing cloud. Therefore, correct prediction of arrival time is of the same importance as the prediction of correct concentration profile which makes realizable k-ε model more realistic.

The third method that has been reviewed is integral model. Easy to use and quick response time are the main advantages of this method. There are several requirements in the design of a dispersion model. A model has to capture the essential physics of the process and gives repeatable and reasonable estimates of concentrations. Several levels of dispersion model have been developed over the years with increasing levels of mathematical sophistication, input data requirements and required expertise of individual. Gross screening models are the low end of the scale where users require only a calculator and spreadsheet. Limitations of these models are that only one source may be treated at a time and they provide the worse-case prediction, therefore, might over-predict the situation. As for intermediate models, various meteorology parameters and more sophisticated source information may be included in the estimations. For example, SCREEN3 model is an intermediate model developed by U.S Environmental Protection Agency. Next on the scale, there is advanced models which require extensive input data for meteorology and gas emissions. Multiple source leakage can be simulated using these models as well. Additional features such as atmospheric stability, complex terrain, ventilations may be included. Examples of advanced model are ISC3, AERMOD and CALPUFF [8].

There is another class of model which is known as specialized model. This type of model is usually used to model dispersion of special hazardous materials. Dense gas dispersion models are used by oil and gas industry to model the behavior of accidental releases of dense gases or vapors. Extensive thermodynamic information is essential to account for release conditions. Examples of specialized model are DEGADIS, HGSYSTEM and SLAB. DEGADIS is a model developed by U.S. Environmental Protection Agency. It models the atmospheric dispersion of dense than air gas. It is able to address dispersion in the fluid flow regime of jet, buoyancy dominated, passive dispersion and stably-stratified. It also manages to into account for large spectrum of surface roughness elements. However, it has several limitations in implementation. It does not account for aerodynamic effects of nearby building and unable to address complex meteorological flow phenomena like mountain-valley flows. Other than that, it can only address pure chemical releases and does not consider chemical mixtures or transformations [9]. HGSYSTEM is a computer-based model used to calculate the release properties of denser than air gases [10]. It was developed by Shell Research and Technology Centre. It is able to model other chemical species with complex thermodynamic properties and spillage of a liquid non reactive compound from a pressurized vessel. Its main limitation is the difficulty to extend the physical or chemical database utility to include additional chemical species. Strong knowledge of the model is required to do such modifications. On the other hand, SLAB model is one of the most widely used dense gas models. It was developed by Lawrence Livermore National Laboratory (LLNL). This model assumes all source input conditions have been determined externally and thus it does not calculate source emission rates. It is well known for being user friendly and fairly accurate results [11].

2.2 Gas Detection and Detector Placement

In general, gas detection can be divided into combustible gas detection and toxic gas detection. When choosing gas detector, there are several issues that must be taken into consideration.

- Nature of gas to be detected i.e. light gas or heavy gas. Light gas like methane rises while heavy gas such as propane sinks when it is first released to the surrounding.
- Devices used in oil and gas industry are mostly set to detect methane or hydrogen sulphide.
- Some detectors show cross-sensitivity where the detector may detect more than one type of gas at different readings.

For combustible gas detection, infra-red absorption and catalytic are the two mainstream technologies available. An infra-red detector can be either point detection or open-path detection. Point detectors measure the concentration of the gas at the sampling point of the instrument. They are calibrated against the Lower Flammable Limit (LFL) of the gas to be detected in which frequently the gas is methane. Unit of measurement can be %volume ration, %LFL or ppm. They need to be placed at where gas dispersion path would possibly be. As for open path gas detectors, also known as beam detectors, typically comprise of a radiation source and a physically separated remote detector. Detectors must be mounted rigidly in order to avoid misalignment between the transmitter and receiver. Average concentration of gas is measured along the path of the beam. Unit of measurement is product of concentration and path length, i.e. %LFL x m or ppm x m. Drawback of this measurement is that it is impossible to differentiate whether a reading is due to high concentration along a short beam or a lower concentration along a longer beam. Thus, it may lead to false reading and alarm [12]. Another type of combustible gas detector, catalytic gas detectors are only available as point detectors. This is because a catalytic detector relies on burning gas in a sintered chamber. They require frequent maintenance; therefore, infra-red detectors are more popular in the process industries in spite of their higher cost.

On the other hand, chemical cell and semiconductor point detectors, open path laser gas detection are technologies available for toxic gas detection. Chemical cell detectors require sensor replacement at intervals dependent on the environment while semiconductor detectors need to be kept active by exposure to the detected gas. New technologies are being developed to improve detection of toxic gases [13].

Detection systems are crucial in preventing escalation of dangerous event. When looking for detectors, engineers need to consider all the specifications from different manufacturers in order to look for the suitable ones. However, high quality detectors are meaningless if they were misplaced. Therefore, correct placement of gas detectors can optimize coverage and ensure that safety goals are achieved. Traditionally, there are two common methods used in detector placement which are heuristic placement and prescriptive placement.

In heuristic placement, detectors are placed based on personal expertise on previous experiences rather than computer modeling. A personal visually determines the possible dispersion path and places detectors according to the visualization without using numeric modeling. This method tends to focus on the location of a potential gas leak instead of the location of total gas accumulation. On the other hand, prescriptive placement employs a strict predefined standard in placing detectors. Detectors are placed solely relying on standards. This method is generally used in turbine areas where clear instructions on locations of detection have been provided by turbine manufacturer [14]. In order to maximize effectiveness of detector, use of a consistent methodology in locating gas detectors has been promoted. Research is initiated to increase understanding in ill-defined areas of detection system. There are many areas of uncertainty due to insufficient number of release scenarios available and locations of detectors for various gases are not defined.

In a study performed by UK HSE’s Offshore Division (OSD), there were many tests being carried out in industry to study gas detection where principal factors such as release rate, module wall configuration, direction of wind and location of leakage were studied. The main findings are as follows [15]:

- Grid based on 5m spacing for point detectors is acceptable; it is able to detect releases when the gas cloud formed is within the flame.
- In case of small cloud or slow cloud growth, detection times increased or may not be detected at all.

- Reducing the detectors spacing distance slightly reducing detection time but number of detectors required will be increased.
- Increasing the detectors spacing distance will increase the detection time
- Infra-red detectors perform better than catalytic detectors, in both terms of detection time and number of releases detected.

Correct placement of detectors can improve the performance of a detection system. Hence, it urges for better understanding in dispersion, process being undertaken and equipment layout when positioning gas detectors.

CHAPTER 3

METHODOLOGY

3.1 Project Flow Chart

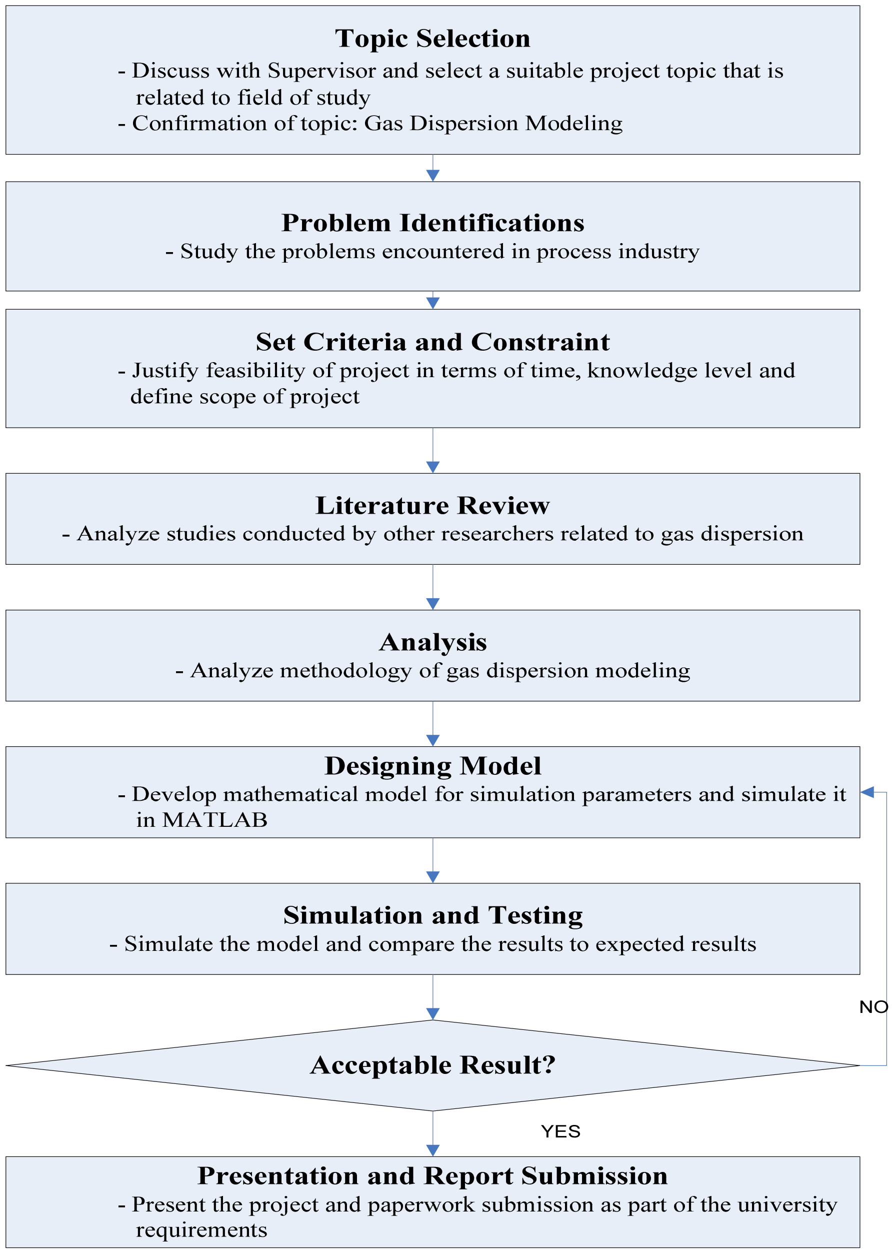

Figure 3.1: Project Flow Chart

3.2 Program Flow Chart

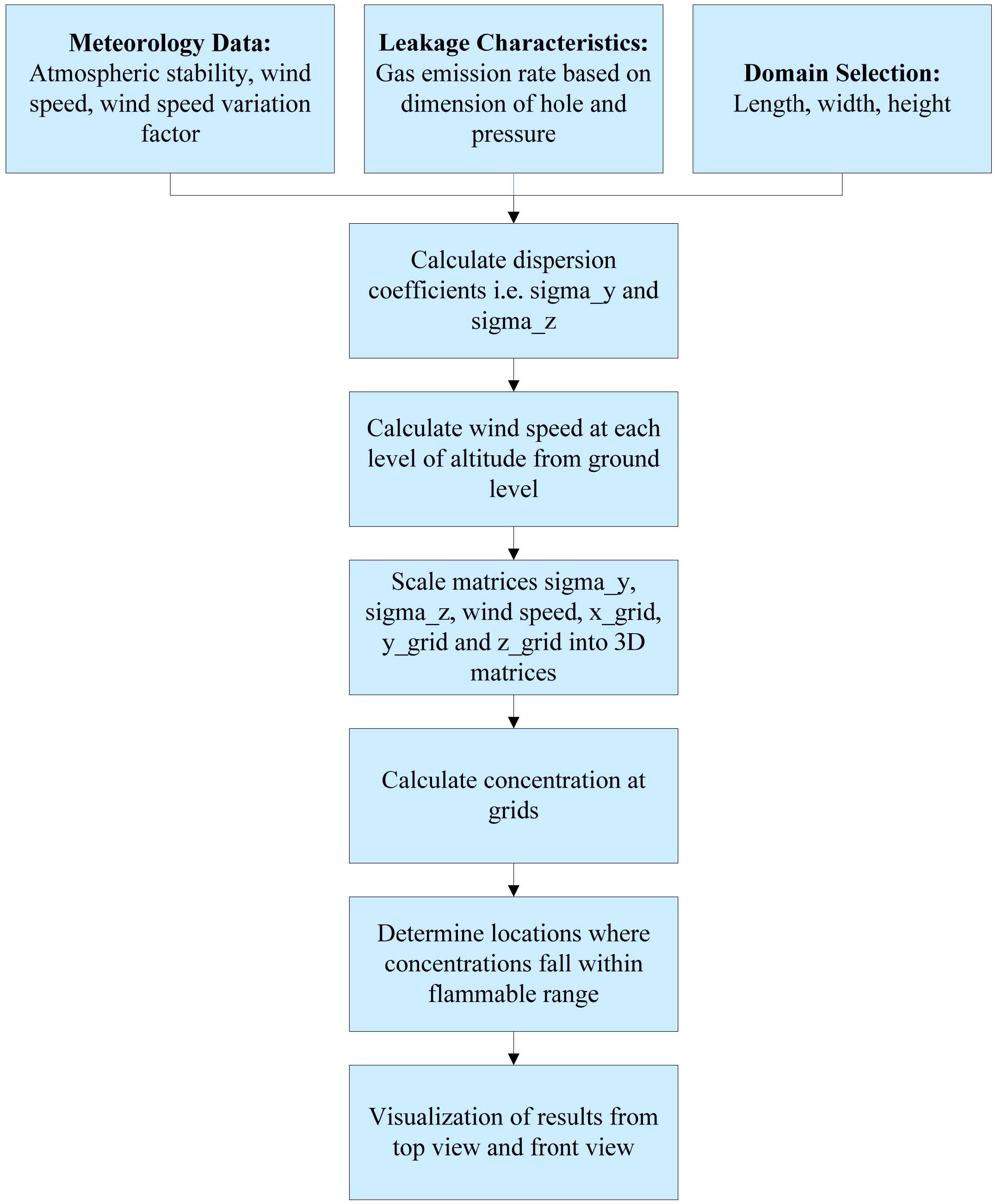

Figure 3.2: Program Flow Chart

3.3 Gaussian Plume Model

The Gaussian model is the most commonly used mathematical model to study gas dispersion from the release source. It describes the behavior of a continuous release of gas. Its solution depends on the properties of gas release, rate of release, atmospheric stability, wind velocity, height of release and distance from release source [16].

3.3.1 General behavior of natural gas dispersion

Density is the ratio of mass to the volume it occupies. When density is compared to air, property of gas can be determined whether it is lighter than air, heavier than air or neutral with air. For light gas, it generally rises when released while heavy gas sinks due to gravity. As for neutral gas, the gas will move with air and move along with air currents. Natural gas comprises of mostly methane and other components include ethane, propane, butane, nitrogen and carbon dioxide [17]. It is lighter than air, therefore, rises when it is released. As the gas cloud rises, it is diluted and expanded laterally density decreases. Eventually, it becomes neutral and being pushed or pulled along the air currents. To detect light gas release, it is recommended to place detectors above and close to potential release points with the consideration of predominant wind direction.

3.3.2 Atmospheric Stability

Meteorological parameters play a major role in gas dispersion behavior. Atmospheric stability and wind velocity are the primary factors in play. Atmospheric stability is an estimate of the turbulent mixing where stable conditions mean least amount of mixing and unstable conditions mean the most. It is generally categorized into six Pasquill stability classes, denoted by the letters A through F. These classes are correlated to wind velocity and amount of sunlight. Table 3.1 below shows the meteorological conditions defining the Pasquill-Gifford Stability Classes.

Table 3.1: Meteorological Conditions Defining Pasquill-Gifford Stability Classes

Surface wind speed, m/s	**Daytime insolation**			**Nighttime conditions**		**Anytime**
	Strong	**Moderate**	**Slight**	**Thin overcast or >4/8 low cloud**	**≥ 3/8 cloudiness**	**Heavy Overcast**
<2	A	A-B	B	F	F	D
2-3	A-B	B	C	E	F	D
3-4	B	B-C	C	D	E	D
4-6	C	C-D	D	D	D	D
>6	C	D	D	D	D	D

Each stability class represents different level of atmospheric stability as shown in Table3.2.

Table 3.2: Stability Classes and Levels

Stability Class	**Level**
A	Extremely unstable conditions
B	Moderately unstable conditions
C	Slightly unstable conditions
D	Neutral conditions
E	Slightly stable conditions
F	Moderately stable conditions

In most cases without detailed meteorological data, class D or F is assumed. Class D is typical for windy daytime while the latter is for still nighttime.

3.3.3 Wind Speed

The emitted gas will be carried away and diluted by the passing volumes of air. Gas will be carried away and diluted faster as the wind speed increases. At the surface layer of earth, wind speed increases with increasing height. In homogenous terrain, under neutral atmospheric stability, wind speed can be computed by using Eq. 1.

$$\frac{u}{u_*} = \frac{1}{\kappa}\left(ln\frac{z}{z_0} + 4.5\frac{z}{L}\right) \quad (1)$$

where

u - wind speed (m/s)

u_* - friction velocity constant which is empirically derived (m/s)

κ – von Karman's constant, 0.41

z - height (m)

z_0 - surface roughness length parameter (m)

L - Monin-Obukhov length (m)

The friction velocity constant u_* is related to the frictional resistance that the ground exerts on the wind which is typically 10% of the wind speed at 10m height. The surface roughness length z_0 is typically 3-10% of the height of obstacles.

Eq. 1 can be further simplified to a power law relation when the velocity is compared to a fixed height velocity:

$$u_z = u_{10}(\frac{z}{10})^p \quad (2)$$

where

p is a power coefficient (unitless). It is a function of atmospheric stability and surface roughness.

Typical values of p are given in Table3.3.

Table 3.3: Typical values of p with respect to stability class and terrain

Pasquill-Gifford stability class	**Power law atmospheric coefficient, p**	
	Urban	**Rural**
A	0.15	0.07
B	0.15	0.07
C	0.20	0.10
D	0.25	0.15
E	0.40	0.35
F	0.60	0.35

3.3.4 Dispersion Coefficients

Dispersion coefficients are the standard deviations of concentration in the respective directions. There are the function of atmospheric conditions and downwind distance from the release source. There are two different sets of parameters used to calculate dispersion coefficients (σ_y andσ_z) for rural terrain and urban terrain.

(i) Rural terrain

Coefficients for rural terrain are based on Pasquill-Gifford stability class. The equations used to calculate σ_y and σ_z are shown in Table 3.4 and Table 3.5 respectively.

Table 3.4: Recommended equations for Pasquill-Gifford Dispersion Coefficients for σ_y (Rural Terrain)

Pasquill Stability Class	$\boldsymbol{\sigma_y}$
A	$0.22x\,(1.0 + 0.0001x)^{-1/2}$
B	$0.16x\,(1.0 + 0.0001x)^{-1/2}$
C	$0.11x\,(1.0 + 0.0001x)^{-1/2}$
D	$0.08x\,(1.0 + 0.0001x)^{-1/2}$
E	$0.06x\,(1.0 + 0.0001x)^{-1/2}$
F	$0.04x\,(1.0 + 0.0001x)^{-1/2}$

Table 3.5: Recommended equations for Pasquill-Gifford Dispersion Coefficients for σ_z (Rural Terrain)

Pasquill Stability Class	$\boldsymbol{\sigma_z}$
A	$0.20x$
B	$0.12x$
C	$0.08x\,(1.0 + 0.0002x)^{-1/2}$
D	$0.06x\,(1.0 + 0.0015x)^{-1/2}$
E	$0.03x\,(1.0 + 0.0003x)^{-1}$
F	$0.016x\,(1.0 + 0.0003x)^{-1}$

(ii) Urban terrain

Dispersion coefficients for urban terrain are based on Pasquill-Gifford stability class as well. Equations used to determine σ_y and σ_z are shown in Table 3.6 and Table 3.7 respectively.

Table 3.6: Recommended equations for Pasquill-Gifford Dispersion Coefficients for σ_y (Urban Terrain)

Pasquill Stability Class	$\boldsymbol{\sigma_y}$
A	$0.32x\ (1.0 + 0.0004x)^{-1/2}$
B	$0.32x\ (1.0 + 0.0004x)^{-1/2}$
C	$0.22x\ (1.0 + 0.0004x)^{-1/2}$
D	$0.16x\ (1.0 + 0.0004x)^{-1/2}$
E	$0.11x\ (1.0 + 0.0004x)^{-1/2}$
F	$0.11x\ (1.0 + 0.0004x)^{-1/2}$

Table 3.7: Recommended equations for Pasquill-Gifford Dispersion Coefficients for σ_z (Urban Terrain)

Pasquill Stability Class	$\boldsymbol{\sigma_z}$
A	$0.24x\ (1.0 + 0.001x)^{1/2}$
B	$0.24x\ (1.0 + 0.001x)^{1/2}$
C	$0.20x$
D	$0.14x\ (1.0 + 0.0003x)^{-1/2}$
E	$0.08x\ (1.0 + 0.0015x)^{-1/2}$
F	$0.08x\ (1.0 + 0.0015x)^{-1/2}$

3.3.5 Plume Model

After getting all the required parameter values, concentration can be calculated using Eq. 3:

$$< C > (x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \times \{exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\} \quad (3)$$

where

$< C > (x,y,z)$ - average concentration (g/m³)

Q - source emitting rate

σ_y, σ_z - dispersion coefficients in the y and z directions

u - wind speed (m/s)

y - cross-wind direction (m)

z- distance above ground (m)

H- height of the source above ground level plus plume rise if any (m)

Figure 3.3 illustrates Gaussian plume model calculated using Eq. 3

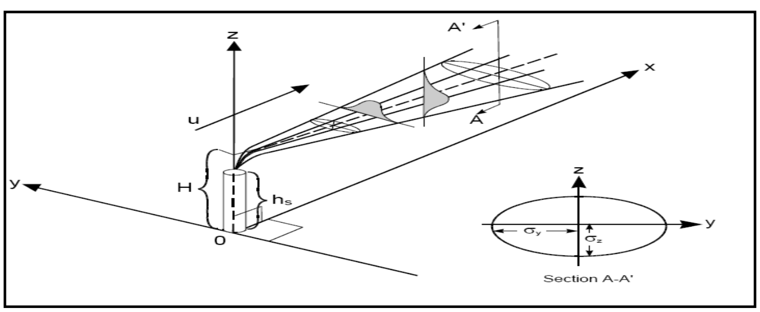

Figure 3.3: Illustration of Gaussian Plume Model

In above figure, 'u' is the wind direction, thus, x-axis represents the downwind distance, y-axis represents the crosswind distance while z-axis represents the vertical distance from ground level. σ_y is the standard deviation of gas concentration in crosswind direction while σ_z is the standard deviation of gas concentration in vertical direction. 'hs' represents the stack height and 'H' is the effective height of release with plume rise taken into account.

3.3.6 Flammability range of natural gas

% Lower flammable limit (LFL) of natural gas is 5% while % upper flammable limit (UFL) is 15%. Below 5% gas in air, natural gas will not burn due to insufficient gas present to support combustion; if there is above 15% gas in air, there will be to too much gas and insufficient air to support combustion. Therefore, by finding out the probable dispersion path where concentration is within the flammable range, placement of gas detectors can be done more precisely.

Since the unit of concentration is kg/m³ in the program, it is necessary to convert the % flammable limits to the same unit, kg/m³. The conversion is done using the following equations:

To convert from % flammable limit to ppm:

$$ppm = \%\ flammable\ limit\ \times 10{,}000 \tag{4}$$

To convert from ppm to kg/m³:

$$\frac{kg}{m^3} = \frac{ppm\ \times molecular\ weight\ of\ gas}{24.45\ \times\ 1 \times 10^6} \tag{5}$$

3.4 Key Milestone

Table 3.8: Key milestone of final year project

	Activities	Duration/Due Date	Status
FYP I	Selection of Project Topic	Week 1 – Week 2	Completed
	Preliminary Research Work	Week 2 – Week 5	Completed
	Submission of Extended Proposal Defense	Week 6	Completed
	Proposal Defense	Week 8 – Week 9	Completed
	Submission of Interim Draft Report	Week 13	Completed
	Submission of Interim Report	Week 14	Completed
FYP II	Submission of Progress Report	Week 8	Completed
	Pre-EDX	Week 11	Completed
	Submission of Draft Report	Week 12	Completed
	Submission of Dissertation	Week 13	Completed
	Submission of Technical Paper	Week 13	Completed
	Oral Presentation	Week 14	Scheduled
	Submission of Project Dissertation	Week 14	Scheduled

Table above shows the key milestones ought to be achieved throughout the project duration which comprises of term I and term II as planned in project Gantt chart (refer to Appendix A). As of now, all activities of Final Year Project I have been completed successfully. Oral presentation and submission of project dissertation have been scheduled. Other activities of Final Year Project II have been accomplished in accordance to the scheduled timeline.

3.5 Tool

The main objective of this project is to simulate gas dispersion in order to study the possible path of gas traveling from leakage source and potential locations of gas detector. MATLAB programming is being employed to fulfill the requirements.

CHAPTER 4

RESULTS & DISCUSSIONS

4.1 Data Gathering

Input parameters to the program are defined as follows:

Table 4.1: Meteorological Data Input

Parameter	Selection
Atmospheric stability class	A - F
Terrain	Rural / Urban
Wind velocity variation factor	Dependent on atmospheric stability class and terrain
Reference wind speed	2m/s
Reference height of measured wind speed	10m

Table 4.2: Gas Leakage Properties

Parameter	Selection
Molecular weight of gas	19.5 (Natural gas)
Diameter of hole	1mm/2mm/5mm/10mm
Release pressure	5 bar(a)/10 bar(a)/50 bar(a)/100 bar(a)

Table 4.3: Domain Selection

Parameter	Selection
Downwind distance	Up to 50m
Crosswind distance	Up to 50m
Altitude from ground level	Up to 10m

Selection of values was based on the approximation conditions due to insufficient information available. Some values were obtained from studies previously published. These values have been determined to study gas dispersion behavior. In the MATLAB program, these parameter values can be modified accordingly by specifying them in the input argument.

4.2 Flammable range of natural gas

%LFL and %UFL of natural gas are converted to unit of kg/m^3 using Eq. 4 and Eq. 5.

(Molecular weight of natural gas is 19.5 g/mol)

5% LFL is equivalent to 0.040 kg/m^3 and 15% UFL is equivalent to 0.120 kg/m^3

The concerned concentration is the flammable range of natural gas. Therefore, concentration falls out of this range is being filtered. The simulation plot would be concentration within flammable range alone.

4.3 Results and Analysis

4.3.1 Simulation results obtained using a predefined setting.

Table 4.4 shows the parameters chosen as default setting. Results of simulation from top view and front view are discussed. Figures 4.1, Figure 4.2 and Figure 4.3 show the top view plot at different height; Figure 4.4, Figure 4.5 and Figure 4.6 show the front view plot at different crosswind distance.

Table 4.4: Set of default parameters chosen

Parameters	Selection
Atmospheric stability class	D (neutral)
Terrain	Rural
Reference wind speed	2m/s
Reference height	10m
Gas emission rate	0.1 kg/s
Hole diameter	10mm
Release pressure	10 bar (a)

(i) Top view results

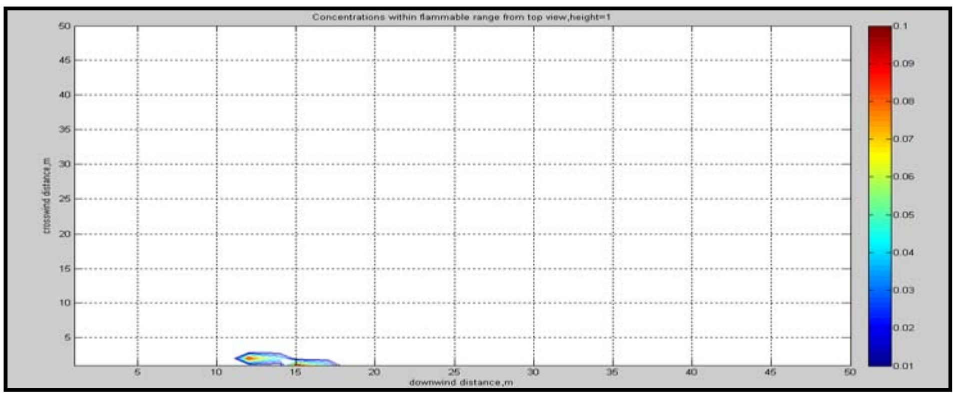

Figure 4.1: Top view plot when height = 1m

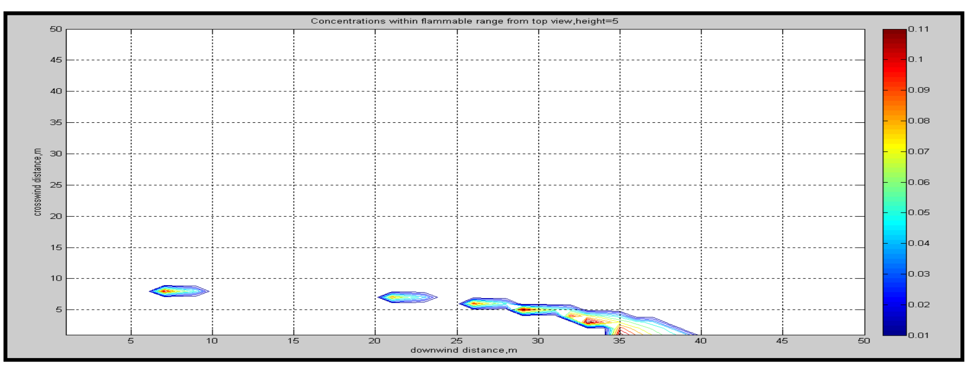

Figure 4.2: Top view plot when height = 5m

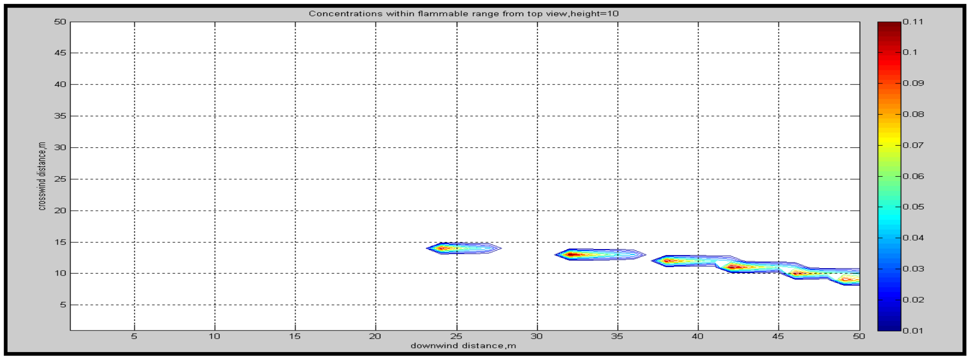

Figure 4.3: Top view plot when height = 10m

Analysis:

For the top view plots, the horizontal axis represents downwind distance while the vertical axis represents crosswind distance. The plot is done by slicing the planes at each layer of height from ground level. It is clearly shown that gas dispersion takes place predominantly in the downwind direction. At height 1m from ground level, concentration of gas is within flammable range at downwind distance of 13-19m and crosswind distance of less than 5m. As height increases, concentration within flammable range occurs at further downwind and crosswind distances.

(ii) Front view results

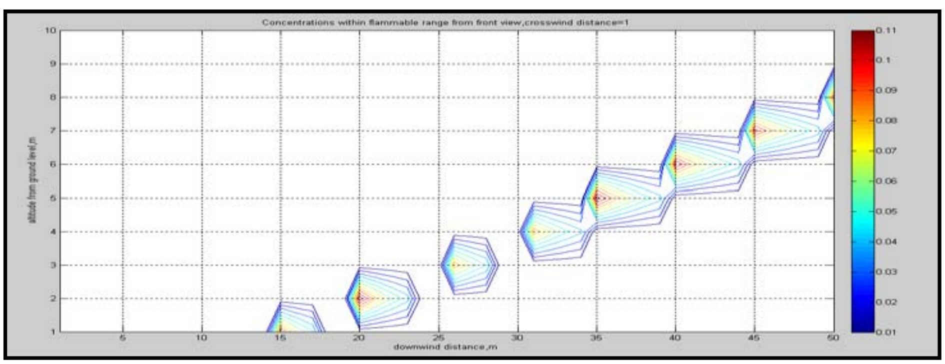

Figure 4.4: Front view plot when crosswind distance = 1m

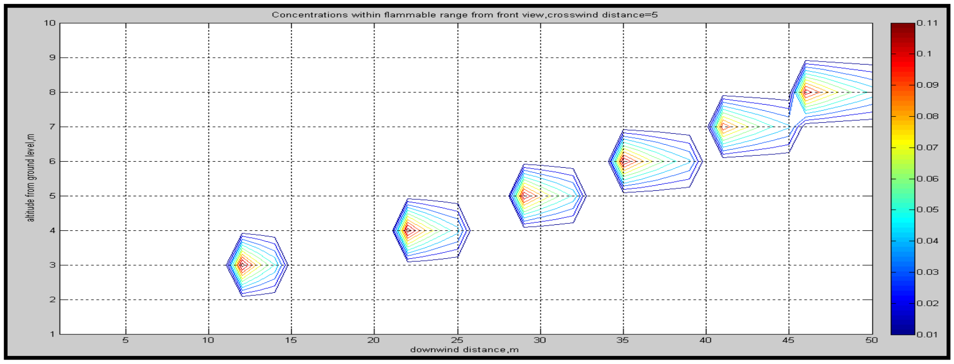

Figure 4.5: Front view plot when crosswind distance = 5m

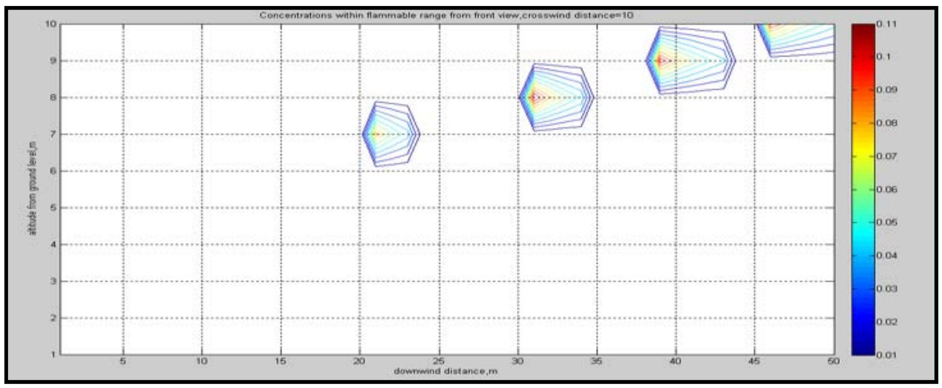

Figure 4.6: Front view plot when crosswind distance = 10m

Analysis:

For the front view plots, horizontal axis represents downwind distance while vertical axis represents altitude from ground level. The plot is done by slicing the planes at each layer of crosswind distance. At 1m crosswind distance from the source of leakage, concentration within flammable range occurs at downwind distance of about 15m. As it getting further down the crosswind distance, flammable concentration occurs at further downwind distance and increasing height.

4.3.2 Effect of parameters

Effects of meteorological parameters (i.e. atmospheric stability, terrain and wind speed) and gas leakage conditions (i.e. emission rate) can be easily observed using the program. Results from previous section are used as reference in order to study the effect of changing parameter. Only one parameter will be changed at one time.

(i) Effect of atmospheric stability

Table 4.5 and Table 4.6 show the set of parameters to study effect of atmospheric stability. Figures 4.7- Figure 4.10 show the top view and front view plots at extremely unstable and slightly stable atmospheric conditions.

Table 4.5: Set of parameters to study effect of atmospheric stability

Parameters	Selection
Atmospheric stability class	**A (extremely unstable)**
Terrain	Rural
Reference wind speed	2m/s
Reference height	10m
Gas emission rate	0.1 kg/s
Hole diameter	10mm
Release pressure	10 bar (a)

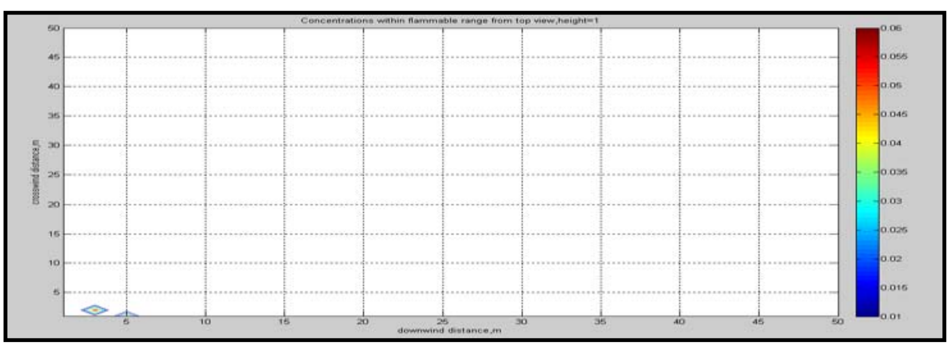

Figure 4.7: Top view plot when height = 1m at extremely unstable atmospheric condition

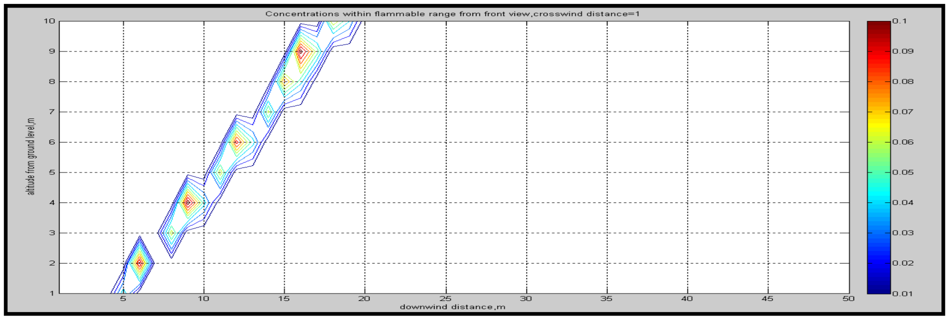

Figure 4.8: Front view plot when crosswind distance = 1m at extremely unstable atmospheric condition

Table 4.6: Set of parameters to study effect of atmospheric stability

Parameters	Selection
Atmospheric stability class	**E (slightly stable)**
Terrain	Rural
Reference wind speed	2m/s
Reference height	10m
Gas emission rate	0.1 kg/s
Hole diameter	10mm
Release pressure	10 bar (a)

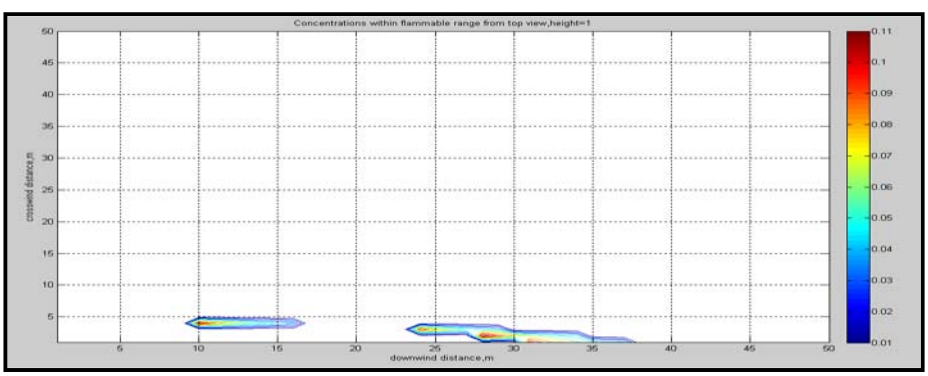

Figure 4.9: Top view plot when height = 1m at slightly stable atmospheric condition

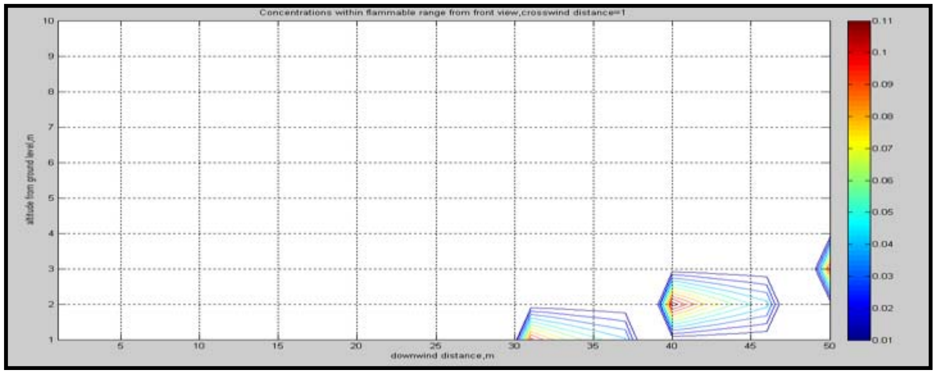

Figure 4.10: Front view plot when crosswind distance = 1m at slightly stable atmospheric condition

Analysis:

Atmospheric stability is an estimate of the turbulent mixing where stable conditions mean least amount of mixing and unstable conditions mean the most. At unstable atmospheric condition (Class A), distribution of gas does not go far in the downwind direction from the source which is shown in Figure 4.8. This is due to amount of turbulent mixing in the atmosphere. On the contrary, at slightly stable atmospheric condition (Class E), gas is not distributed well and travels further down in the downwind direction which is shown in Figure 4.10. Therefore, under unstable atmospheric condition where turbulent mixing is the most, gas distribution occurs faster and does not go far whereas under stable atmospheric condition where turbulent mixing is less, gas is not distributed well and travels further.

(ii) Effect of wind speed

Table 4.7 shows the set of input parameters to study effect of wind speed. Wind speed is changed from 2m/s to 5m/s. Figure 4.11 and Figure 4.12 are the top view plot at height 1m and crosswind distance 1m respectively.

Table 4.7: Set of parameters to study effect of wind speed

Parameters	Selection
Atmospheric stability class	D (neutral)
Terrain	Rural
Reference wind speed	**5m/s**
Reference height	10m
Gas emission rate	0.1 kg/s
Hole diameter	10mm
Release pressure	10 bar (a)

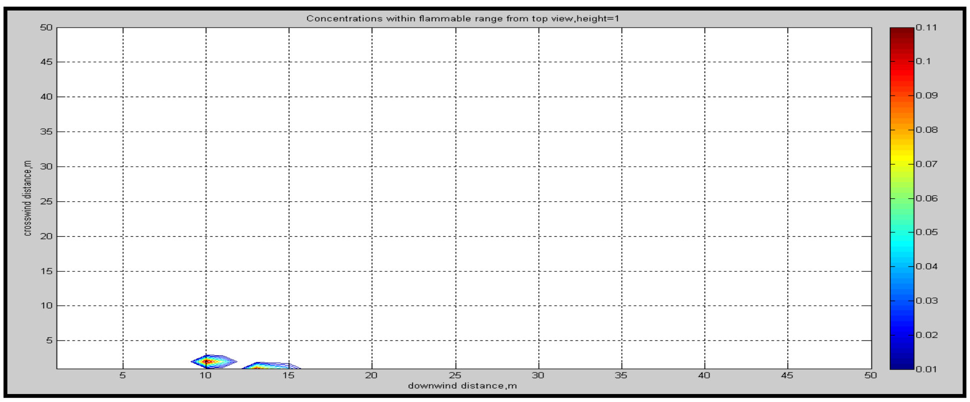

Figure 4.11: Top view plot when height = 1m at wind speed of 5m/s

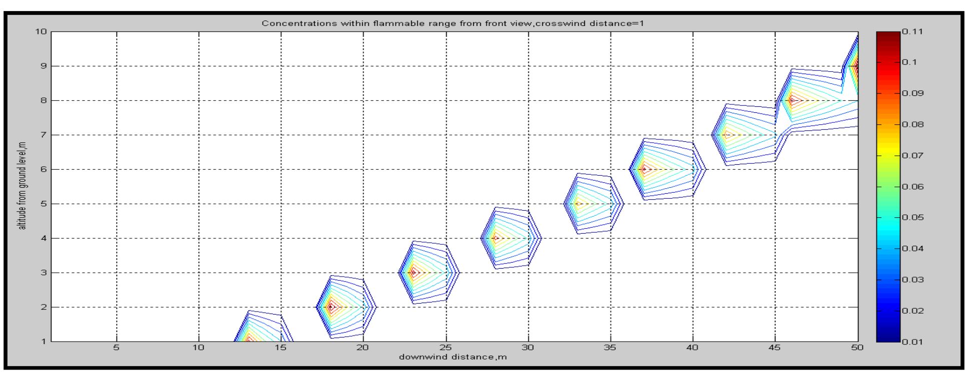

Figure 4.12: Front view plot when crosswind distance = 1m at wind speed of 5m/s

Analysis:

As wind speed increases, the gas are diluted and carried downwind faster. Therefore, gas dispersion decreases when wind speed increases and it travels further from the source of leakage.

(iii) Effect of terrain

Table 4.8 shows the set of input parameters to study effect of terrain. Terrain is changed from rural terrain to urban terrain. Figure 4.13 and Figure 4.14 show the top view and front view plot at height 1m and crosswind distance 1m respectively.

Table 4.8: Set of parameters to study effect of terrain

Parameters	Selection
Atmospheric stability class	D (neutral)
Terrain	**Urban**
Reference wind speed	2m/s
Reference height	10m
Gas emission rate	0.1 kg/s
Hole diameter	10mm
Release pressure	10 bar (a)

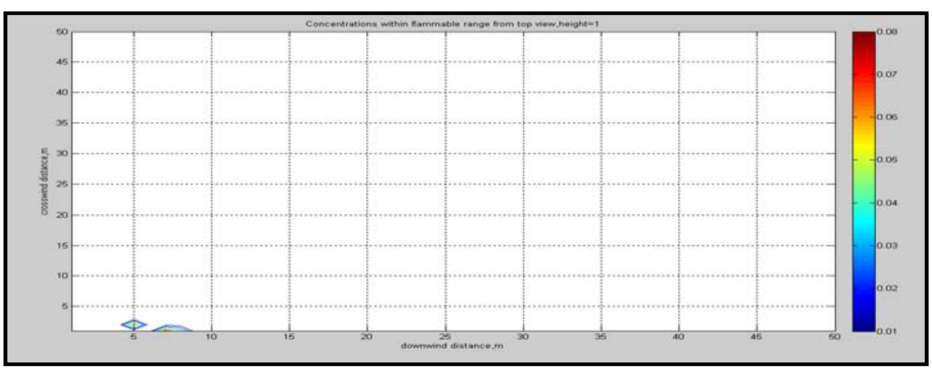

Figure 4.13: Top view plot when height = 1m in urban terrain

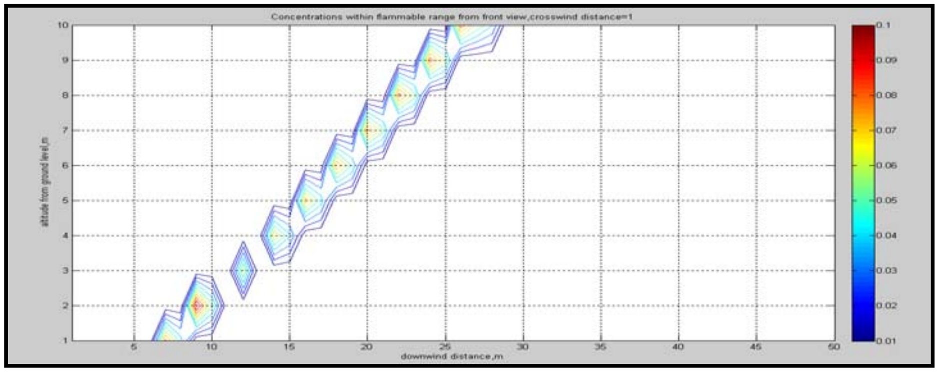

Figure 4.14: Front view plot when crosswind distance = 1m in urban terrain

Analysis:

Terrain characteristics contribute to the mechanical mixing of the air as it flows over the ground. Different terrain would lead to different gas dispersion pattern. In rural terrain, it is considered flat ground and thus fewer obstacles. On the other hand, in urban terrain, there is more obstacles which are affecting the dispersion path. The difference can be studied by comparing Figure 4.4 and Figure 4.14. In Figure 4.4(rural terrain), distribution of gas travels further downwind due to smooth and flat ground; in Figure 4.14 (urban terrain), distribution of gas does not go far from the source due to obstacles blocking away the dispersion path.

(iv) Effect of gas emission rate

Table 4.9 shows the set of input parameters to study effect of gas emission rate. Emission rate is changed from 0.1kg/s to 1.5kg/s. Figure 4.15 and Figure 4.16 show the top view and front view plot at height 1m and crosswind distance 1m respectively.

Table 4.9: Set of parameters to study effect of gas emission rate

Parameters	Selection
Atmospheric stability class	D (neutral)
Terrain	Rural
Reference wind speed	2m/s
Reference height	10m
Gas emission rate	**1.5 kg/s**
Hole diameter	10mm
Release pressure	100 bar (a)

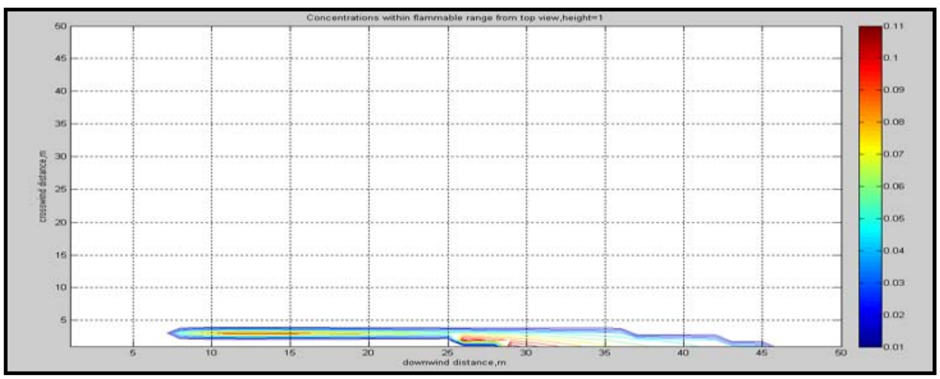

Figure 4.15: Top view plot when height = 1m with 1.5kg/s emission rate

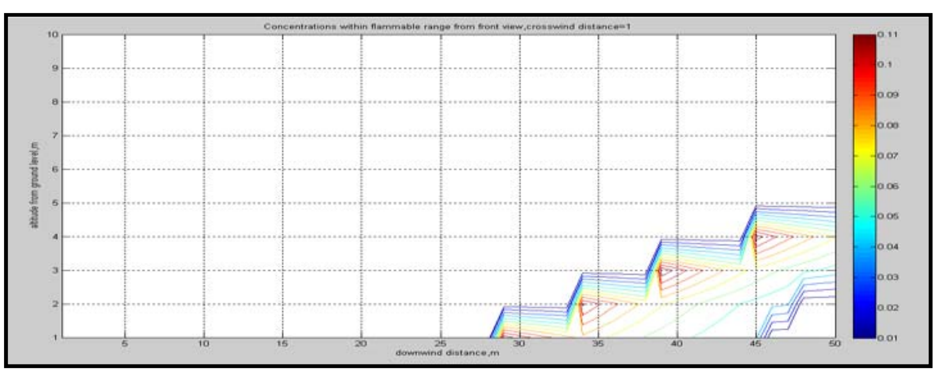

Figure 4.16: Front view plot when crosswind distance = 1m with 1.5kg/s emission rate

Analysis:

As gas emission rate increases, it means that concentration of gas in the air increases. This also implies that the coverage of gas concentration within flammable range is bigger. Effect of increasing emission rate can be easily observed by comparing Figure 4.1 and Figure 4.15. Gas accumulation would be of higher concentration and thus it has higher risk.

4.4 Placement of gas detector

In this section, possible locations of gas detector will be determined based on the simulation results in section 4.3.1. Point detectors are considered in this project, therefore, 5m head spacing is assumed.

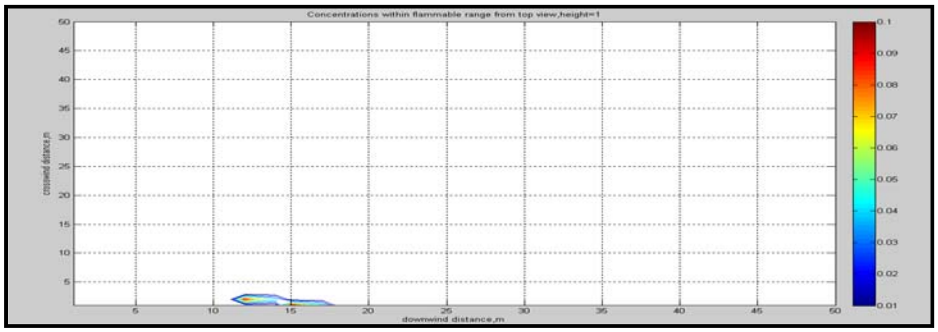

Figure 4.17: Possible locations of point gas detectors from top view plot when height = 1m

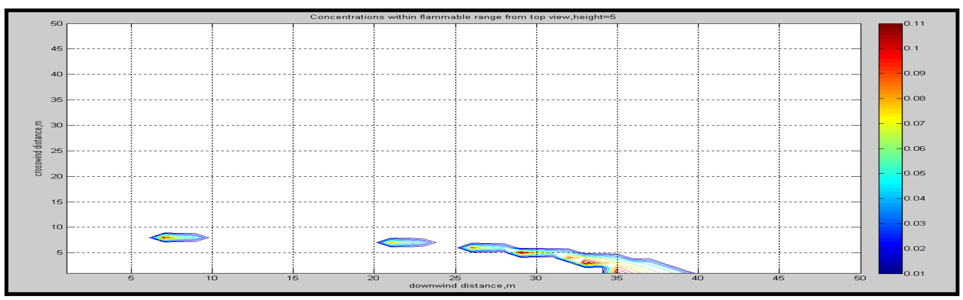

Figure 4.18: Possible locations of point gas detectors from top view plot when height = 5m

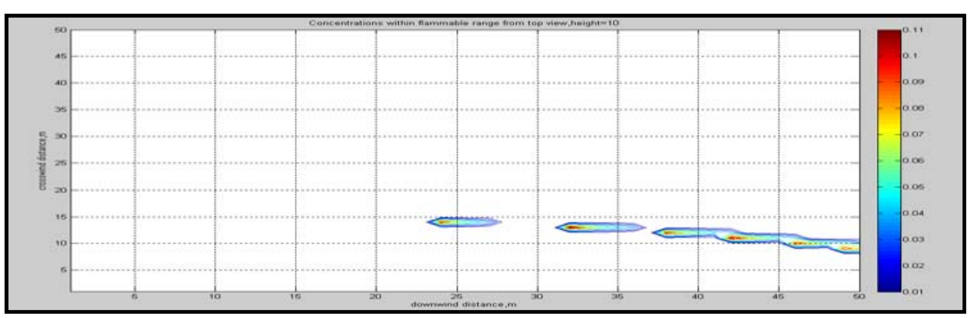

Figure 4.19: Possible locations of point gas detectors from top view plot when height = 10m

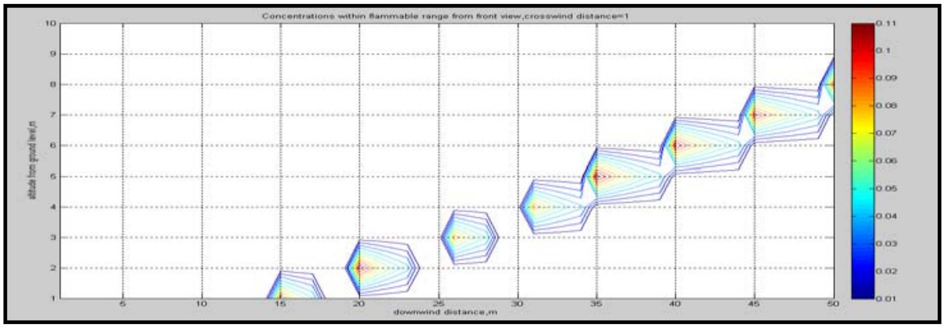

Figure 4.20: Possible locations of point gas detectors from front view plot when crosswind distance = 1m

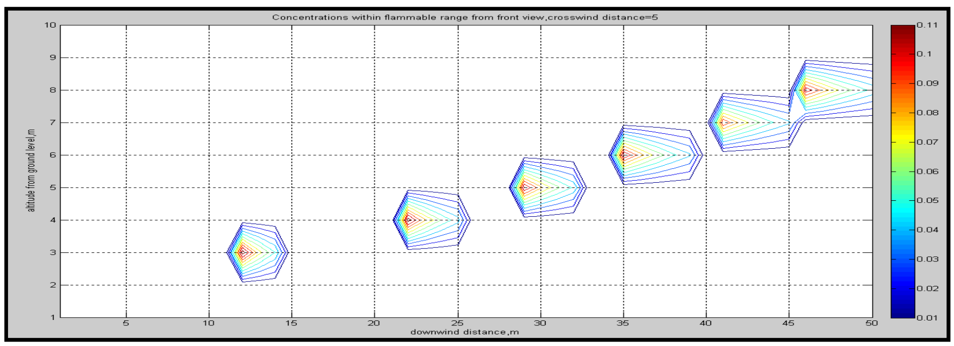

Figure 4.21: Possible locations of point gas detectors from front view plot when crosswind distance = 5m

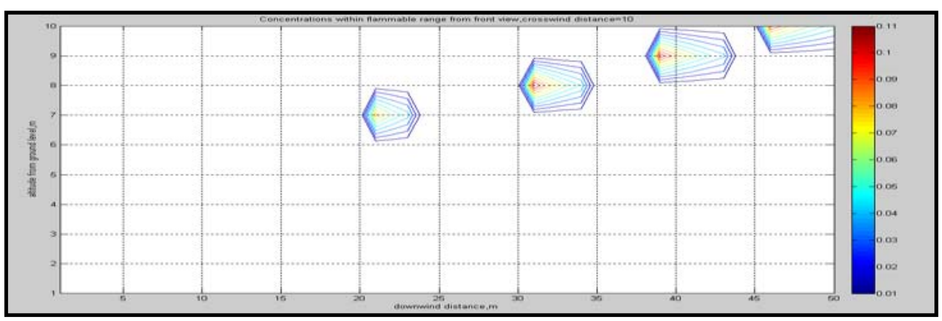

Figure 4.22: Possible locations of point gas detectors from front view plot when crosswind distance = 10m

Another view to determine the possible locations of point gas detectors is in a 3-dimension plot by combining all the slices of plane. Plot of concentrations within flammable range is shown in Figure 4.23.

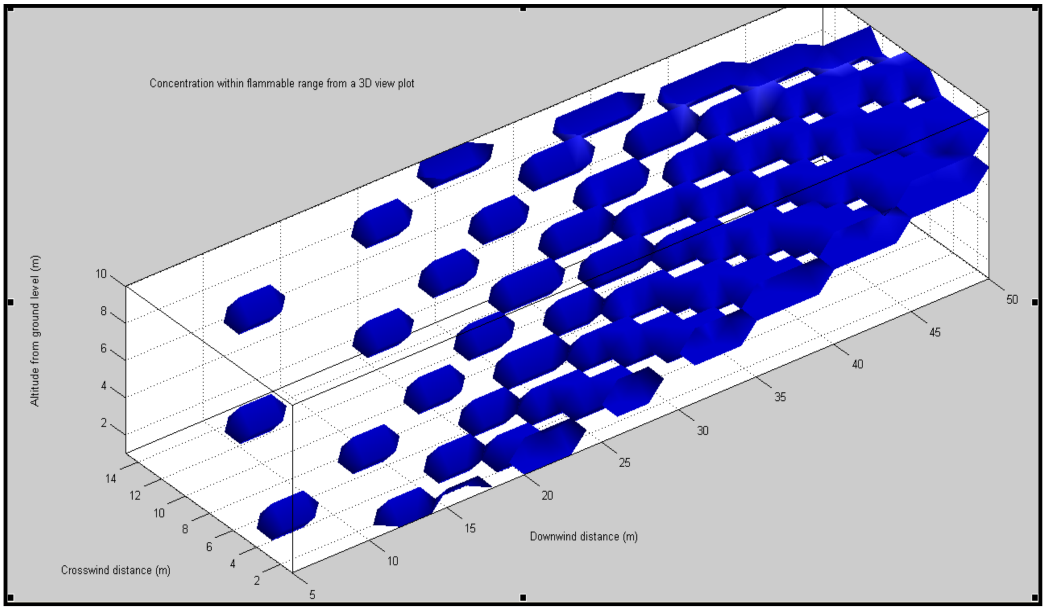

Figure 4.23: Concentration range within flammable range from 3D view plot

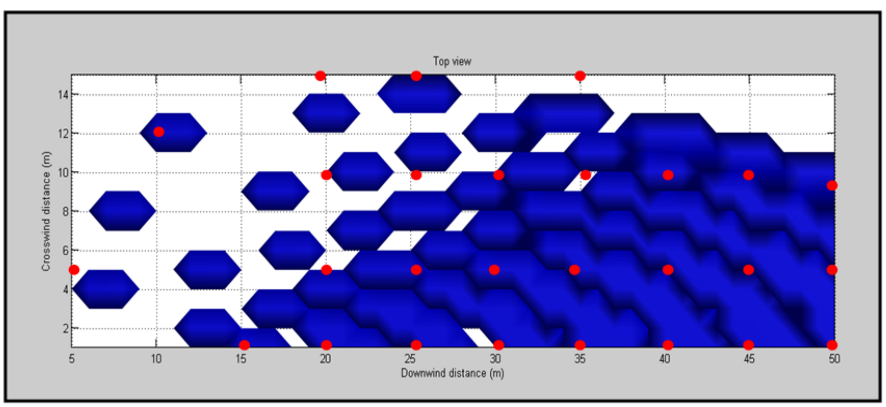

Figure 4.24: Possible location of point gas detector from top view plot

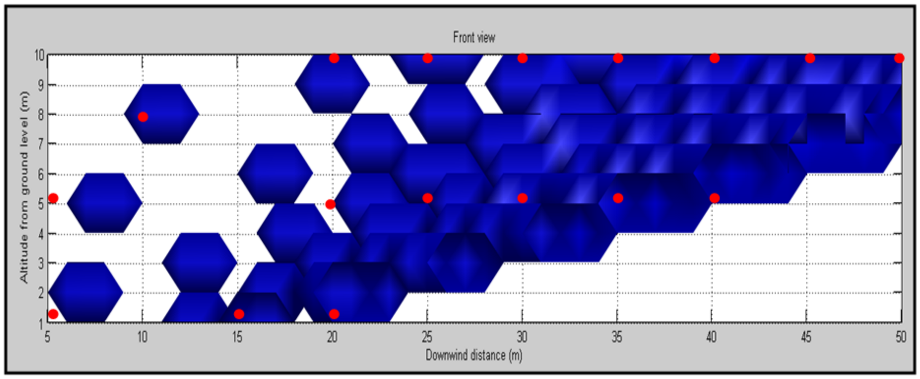

Figure 4.25: Possible location of point gas detector from front view plot

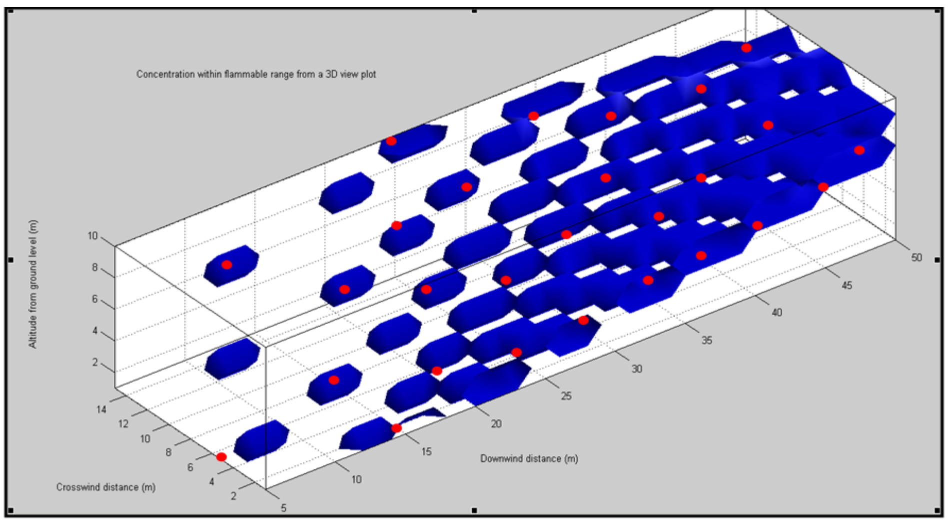

Figure 4.26: Possible location of point gas detector from 3D view plot

Location and number of point gas detector can be optimized using 3-dimension view plot. Height at which detector should be placed can be observed clearly from front view plot while top view plot shows the possible locations in terms of crosswind distance as well as downwind distance. Same as before, point detectors are considered in this project, therefore, 5m head spacing is assumed.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In conclusion, this project is about the study on the modeling of gas dispersion using Gaussian plume model. In the first chapter, background of this project was being discussed. Due to involvement of flammable or toxic materials in a process plant especially in oil and gas industry, chances of accident or substance leakage are inevitable. Even small amount of release can cause harm to people, environment and property. In order to prevent escalation of dangerous event, early detection system plays a vital role and hence must be designed and implemented. In industry, positioning of gas detectors has always been based on heuristic placement or prescriptive placement. In heuristic placement method, detectors are placed based on personal expertise and experience. It emphasizes more on the location of potential leakage rather than locations of total gas accumulation. Furthermore, leakage conditions and detection are considered ill-defined areas. Therefore, researches on dispersion and detection have been initiated to promote the use of a consistent methodology in designing detection system. In this project, the main objective is to develop a gas dispersion modeling tool to study the behavior of natural gas dispersion.

In the second chapter, literature reviews on gas dispersion modeling tools and detection system had been done. Based on previous studies completed by other researchers, various methods are being developed. Strengths and limitations of some methods are discussed. Apart from that, current technologies for detectors had been studied. Gas detectors are mainly classified into two categories, i.e. combustible gas detectors and toxic gas detectors. Placement of detectors is affected by their nature whether they are point detectors or open-path detectors.

The third chapter comprised of methodology employed throughout the project duration. Project flowchart, key milestones and Gantt chart ensure that the project is according to plan from time to time. On top of that, detailed discussion of Gaussian plume model was included in this chapter. Various factors affecting gas dispersion were being studied.

In the following chapter, results and discussions, simulation results were analyzed using the top view and front view plots. Using a set of default setting, gas dispersion behavior was first studied. Since the range of concerned concentration is the flammable range of natural gas which is within 5% lower flammable limit (LFL) to 15% upper flammable limit (UFL), other concentrations fall out of this range were filtered. From both top view and front view plots, gas is distributed predominantly in the downwind direction and drifted away as height increases. Furthermore, effects of different meteorological parameters and gas leakage conditions were studied and analyzed. This proves that the program can be utilized to study gas dispersion in different conditions.

This project has been successfully accomplished and met the objectives. A program is developed to study dispersion of light gases using Gaussian plume model. Probable gas dispersion path and locations where gas accumulation occurs have been identified and analyzed under different conditions. This project can be extended in the future to enhance the flexibility of the program. Some suggestions on the future work are listed in the following section.

5.2 Future Recommendations

Future work may include:

- Gaussian plume model applies only to neutrally buoyant dispersion of gases like natural gas. Project work can be extended to develop a program to study dispersion of heavy gases.
- One source of leakage was considered in this project. It can be extended to multiple sources to optimize locations of detector.
- Possible locations of detector were discussed based on point detection. It could be extended to include open-path detectors.

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APPENDIX A: PROJECT GANTT CHART

	FYP I														SEMBREAK	FYP II													
Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of Project Topic	■	■																											
Preliminary Research Work		■	■	■	■																								
Submission of Extended Proposal Defense						■																							
Proposal Defense								■	■																				
Progress on Project										■	■	■	■	■		■	■	■	■	■	■	■	■	■	■				
Submission of Interim Draft Report													■																
Submission of Interim Report														■															
Submission of Progress Report																							■						
Pre-EDX																										■			
Submission of Draft Report																											■		
Submission of Dissertation																												■	
Submission of Technical Paper																												■	
Oral Presentation																													■
Submission of Project Dissertation																													■

Figure A1: Project Gantt chart

APPENDIX B: MATLAB CODING

```
% CHING SHIH GIN 11910 EE
% FYP: GAS DISPERSION MODELING
%
%
% Gaussian Plume Model is the most commonly used model for gas
dispersion.
% Output of the model is a three-dimensional matrix of emitted gas
% concentration with the x-axis representing the downwind direction; y-
axis
% representing the crosswind direction and z-axis representing the
height.
%
%
% function [C] = dispersion(varargin)
%
%
% Input arguments include
% Gas emission flow rate, Q (kg/s)
%
% Stability class, A- extremely unstable; B- moderately unstable; C-
% slightly unstable; D- Neutral; E- Slightly stable; F-Moderately
stable
%
% Terrain, Urban/Rural
%
% Altitude above ground level of measured wind speed, h_ref (m)
%
% Wind speed measured at h_ref, u_ref (m/s)
%
% Stack height, h (m)
%
% Top view plot parameter, topv slices the 3D matrices of concentration
at
% topv height
%
% Front view plot parameter, frontv slices the 3D matrices of
concentration
% at frontv crosswind distance
%
%
% Example command in command window to get the 3D concentration matrix
% without plotting
% C=dispersion('topv',[],'frontv',[]);
%
% Example command in command window to get top view plot
% C=dispersion ('topv',1,'frontv',[]);
%
% Example command in command window to get front view plot
% C=dispersion ('topv',[],'frontv',1);
%
%
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% Output argument, C (kg/m^3) is a 3D matrix of Gaussian plume
distribution
% concentration after filtering out the concentrations out of flammable
% range

function [C,x,y,z] = dispersion(varargin)
%Set emission rate
%For a typical methane-rich natural gas with 10 bar release pressure
and
%10mm release hole diameter, release flow rate is 100g/s
Q = 0.1;    %Gas emission rate is 0.1kg/s

%Set default values for meteorological data
stability ='D'; %Guifford-Pasquill stability class
terrain = 'rural';  %Rural or Urban
h_ref = 10;  %Altitude above ground level of measured wind speed, m
u_ref = 2;  % Wind speed measured at h_ref, m/s
h =1;   %Stack height,m
a=0;    %Wind angle with respect to x

% Domain selection
x = [1:1:50];  % Downwind distance of sampled points
y = [1:1:50];  % Crosswind distance of sampled points
z = [1:1:10];  % Altitude above ground level

%Optional setting can be changed according to the requirements
for argnum=1:2:length(varargin)
    switch (varargin{argnum})
        case 'Q'
            Q = varargin{argnum+1};
        case 'stability'
            stability = varargin{argnum+1};
        case 'terrain'
            terrain = varargin{argnum+1};
        case 'u_ref'
            u_ref = varargin{argnum+1};
        case 'X'
            x = varargin{argnum+1};
        case 'Y'
            y = varargin{argnum+1};
        case 'Z'
            z = varargin{argnum+1};
        case 'topv'
            topv = varargin{argnum+1};
        case 'frontv'
            frontv=varargin{argnum+1};

    end
end

% Form row vectors from x, y and z
if (size(x, 1)==1)
    x = x';
end
if (size(y, 1)==1)
    y = y';
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end
if (size(z, 1)==1)
    z = z';
end

%Mapping x and y to new wind angle
x_new=x.*cos(a)-y.*sin(a);
y_new=x.*sin(a)+y.*cos(a);

% Compute the dispersion coefficients. For both rural and urban cases,
% dispersion coefficients are obtained from Pasquill-Guifford curves.
switch(terrain)
    case'rural'
        switch(stability)
            case 'A'
               sigma_y=0.22.*x.*(1+0.0001.*x).^(-0.5);
               sigma_z=0.20.*x;
                      %Wind speed correction factor
                      p = 0.07;
            case 'B'
                sigma_y=0.16.*x.*(1+0.0001.*x).^(-0.5);
                sigma_z=0.12.*x;
                      p = 0.07;
            case 'C'
                sigma_y=0.11.*x.*(1+0.0001.*x).^(-0.5);
                sigma_z=0.08.*x.*(1+0.0002.*x).^(-0.5) ;
                p = 0.10;
            case 'D'
                sigma_y=0.08.*x.*(1+0.0001.*x).^(-0.5);
                sigma_z=0.06.*x.*(1+0.0015.*x).^(-0.5) ;
                p = 0.15;
            case'E'
                sigma_y=0.06.*x.*(1+0.0001.*x).^(-0.5);
                sigma_z=0.03.*x.*(1+0.0003.*x).^(-1) ;
                p = 0.35;
            case'F'
                sigma_y=0.04.*x.*(1+0.0001.*x).^(-0.5);
                sigma_z=0.016.*x.*(1+0.0003.*x).^(-1) ;
                p = 0.55;

        end


    case 'urban'
        switch (stability)
            case 'A'
                sigma_y=0.32.*x.*(1+0.0004.*x).^(-0.5);
                sigma_z=0.24.*x.*(1+0.001.*x).^(-0.5);
                p = 0.15;
            case 'B'
                sigma_y=0.32.*x.*(1+0.0004.*x).^(-0.5);
                sigma_z=0.24.*x.*(1+0.001.*x).^(-0.5);
                p = 0.15;
            case 'C'
                sigma_y=0.22.*x.*(1+0.0004.*x).^(-0.5);
                sigma_z=0.20.*x;
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                p = 0.20;
            case 'D'
                sigma_y=0.16.*x.*(1+0.0004.*x).^(-0.5);
                sigma_z=0.14.*x.*(1+0.003.*x).^(-0.5);
                p = 0.25;
            case 'E'
                sigma_y=0.11.*x.*(1+0.0004.*x).^(-0.5);
                sigma_z=0.08.*x.*(1+0.0015.*x).^(-0.5);
                p = 0.40;
            case 'F'
                sigma_y=0.11.*x.*(1+0.0004.*x).^(-0.5);
                sigma_z=0.08.*x.*(1+0.0015.*x).^(-0.5);
                p = 0.60;

        end
end

% Form 3D matrices of sigma y and sigma z
sigma_y=shiftdim(sigma_y, -1);
sigma_z=shiftdim(sigma_z, -1);
sigma_y=repmat(sigma_y, [length(y) 1 length(z)]);
sigma_z=repmat(sigma_z, [length(y) 1 length(z)]);



% Compute wind velocity and create 3D matrix of wind speed
u_matrix=((z./h_ref).^p).*u_ref;
u_matrix=shiftdim(u_matrix, -2);
u_matrix=repmat(u_matrix, [length(y) length(x) 1]);



% Form 3D matrices of x, y, and z
sx=size(x_new, 1);
sy=size(y_new, 1);
sz=size(z, 1);
x1=shiftdim(x, -1);
x=repmat(x1, [sy 1 sz]);
y=repmat(y, [1 sx sz]);
z1=shiftdim(z, -2);
z=repmat(z1, [sy sx 1]);




% Calculate the concentration
C=Q./(2.*pi.*u_matrix.*sigma_y.*sigma_z).*exp...
    ((-y.^2)./(2.*sigma_y.^2)).*((exp((-z-h).^2./...
    (2.*sigma_z.^2)))+(exp((-z+h).^2./(2.*sigma_z.^2))));  %kg/m^3

%Set all NaN or inf values into 0
ii=find(isnan(C)| isinf(C));
C(ii)=0;



%Filter the values stay within the flammable range by replacing others
to 0
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%LFL - UFL of natural gas is 5% -15%
%Convert the flammable limit to kg/m^3 obtain flammable range of
%0.040kg/m^3 - 0.120kg/m^3
oor = find((C<0.04)|(C>0.12));
C(oor)=0;



%Show the plot of concentration from top view only when there is 'topv'
in
%input argument
%'topv' defines at which level of height where the top view is taken
if topv~=0
    %frontv=[];
    % Obtain the layer of array from C in order to plot top view at
'topv'
    % height
    top=C(:,:,topv);
    contour(top);
    grid;
    xlabel('downwind distance,m');
    ylabel('crosswind distance,m');
    title(['Concentrations within flammable range from top
view,height=',sprintf('%d',topv)]);
    colorbar;

end



% Show the plot of concentration from front view only when there is
% 'frontv' in input argument
%'frontv' defines the crosswind distance where the front view is taken
if frontv~=0
    %topv =[];
    % Obtain the layer of array from C in order to plot front view at
    % 'frontv' crosswind distance
    front=(shiftdim((C(frontv,:,:)),1))';
    contour(front);
    grid;
    xlabel('downwind distance,m');
    ylabel('altitude from ground level,m');
    title(['Concentrations within flammable range from front
view,crosswind distance=',sprintf('%d',frontv)]);
    colorbar;

end
```