COMPUTATIONAL FLUID DYNAMICS STUDY OF AIR POLLUTANT DISPERSION AROUND KUANTAN

NORLIYANA BINTI ERAIN

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

DECLARATION OF THESIS AND COPYRIGHT

Author's Full Name : NORLIYANA BINTI ERAIN

Date of Birth : 08 OCTOBER 1989

Title : COMPUTATIONAL FLUID DYNAMICS STUDY OF AIR POLLUTANT DISPERSION AROUND KUANTAN

Academic Session : SEM 2 2018/2019

I declare that this thesis is classified as:

☐ CONFIDENTIAL (Contains confidential information under the Official Secret Act 1997)*

☐ RESTRICTED (Contains restricted information as specified by the organization where research was done)*

☑ OPEN ACCESS I agree that my thesis to be published as online open access (Full Text)

I acknowledge that Universiti Malaysia Pahang reserves the following rights:

1. The Thesis is the Property of Universiti Malaysia Pahang
2. The Library of Universiti Malaysia Pahang has the right to make copies of the thesis for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by:

____
(Student's Signature)

891008-11-5294
New IC/Passport Number
Date:

____
(Supervisor's Signature)

Assoc. Prof. Dr. Jolius Gimbun
Name of Supervisor
Date:

NOTE : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach a thesis declaration letter.

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

____

(Supervisor's Signature)

Full Name : DR. JOLIUS GIMBUN

Position : ASSOCIATE PROFESSOR

Date :

____

(Co-supervisor's Signature)

Full Name : EN NORAM IRWAN BIN RAMLI

Position : LECTURER

Date

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : NORLIYANA BINTI ERAIN

ID Number : MKC15004

Date :

COMPUTATIONAL FLUID DYNAMICS STUDY OF AIR POLLUTANT DISPERSION AROUND KUANTAN

NORLIYANA BINTI ERAIN

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Master of Science

Faculty of Chemical & Natural Resources Engineering

UNIVERSITI MALAYSIA PAHANG

AUGUST 2019

ACKNOWLEDGEMENTS

First and foremost, I want to thank my supervisor Assoc. Prof. Dr. Jolius Gimbun on his brilliant ideas in computational fluid dynamics study and endless time during my first step doing this research till the end. His continuous support encourages me to finish this research. Secondly, I also want to show my gratitude to my co-supervisor En Noram Irwan bin Ramli for his impressive ideas in topographical design and research writing.

I am also heartily thankful to Ministry of Higher Education Malaysia for the MyBrain15 scholarship towards the end of my study. Also, I acknowledge financial support from UMP through grant RDU150314. Besides that, thank you so much to the lectures and members of staff of Centre of Excellence for Advanced Research in Fluid Flow (CARIFF) and Faculty of Chemical and Natural Resource Engineering (FKKSA), UMP for their help and continuity support either mentally or physically. I really want to show my appreciation to my friend, Law Woon Phui who helps me in finishing this research. She never gives up and her patience also encourages me to finish this research no matter what.

Last but not least, my special thanks goes to my beloved husband, parents and family members for their full support and encouragement to complete this study.

ABSTRAK

Pencemar udara seperti klorin berbahaya kepada benda hidup, alam sekitar dan struktur bangunan apabila ia terkumpul di udara dalam kepekatan yang cukup tinggi. Pendedahan kepada gas klorin boleh menyebabkan kesan akut atau kronik bergantung kepada kepekatannya. Di malaysia, kawasan perindustrian Gebeng merupakan salah satu kawasan perindustrian terbesar yang terdiri daripada pelbagai kilang pemprosesan seperti petrokimia dan kilang polimer di mana klorin biasanya digunakan dalam petrokimia dan polimer seperti Polyplastics Asia Pacific, Lynas, Petronas-MTBE dan Kaneka Malaysia. Oleh sebab itu, terdapat potensi yang tinggi untuk pembebasan tidak sengaja klorin di kawasan yang dipilih itu dan juga adalah sebab utama dalam memilih klorin sebagai bahan pencemar. Penyebaran pencemar udara dipengaruhi oleh keadaan cuaca dan topografi. Pengukuran dalam bidang eksperimen mempunyai batasan untuk memberikan maklumat terperinci terhadap aliran udara di kawasan kompleks dan oleh itu *computational fluid dynamics* (CFD) digunakan untuk memberikan maklumat yang komprehensif mengenai pengangkutan spesies dan pergolakan pada masa yang sama. Untuk memastikan ketepatan aliran udara pada model CFD, ia mesti disahkan sebelum ia digunakan secara rutin. Jadi, salah satu objektif kajian ini adalah untuk mengkaji aliran angin melalui model yang berskala kecil dengan menggunakan pengukuran *particle image velocimetry* (PIV) dan membandingkannya dengan simulasi CFD. Untuk mencapai objektif ini, parameter seperti kelajuan angin dan arah dikumpulkan dan akan digunakan untuk mendapatkan keputusan dengan menggunakan CFD sebagai alat simulasi. Angin timur biasa dengan kelajuan angin 1.78 m/s digunakan. Aliran perolakan telah dimodelkan dengan menggunakan model *scale-adaptive simulation* (SAS). Model ini telah disahkan dengan pengukuran PIV pada model topografi skala kecil. Ramalan CFD menunjukkan persetujuan yang baik dengan sisihan antara 1.5 hingga 2.6 % daripada pengukuran PIV itu. Oleh itu, model ini boleh digunakan untuk menilai kesan yang menggabungkan permukaan rupa bumi, arah angin dan kelajuan pada penyebaran pencemaran di sekitar kawasan perindustrian Gebeng. Hasil kajian mendapati bahawa kawasan kediaman R1 (Kampung Baru Gebeng, Tanjung Rhu, Kampung Sungai Ular, Kampung Darat Sungai Ular dan Kampung Baging) dan R2 (Kampung Selamat, Kampung Berahi, Kampung Balok, Kampung Seberang Balok, Kampung Balok Baru dan Kampung Balok Perdana) akan tejejas apabila kebocoran klorin berlaku pada bulan Jun hingga September dan November hingga Jan. Pelepasan yang tidak disengajakan gas klorin ini mungkin telah membawa kepada hal kecemasan. Oleh itu, ia juga penting untuk membangunkan pelan pemindahan keselamatan yang sesuai sekiranya berlaku kemalangan kebocoran klorin. Laluan dan pusat pemindahan keselamatan yang sesuai adalah dicadangkan untuk kes apabila kawasan perumahan R1 dan R2 terjejas.

ABSTRACT

Air pollutant like the chlorine is harmful to living things, environment and building structures when it accumulates in the air in sufficiently high concentration. Exposure to chlorine gas can cause acute or chronic effects depending on its concentration. In Malaysia, Gebeng industrial area is one of the largest industrial area that consists of various processing plant such as petrochemical and polymer plant where the chlorine is commonly used in the petrochemical and polymer plants such as Polyplastics Asia Pacific, Lynas, Petronas-MTBE and Kaneka Malaysia. So, there are high potential to accidental release of chlorine in the selected area thus as the main reason on choosing the chlorine as pollutant. Air pollutant dispersion is significantly affected by the meteorological and topographical conditions. The field experiment measurement has the limitations to provide detail information of air flow on complex terrain and hence computational fluid dynamics (CFD) techniques is applied to provide the comprehensive information on the species transport and turbulence simultaneously. To ensure the accuracy of the air flow on CFD model, it must be validated before it routinely used. So, one of the objectives for this study is to model the wind flows past a scaled-down model using particle image velocimetry (PIV) measurement and compare with the CFD simulation. To achieve this objective, parameter such as wind speeds and directions was collected and will be used to obtain the results by using CFD as a simulation tools. The typical eastern wind with wind speed 1.78 m/s is used. The turbulence flow was modelled using scale-adaptive simulation (SAS) turbulence model. The model was validated with the PIV measurement on the scale down topography model. The CFD prediction showed good agreement with the error ranging 1.5 to 2.6% from the PIV measurement. Hence, the model can be used to evaluate the combine effect of surface terrain, wind direction and speed on the pollution dispersion around Gebeng industrial area. It was found that the residential area R1 (Kampung Baru Gebeng, Tanjung Rhu, Kampung Sungai Ular, Kampung Darat Sungai Ular and Kampung Baging) and R2 (Kampung Selamat, Kampung Berahi, Kampung Balok, Kampung Seberang Balok Kampung Balok Baru and Kampung Balok Perdana) are affected when the chlorine leakage occurs during June to September and November to January, respectively. Accidental release of this chlorine gas may have led to the emergencies. Hence, it is also important to develop a suitable safety evacuation plan in the event accidental chlorine leak. Suitable safety evacuation route and points is proposed for the case when the residential area R1 and R2 are affected.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

α	Speed of sound (m/s)
C_μ	Coefficient of turbulent viscosity
$C_{1\epsilon}$	Constant of production rate
$C_{2\epsilon}$	Constant of destruction rate
$C_{3\epsilon}$	Coefficient of production rate
D_m	Diffusion coefficient (m^2/s)
D_t	Turbulent diffusion coefficient (m^2/s)
G_k	Production term of turbulence kinetic energy
G_b	Production term due to turbulence buoyancy
g_i	Gravitational vector
$\vec{J}$	Diffusion flux
k	Turbulent kinetic energy (m^2/s^2)
L	Length scale in SAS model
L_{vK}	Von Karman length scale
M_t	Turbulent Mach number
P_k	Production rate term in SAS model
Pr_t	Turbulent Prandtl number
R	Source term by chemical reaction
S	Mean strain rate
S_i	Additional term
T	Temperature (K)
$\vec{u}$	Velocity (m/s)
Y	Mass fraction
Y_M	Dilatation dissipation term
β	Thermal expansion coefficient
μ_t	Turbulent viscosity (kg/m.s)
ρ	Density (kg/m^3)
μ	Viscosity of fluid (kg/m.s)
σ_ϵ	Turbulent Prandtl number for turbulent dissipation rate
σ_k	Turbulent Prandtl-Schmidt number for turbulent kinetic energy
σ_Φ	Turbulent Prandtl number for SAS model

ε	Turbulent dissipation rate (m^2/s^3)
Φ	Coefficient
γ	Ratio of specific heat
$\zeta_1, \zeta_2, \zeta_3$	Constant

LIST OF ABBREVIATIONS

AABL	Adiabatic atmospheric boundary layer
ABS	Acrylonitrile butadiene styrene
AP	Aspiration probe
CCD	Charged-couple device
CFD	Computational fluid dynamics
FFID	Fast flame ionisation detector
GIE	Gebeng Industrial Estate
IBM	Immersed Boundary Method
LDA	Laser Doppler anemometry
LDV	Laser Doppler velocimetry
LES	Large eddy simulation
LS-PIV	Large scale-particle image velocimetry
LST	Light scattering technique
MADM	Module for the atmospheric dispersion modelling
MIC	Methyl isocyanate
MIDA	Malaysian Investment Development Authority
MSL	Mean sea level
MTBE	Methyl tert-butyl ethylene
PIV	Particle image velocimetry
PPM	Parts per million
PTV	Particle tracking velocimetry
RANS	Reynolds-averaged Navier-Stokes
RKE	Realizable k-ε
RNG	Renormalized k-ε
RSM	Reynolds stress model
SAS	Scale adaptive simulation
SKE	Standard k-ε
TIN	Triangulated irregular network
URANS	Unsteady Reynolds-averaged Navier-Stokes

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Air pollution may affect human health, ecosystems and materials in a variety of ways, and deserves appropriate attention. Even long distances away to other media, the atmosphere can act as a means for transporting local pollution emissions to other locations. As we all know, air pollution is the presence of toxic chemicals or compound in the air, at levels that pose a health risk. It can occur in many forms, but can generally be a mixture of gases, dust particles, fumes or smoke or odour when they are introduced into the atmosphere. Three main sources of air pollutions are the emissions from the industries and manufacturing activities, fossil fuels burning, also from the household and farming chemicals. In the abundance of industrial estate in the country, one of the main contributors to the toxic air pollutions is from chemical industrial sector which led to the worst accident. Accidents in the chemical industry may occur due to failure of the process equipment, operational mistakes, and human error or due to external interruptions like natural disasters. This study highlighted the accidental release of chlorine. The leakage of chlorine may harm the living things, buildings structure and the environment when it accumulates in the air in sufficiently high concentration. Based on the Institution of Occupational Safety and Health, chlorine has a detectable odour even at low concentration between 0.1 and 0.2 ppm (IOSH, 2008). Exposure to chlorine can cause acute or chronic effects depending on its concentration. For instance, chlorine can cause a tickling of nose and throat at the level of 0.014 ppm (Calabrese and Kenyon, 1991). A mild irritation of eyes, respiratory system, and headache can occur at levels above 1 ppm. Higher level at 30 ppm may cause a life-threatening effect such as chest pain, nausea, dyspnea and cough. Meanwhile pneumonitis and pulmonary edema can occur at a level ranging from 46 to 60 ppm (HHS, 1993). Chlorine can cause death after

30 min exposure to 430 ppm. Thus, it is dangerous when accidental leaks of chlorine occur nearby the residential area.

Several chlorine leak incidents occurred in Malaysia in the past 3 years. On 18 September 2016, the chlorine gas leak incident happened in Malay–Sino Chemical Industries Sdn Bhd, Bukit Merah industrial area, Perak. The incident was triggered by a ferric acid tank fall and collapse. The leaked acid reacted with sodium hypochlorite in the pipe which produces chlorine gas. Chlorine gas concentration up to 3 ppm was detected around the factory. Two workers and one fireman were being hospitalized and one of the workers was diagnosed with pneumonia. Part of residents nearby the factory suffered irritation to eyes, nose and throat (Yeap, 2016). On 21 July 2017, chlorine leakage happened at the Water Department in Kota Belud, Sabah. The leak is caused by a hole in one of the valves connected to the chlorine tank. They managed to stop the leakage by tightening the valve immediately. No injury was reported from this incident (Goh, 2017). Another chlorine leak incident is occurring on 28 September 2017 where the chlorine gas leaked from illegal dumping of several chlorines drum close to residential area at Kampung Tambak Paya, Melaka. The chlorine plume dispersed into the air approximately within 1 km in radius. During this incident, about fifty residents were hospitalized, including four firemen. Most of them suffered from breathlessness. About two hundred and fifty residents were evacuated (Koh, 2017). Latest issue was in October 2018 when an excavator accidentally ran over a chlorine gas cylinder, causing a leak at the scrap metal yard in Miri, Sarawak. The leak went unnoticed until the owner of the scrap metal yard with his eight workers began experiencing dizziness, with several of them subsequently fainting. Personnel from the Lopeng Fire and Rescue department were deployed to the scene to deal with the gas after receiving an emergency call from Miri Hospital whereby the affected workers got their treatment (Laeng, 2018). It is clear from abovementioned incidents that the safety of plant workers and nearby residents as well as the firemen can be seriously affected. The chlorine is commonly used in the petrochemical and polymer plants such as Petronas-MTBE and Poly-plastics Asia Pacific. To the best of our knowledge, no previous study the chlorine dispersion around Gebeng industrial area and hence the risk of chlorine leak is the concern of this study. Besides, it is important to develop a suitable safety evacuation plan for residents to avoid fatality in the event accidental chlorine leak.

Air pollution dispersion is affected by many factors such as meteorological conditions, the emission height, the pollutant source, and topographical condition. Different types of topography conditions may affect the dispersion of air pollutants. De la Torre et al. (2015) found that the wind pattern over Southern Andes Mountain is affected by the local topography. Fesquet et al. (2009) also found that the wind pattern is more affected by the terrain condition compared to the atmospheric stability. This has resulted in increased research to investigate the atmospheric flow and pollutant dispersion in complex terrain using experimental and numerical methods (Deng et al., 2018; Liu et al., 2016; Michalek and Zancho, 2015). Finardi and Morselli (1997) reported that different terrain flows can effectively influence the atmospheric dispersion of pollutants. Wind speed and wind directions may affect the dispersion of air pollutants as well. In the windy weather, it can cause the pollution to disperse while in the still weather it allows the pollution to build up. The pollutions levels may higher in the town or city or residential if the wind is blowing from the industrial area. This is one of the main objectives of this study.

Basically, satellite-based instrument like the multi-angle imaging spectro-radiometer is ideally used to observe and understand the atmospheric flow in a complex terrain. However, this method is not suitable for routine daily monitoring and may produce an incorrect data due to its low frequency (Liu et al., 2009). Experimental measurement such as particle image velocimetry (PIV) is widely used in capturing the velocity flow of topographic terrain study (Rasouli et al., 2009; Kamada et al., 2019). However, this technique is not practical for a large scale terrain study. Alternatively, computational fluid dynamics (CFD) can provide comprehensive information on the fluid flow around the complex terrain such as the Gebeng industrial area in the present work. Reynolds-averaged Navier-Stokes (RANS) based turbulence models such as k-ε models are commonly used to model atmospheric flow and pollutant dispersion around the complex terrain as they offer relatively fast computations of the mean flow in most cases. For instance, Balogh et al. (2012) investigated the wind flow in a complex terrain using standard k-ε (SKE) model. They reported that SKE is capable to predict the mean wind velocity, but gave a poor prediction of turbulent flow. Furthermore, Blocken et al. (2007) claimed that the standard wall function of RANS model caused a large discrepancy between the CFD prediction and experimental results. The previous works showed that RANS models may provide a good prediction of the mean velocity, but may not provide an accurate prediction of turbulent flow. Kumar et al. (2017) recommended the use of unsteady RANS instead of the RANS to resolve the plume dispersion under an unstable wind condition. The use of unsteady RANS can somewhat provide some characteristic of turbulent flow however an accurate prediction is still not achieved.

Besides the RANS models, large eddy simulation (LES) is also often used for the turbulent flow in complex terrain. LES generally performs well because it resolved directly the larger turbulent eddies and modelled the smaller eddies near the boundary layers using a sub-grid scale approach. Tominaga and Stathopoulos (2011) performed a simulation of pollution dispersion in a street canyon using renormalized (RNG k-ε) and LES. They reported that the overall recirculation flow pattern predicted using LES closely resemble to the one obtained from experimental measurement. RNG k-ε underestimated the turbulent diffusion in the street canyon, while the LES resolved well the concentration distribution.

A CFD modelling of SKE, Reynolds stress model (RSM) and LES of pollutant dispersion in an urban street canyon has been investigated by Salim et al. (2011). They performed detail simulation on the mean flow and pollutant concentration. It was found that LES performed better than the SKE and RSM in resolving the transient mixing, dispersion and diffusion of the pollutant, although longer computational time is needed. Simulation using SKE, RSM and LES took about two hours, a day and two weeks, respectively to complete. Gousseau et al. (2011) performed a study on the gas pollutant dispersion around a building group in downtown Montreal by comparing the accuracy of RANS and LES models. The finding showed that LES provided a better prediction of the pollutant flow and concentration compared to the SKE. Nevertheless, they reported that LES requires seven times more computational demand than SKE for similar cases. LES simulation is costly because the grid resolution requirement at the boundary layer does not differ to that of direct numerical simulation (DNS) (Spalart, 2000). A massive number of grid cells required for a large terrain (15 km x 14 km) in the present work when LES is used. Furthermore, LES is relatively sensitive to computational grid.

A hybrid turbulence model like the scale adaptive simulation (SAS) resolve the dynamics of the larger scale eddies like the LES and adopting RANS in modelling the smaller eddies near the wall boundary (Rotta, 1972). SAS is not sensitive to computational grid, unlike the LES (Menter and Egorov, 2006). SAS has been used to study air pollution such as the dispersion of vehicular pollutants in deep street canyons (Murena and Mele, 2016) and pollutant dispersion around a model building (Jadidi et al., 2018). However, the previous works only emphasized on the pollutant dispersion around buildings with a height below 20 m. To the best of the author knowledge, no previous study using SAS to study pollutant dispersion around complex terrain e.g. hills with height up to 215 m. In addition, limited works concerning the effect of topographical and wind condition on the pollutant dispersion using the SAS model. Hence, this is one of the aims of this work.

1.2 Problem Statement

Air pollutant like the chlorine is harmful to living things, environment and building structures when it accumulates in the air in sufficiently high concentration. Exposure to chlorine gas can cause acute or chronic effects depending on its concentration. Main contributor to the chlorine accident is from the industrial sector. Chlorine can act as toxic gas when it accidentally disperses into the air by the failure of process equipment, human error and operational mistakes. In Malaysia, several chlorine leak incidents happened in the past due to the aforementioned factors. The incidents affect the nearby residential area causing people to be treated in hospital and in some instances treated critically in the intensive care unit of the hospital. Hence, it is important to study how the chlorine disperses from the industrial area to the nearby residential area. The area of concern of this work is Gebeng industrial area, which consists of several chemical processing plants that is using chlorine, such as Polyplastics Asia Pacific and Petronas-MTBE. This study area is selected because it is located nearby the residential area, which is situated only 2 km in radius range from residential area and located at the main road connecting Terengganu to Pahang via Gebeng bypass highway. Surface terrain at Gebeng industrial contains a combination of several hills and flat terrain which may complicates the prediction of chlorine dispersion. Moreover, the wind speed and direction is affected by the monsoon season (northeast and southwest) with two inter-monsoons. Prior to this work, no previous study available on chlorine dispersion around Gebeng industrial area in the event of an accidental gas leak, and hence, this is the aim of the current work.

Pollution dispersion is significantly affected by the terrain surface and meteorological condition (de la Torre et al., 2015; Sudarsan et al., 2016). Gebeng industrial area is surrounded by the combination of hills and flat terrain. In addition, the monsoon wind around Gebeng industrial area is changing in a cyclic pattern of four times a year. Hence, it is important to study the effect of terrain surface and wind condition on the chlorine leak dispersion. Ideally, satellite or laser based experimental measurement is the best method to study and understand the air flow in a lab scale unit. However, the experimental methods have limitation to provide detail information of flow around complex terrain. Alternatively, CFD simulation was used since it can provide comprehensive information on the species transport and turbulence simultaneously. The study of air flow around Gebeng industrial area is not available from literature, and hence the CFD model must be validated before it can be routinely used. The validation was performed by comparing the CFD simulation with the PIV measurement on a scale-down terrain model. Once validated, the model can be used to evaluate the combine effect of surface terrain, wind direction and speed on the pollution dispersion around Gebeng industrial area. Accidental release of this chlorine gas may lead to the emergencies. Hence, this work aims to develop a suitable safety evacuation route in the event accidental chlorine leak based on the predicted chlorine dispersion plume. This evacuation plan might be usable as a guide to the authority to evacuate the affected area.

1.3 Objectives of Study

The objectives of the study are:

i. To model the wind flows past a scaled-down terrain model using PIV and to compare with the CFD simulation.

ii. To elucidate the effect of terrain surface and wind condition on the chlorine dispersion around Gebeng industrial area.

iii. To propose the safety evacuation route in the event of accidental chlorine leak based on the predicted chlorine dispersion plume.

1.4 Scopes of Study

The following scopes are necessary to achieve the research objectives:

i. To build a topographical model using SketchUp software of Gebeng Industrial area. The triangulate irregular network (TIN) structure is created by using a Sandbox Tool.

ii. To create the real solid surface from the TIN structure file using Rhinoceros software to create an ANSYS GAMBIT readable geometry.

iii. To create the CFD case volume in ANSYS GAMBIT before exporting the model in ANSYS Workbench Mesher for mesh generation purpose.

iv. To create a 1:4500 scale on topographical model of Gebeng industrial area using a 3D printer based on Google Earth geometry.

v. To develop a wind tunnel rig for PIV measurement of air flow around the scale down Gebeng industrial area model (1:4500).

vi. To compare the flow field around the scale-down Gebeng industrial area and CFD prediction.

vii. To analyse the effect of wind speed, wind direction and terrain surface on the chlorine leak dispersion around Gebeng industrial area. The wind speed and direction is based on the meteorological data at the beginning of this work, i.e. 2014.

viii. To identify a safety evacuation route in the event of a gas release accident at Gebeng industrial area.

1.5 Contribution of this Work

This work is to alert the residents about the potential risk of chlorine gas leaks from Gebeng industrial area. The terrain surface and the wind condition can significantly affect the chlorine gas dispersion, which may affect the nearby residential areas. The prediction result may provide useful guide to estimate the risk zone from a potential chlorine leak which can be used for evacuation plan. This evacuation plan can be considered as the industrial accident preparedness and the authority can use as a guide in the emergency release.

1.6 Structure of Thesis

The structure of the remainder thesis is outlined as follows:

Chapter 2 identifies the problems existed from the air pollutant leakage that occurred in industrial sector. The previous CFD studies on air pollutant dispersion are reviewed. The numerical and experimental methods used for air pollutant dispersion are discussed. The knowledge gaps are highlighted.

Chapter 3 describes the three-dimensional geometry drawing, meshing, surface draping, numerical setup, simulation and data extraction by using SketchUp, Rhinocerous, GAMBIT, ANSYS Mesher and ANSYS FLUENT. The turbulence models and species transport equations are presented. The meteorological information such as wind speed and wind direction is given. The detailed setup and measurement of a scaled-down terrain model using PIV is also presented.

Chapter 4 presents the validation of the CFD model and the findings of effect of terrain surface and meteorological condition. The CFD prediction of velocity flow is validated with the PIV measurement on a scaled-down terrain model. The effects of terrain surface, wind speed and wind direction on the chlorine leak dispersion is discussed. The safe evacuation route is proposed based on the prediction results.

Chapter 5 concludes the findings and the contribution of the present work. The recommendation for future work is also proposed.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This section discussed about the air pollutants dispersion around industrial area. The current issues regarding accidental release of air pollutants is presented. Previous studies on air pollutant dispersion using CFD simulation are reviewed, whereas factors that contributing to the air pollutants dispersion is highlighted. The safe evacuation route for short emergency notice is discussed. The turbulence modelling used for the air pollutant dispersion is reviewed. Experimental techniques for the velocity flow in terrain are also explained. Lastly, the research gaps are highlighted to reach the research objectives.

2.2 Air Pollution Phenomenon

Air pollution is the presence of high concentration of contamination, various hazardous chemicals, particulate matter, toxic substances and biological organisms into the earth atmosphere. This study focus on the accidental releases of noxious gases that may affect human health since the study area is near to the residential area. Previous study of air pollution is summarized and reviewed.

Warner (1976) mentioned that air pollution can be defined as the condition that exists when the atmosphere contains a concentration of some substances that produces an objectionable effect. Such a wide development of industrial area, accompanied with increase in population and housing density has given many negative effect on human health and resulted in various environmental problems. The air pollution from industrial area may affect human health and led to many serious risks such as respiratory and heart problem, and global warming.

There are wide ranges of industries and the pollutants introduced largely depends on the type of industry, raw material characteristics, specific process methods, efficacy of facilities, operating techniques, product grades and climatic conditions (Onianwa, 1986). Major air pollutant was identified, their source, how they cause air pollution, effects and control measures were analysed (AlHassan and Jimoh, 2006). Many researchers did their air quality studies either on indoor, urban or industrial pollutions. Griogoras et al. (2012) has studied the air pollution dispersion in a polluted industrial area of complex terrain from Romania. The atmospheric dispersion study of pollutants in the surveyed area was made using the pollutants emitted by non-ferrous metal industrial facilities existing in Baia Mare area and the emissions from other local anthropic activities (residential heating, traffic, dump heaps). Other study for industrial area has been made by AlHassan and Jimoh (2006) on how to develop a model equation for predicting air pollutant dispersion in Nigeria. By comparing model and simulated results, the pollutants such as NO, CO, and CO_2 are dispersed in accordance with the law of the dispersion.

Noxious gases or toxic gases are mostly same meaning. These gases are harmful to living things. It can easily build up in confined working spaces when the production process uses noxious gases. The accidental releases of gas can occur during an explosion, equipment failure, or a transportation accident. It is difficult to predict the timing and the amount of gas released during accidental releases. One of the toxic gases is chlorine gas. The releases of chlorine gas to atmosphere may significantly affect human health and also to the environment. The effects of chlorine on human health depend on the amount of chlorine is present, and the length and frequency of exposure. Breathing small amounts of chlorine for short periods of time adversely affects the human respiratory system. Table 2.1 shows the acute effect of the chlorine gas leakage to the human health from EPA, 1999. Several acute (short-term) studies have reported the discomfort ranging from ocular and respiratory irritation to coughing, shortness of breath and headaches when expose to the level above 1.0 ppm. For the chronic effects, workers chronically exposed to chlorine gas have exhibited respiratory effects, such as eye and throat irritation and airflow obstruction. Workplace exposure limits for chlorine include a short-term exposure limit for up to 15 minute exposures not to exceed 1 ppm. That for a long-term exposure limit is up to 6 hour exposures not to exceed 0.5 ppm (White and Martin, 2010).

Table 2.1 Health hazard information for different chlorine concentration

Chlorine concentration (ppm)	Acute effects
0.014-0.054	Tickling of the nose
0.04-0.097	Tickling of the throat
0.06-0.3	Dryness of the nose and throat
0.35-0.72	Burning of the conjunctiva and pain after 15 minutes stay in this level
1-3	Mild mucous membrane irritation
30	Chest pain, vomiting, dypsnea and cough
46-60	Toxic pneumonitis and pulmonary edema

Source: EPA (1999)

In the environment, chorine dispersed into the atmosphere mainly from the industrial and commercial locations. Chlorine gas is heavier than air and will initially remain in low-lying areas unless wind or other conditions provide air movement. It can hydrolyse in water to form hypochlorite and hypochlorous acid. Hypochlorous acid is an oxidizing agent which has a sanitizing effect on organic and inorganic contaminants (EPA, 1999).

Currently, many incidents related to the accidental release of chlorine gas. In Malaysia, they were reported that the accident happened in every year since 2016. Latest issue was in October 2018 when an excavator accidentally ran over a chlorine gas cylinder, causing a leak at the scrap metal yard in Miri, Sarawak. The leak went unnoticed until the owner of the scrap metal yard with his eight workers began experiencing dizziness, with several of them subsequently fainting. Personnel from the Lopeng Fire and Rescue department were deployed to the scene to deal with the gas after receiving an emergency call from Miri Hospital whereby the affected workers got their treatment (Laeng, 2018). A year before, in September 2017, the chlorine gas was leaked at Kampung Tembak Paya, Melaka. Seven conveniently disposed 1,000 kg cylindrical gas tanks which contained chlorine gas were found at the abandoned house. Over 210 residents were ordered to evacuate their homes. 93 people were evacuated to a relief centre in Sekolah Kebangsaan Paya Tembak, while 117 villagers went to their friends' and relatives' houses outside of the 3 km radius zone. From the incident, 61 people including three firemen and a policeman being treated at the Melaka Hospital (43 victims) and the Jasin Hospital (18 victims). All of them are experienced breathing difficulties (Koh, 2017). Previously in July 2017, the chlorine gas leakage is occurring at Water Department in Kota Belud, Sabah. The Hazardous Material Handling Team

(Hazmat) team believed that the cause of the leak is due to a hole at one of the valves which is directly connected to the chlorine tank. They managed to tighten the valve and the reading of the chemical went back to normal. Fortunately, no victims reported (Goh, 2017). In September 2016, other chlorine gas incidents occurred in Menglembu, Perak where a ferric acid tank in a factory processing chlor–alkali (chlorine-alkaline) fell and leaked its content on hypochlorite pipe resulting in the formation of chlorine gas. The factory is located nearby to Kampung Baru Bukit Merah. From the incident, two factory workers were hospitalized and one of them suffering pneumonia due to inhaling chlorine gas during the incident. Other six fire-fighters suffered from extreme exhaustion and being hospitalized after carrying five tons of sodium during the neutralization process. The villagers also claimed that the leak gas had cause an unpleasant smell. One of the villagers who live nearby the chemical plant complained that he and his family of four suffered from throat itchy (Yeap, 2016).

It is clear from the aforesaid review of several chlorine leak incidents, that that chlorine gas leak significantly affects human health depending on the level of exposure. The chlorine becomes dangerous to inhale when it accumulates in the air in sufficiently high concentration. At low concentration (0.014 ppm), it may cause the tickling effect on nose and throat, whereas at higher concentration (>1 ppm) it may cause mild irritation of eyes, respiratory system, and headache (Calabrese and Kenyon, 1991). At very high levels of 30 ppm it can cause chest pain, nausea and dyspnea (HSS, 1993). Chlorine is also commonly used in industry, especially in Gebeng industrial area by Polyplastics and Petronas-MTBE. The review also shows that chlorine leak occurs due to various reasons such as improper maintenance and improper handling, which may cause a serious health implication to the surrounding residential area. Therefore, chlorine was chosen in this work due to it perceived risk and due to the fact that no scientific work in this topic is available for Gebeng industrial area.

The study area concern in the present work is one of the biggest industrial area in Malaysia situated in Gebeng which is nearby to the residential area. Besides that, the topographical conditions affected air pollutant dispersion. The Gebeng industrial area has a combination of flat and hilly terrain so this is one of the study concern to study the effect of terrain on the dispersion of air pollutant. The GIE is located on the Kemajuan Tanah Tanah Merah area where Bukit Tanah Merah was flattened to construct the GIE.

The GIE is located within the Sungai Balok catchment. The catchment is low-lying and is predominantly swampy. The estimated average land elevation is 7 m above mean sea level (MSL). The hilly area is Bukit Pengorak which rises 197 m above MSL and Bukit Cerung Kelubi which rises 38 m above MSL is located 7.5 km southeast of the industrial estate. Another hill is Bukit Kecik with 31 m elevation which is located at west of Kuantan Port while Bukit Tanjung Gelang with 105 m elevation is located at the south of Kuantan Port. Sungai Balok river flows 3 km west of area flowing in the southerly direction. The nearest coastline is 3 km to the east. The topographical survey indicates that the site is relatively flat with an overall natural gradient of 0°. The ground levels at the site generally ranged between 7.4 m and 7.8 m above MSL.

Based on the factors stated earlier, wind speed and wind direction may have affected the dispersion of air pollutant as well. Southwest monsoon season occurs on the latter half of May or early June and ends in September. Another monsoon season is Northeast monsoon season that occurs on the early of November and ends in March. To ensure the great accessibility in the transfer of the freight and raw materials to and from the Gebeng Industrial Estate to both domestic and international markets, the government build the Gebeng by-pass direct linked with the East West Expressway which connects Kuala Lumpur and Kuantan. This by-pass may ease the traffic flow between the Gebeng Industrial Estate and Kuantan Port. The petrochemical plants in Gebeng is producing acrylic acid and esters, syngas, butyl acrylate, oxo–alcohols, MTBE, dispersion polyvinyl chloride and many more (MIDA, 2013). Chlorine is used in many industrial processes, including those used to make plastics, vinyl, and nylon, as well as pharmaceuticals and the food or beverage industry too. The electronics industry relies on chlorine in the production of microprocessors and computers. Manufacture of gasoline additives, brake fluid, and antifreeze also utilise chlorine (Austin, 2005). Gebeng Industrial Estate (GIE) is considering as the study area for the present work because of the high potential of accidental of chlorine leak since the chlorine is commonly used for polymer and petrochemical plants such as Petronas-MTBE, Kaneka Malaysia and Polyplastics Asia Pacific. The pollution related studies in GIE have been widely investigated by a few numbers of researchers. Most of the previous studies emphasized on the heavy metals and water pollution in GIE (Sujaul et. al., 2013; Abdullah et al., 2014; Sobahan and Islam, 2015; Abdullah et al, 2015). However, no study available for the accidental release of toxic gas in GIE and hence this is one of the aims of the present work.

2.2.1 Factors Affecting Air Pollutant Dispersion

There are many factors that affect the dispersion of air pollutant. The dispersion of air pollutant is significantly affected by the meteorological condition such as the wind speed and wind direction (Sudarsan et al., 2016; Corsmeier et al., 2005). Other than that, the topographical condition also affects the pollution dispersion. Other meteorological factors that affect the air pollutant transportation are temperature and relative humidity (Jayamurugan et al., 2013; Dominick et al., 2012; Zaharim et al., 2009). They explained that the temperature and relative humidity may affect the pollutant concentration as higher temperature may increase evaporation rates. However, in this work temperature and humidity is not thought to give greater effect on chlorine evaporation rates because the leak is considered to be in gas form in the current work. Hence, the question about effect of temperature and humidity on chlorine concentration or evaporation rates is not important. Moreover, the focus of the current work is on chlorine gas dispersion, not the chlorine evaporation. It is known that gas dispersion is mainly affected by the wind pattern and local terrain. For instance, De la Torre et al. (2015) found that the wind pattern over Southern Andes Mountain is affected by the local topography. Fequest et al. (2009) also found that the wind pattern is more affected by the terrain condition compared to the atmospheric stability. This has resulted in increased research to investigate the atmospheric flow and pollutant dispersion in complex terrain using experimental and numerical methods (Deng et al., 2018; Liu et al., 2016; Michalek and Zacho, 2016). It is also important to note that humidity and temperature variation in tropical climate is not significant, unlike those countries in four season's climate. Since, this study focuses on gas dispersion and that Gebeng industrial area is located in a tropical climate zone, thus the effect of temperature and humidity is not included.

Zhang et al. (2015) has been study about the influence of meteorological conditions on pollutant dispersion in street canyon. The findings explained that the wind is an important factor on transportation of the valley pollutants, which means the wind determines the pollutant migration direction that makes downwind pollutant concentrations higher than upwind pollutant concentrations. Another finding briefed that the greater the wind speed, the more dilution of pollutants while in the street valley. In the higher wind speed condition, the pollutant concentration will lower.

In the effect of topographical condition, the winds will be squeezed over the top and around the side of the hill so that the wind is accelerated on the upwind side caused by the isolated hill. Winds reduce in speed and are often very turbulent in the lee of the hill. Besides that, topography can also channel winds through narrow gaps and cause an increase in wind speed. The winds will slow down after leaving the constriction.

On the top of hills, the wind velocity increases due to the Venturi phenomenon (Katsaprakakis and Christakis, 2012). When the wind blows above the top of hills or mountains, the air pressure decreases and the wind velocity increases. The wind velocity on top of hills or mountains exhibits higher values compared to those in lower altitudes. Figure 2.1 shows the maximization of the wind velocity above the top of a hill as abovementioned.

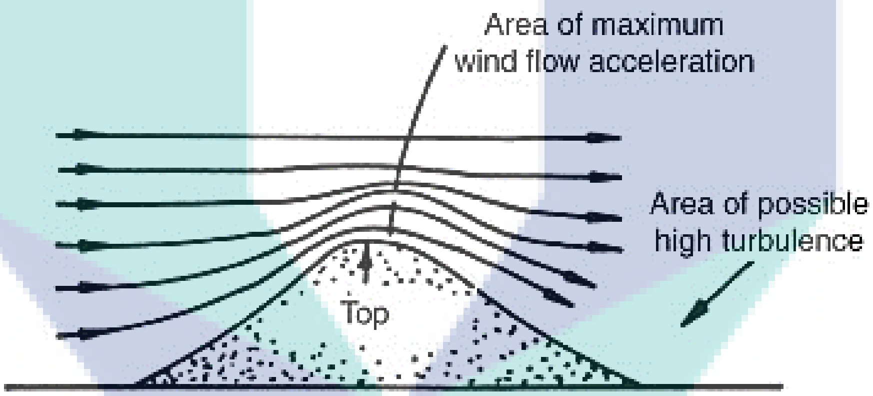

Figure 2.1 Maximization of the wind velocity above the top of a hill
Source: Katsaprakakis and Christakakis (2012)

Gebeng industrial area is known surrounded by the combination of hills and flat terrain as mentioned in previous section. In addition, the wind monsoon around Gebeng industrial is changing with time. Hence, it is important to study the effect of topographical and wind condition on the chlorine dispersion around the Gebeng industrial area.

2.3 Application of CFD on Topographical Modelling

Computational fluid dynamics (CFD) is one of the most powerful tools for studying the atmospheric environment. Previously, many applications used to study the atmospheric dispersion. Box model was an early and simple method based on the conservation of mass. This was followed by Gaussian model, and Lagrangian or Lagrangian-Eulerian models and more recently by CFD models (Holmes & Morawska, 2006). Riddle et al. (2004) stressed that CFD models were more appropriate for situations in complex environment compared to ADMS model. CFD models can provide comprehensive information on the fluid flow over complex terrain, although they require more computing time and costs compared to the other models (Holmes and Morawska, 2006; Riddle et al., 2004).

The CFD modelling solves the complex fluid flow based on the Navier-Stokes equation. When the flow is turbulent, it solves the modified Navier-Stokes equations using an additional turbulence model. Because most air flow within the atmospheric boundary layer is turbulent, almost all simulation studies require an appropriate turbulence model to predict the real and complex wind field (Hong et al., 2011). CFD has the potential to provide realistic simulations for geometrically complex scenarios (Scargiali et al., 2005; Gilham et al., 2000; McBride et al., 2001) since the heavy gas dispersion process is described by basic conservation equations with a reduced number of approximations (Scargiali et al., 2011).

Ha et al. (2018) has developed a micro-scale CFD model to predict wind environment on mountainous terrain. The study was conduct as for the installation on an observation system on mountainous terrain to observe the accurate weather information and the effective prediction of pollutant of airborne virus dispersion and also mountain disaster such as a fire or landslide. The ground model surface of the CFD model was classified and designed based on the digital contour map provided by the National Geographic Information Institute (NGII) and a forest type map provided by Korea Forest Service (KFS) in order to simulate air resistance of trees from the study area. The developed 3D CFD model was then validated using a distribution of wind velocity and direction data measured in mountainous terrain. Although CFD simulation have many advantages in understanding the air flow study, it also has some limitations. The model used in CFD always built in full scale (1:1) compared to the physical measurement. Care must be taken to ensure the CFD models in correct number, size and shape of computational cells are used, and the level of detail to include must be considered in a scaled model to ensure geometric and dynamic similarity is maintained (Linfield and Mudry, 2008)

The summary of previous work on CFD simulation over complex terrain with the acceptable of validations error is shown in Table 2.2. Different turbulence model was used from previous study and mostly use LES model to overcome the shortcoming of RANS based model but in this study, another turbulence model was used and will be discussed in the next session 2.4 due to the limitations on LES model. This topographical modelling will be used in the simulations of air pollutants dispersion. The various studies on air pollutant dispersion by using topographical model will be explaining in next session 2.3.1.

Table 2.2 Validations acceptable on topographical modelling

Author	**Application**	**Dimension**	**Model**	**Validation**
Hong et al. (2011)	Livestock odor dispersion	3D	Std k-ε RNG k-ε RSM LES	48% error Wind speed validation (CFD-MADM)
Liu and Ishihara (2014)	Turbulent flow fields over complex topography	3D	LES	2.63% error Mean wind speed validation (CFD-AABL)
Diebold et al. (2013)	Flow over hills	3D	LES	36% error Velocity validation (CFD-IBM)

2.3.1 Application of CFD on Air Pollutant Dispersion

There are many studies on air pollutant dispersion by using topographic model as mentioned in previous session. It is hard to understand the air flow over flat ground, thus changing the terrains to hills makes the air flow is more complex. The wind profile is the relation between the wind speed and height. Based on Teneler (2011), the wind speed increases with height where the increment is depending on the friction against the surface. The wind is influenced by the Earth’s surface when it gets closer to the ground. In this section, various studied by using topographic modelling is discussed.

Maharani et al. (2009) used the topographic modelling to study the topographical effects on wind speed over various terrains in Korean Peninsula. The main purpose of the study is to observe the comparison wind speed for different ground feature condition, through conversion on identical ground feature, the flat round. The findings show that the altering flow of topographic factors along terrain has identical pattern with terrain feature. It gives the better agreement that the presence of hills, ridges and escarpments can have significant number of effects in different scales of topographic factor.

Previously, Dharmavaram and Hanna (2007) used the topographic modelling on accidental release of heavy gases in industry. The case was considering a very large amount of liquid chlorine release from a rail car derailment in a complex valley. The amount of this hypothetical release was assumed at 1500 kg/s for 35 s. Normally, the chlorine was transported under pressure 8 to 10 bar in a liquefied form in a rail car. When liquid chlorine is released from containment, the flashing phenomenon results is in the form of 20% vapour and 80% liquid as it exits the hole. In this case, an assumption has been made that all the liquid remains entrained along with the vapour in form of tiny droplets, with the fluid being much heavier than air. Figure 2.2 shows the dispersion of a large chlorine release in a complex terrain at 3 m/s wind speed. From this 3D modelling, it clearly shows that the plume hugs the ground and diverges along the valley. So from this result, it can be used for emergency preparedness and protecting people who might be in the path of a chlorine plume.

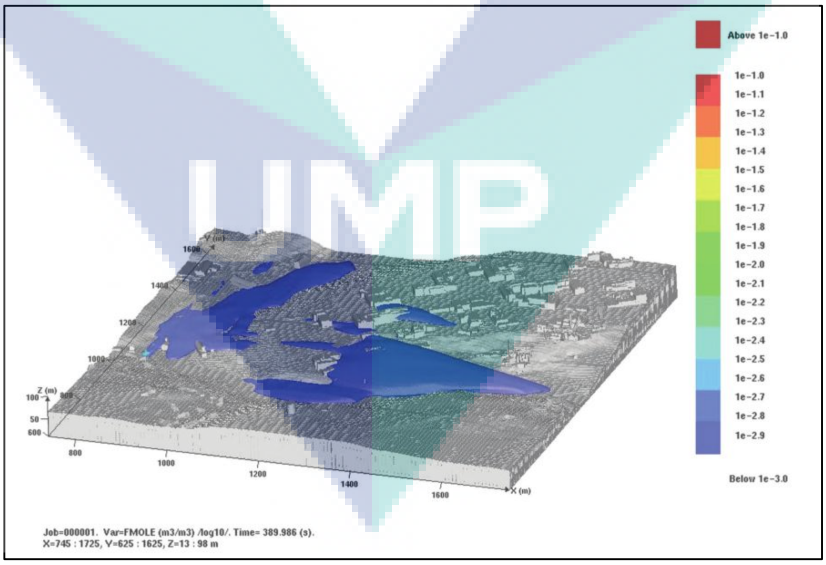

Figure 2.2 Dispersion of a large chlorine release in a complex terrain

Source: Dharmavaram and Hanna (2007)

Scargiali et al. (2005) studied the effect of time-dependent on accidental release of 30 ton of heavy gas dispersion from the ground release point by using topographic modelling. Figure 2.3 reports a three dimensional view of ground level chlorine mass fraction at 08.00 hrs, 15, 30 and 45 min after release. As can be seen after 15 minutes from the release the cloud has already spread out to cover a fairly wide area with concentrations well above the toxicity limits. After 30 minutes the cloud has further spread out and moved away from the release point with peak concentrations smaller than the previous figure though still dangerous for human health. After 45 min the cloud is about crossing the hills that separate the Augusta Priolo gulf from the towns of Floridia and Syracuse with maximum mass fractions still in the range of 50 x 10^{-6}. From the results, an evacuation program is not feasible to actuate once the heavy gas cloud is released from the industrial site of Priolo as the time goes by before the gas cloud reaches the urban site in the area is far too short. So in this case, mitigations measures such as installing loudspeakers to warn the population to stay indoors and take action to seal windows and doors are possibly the most useful to undertake.

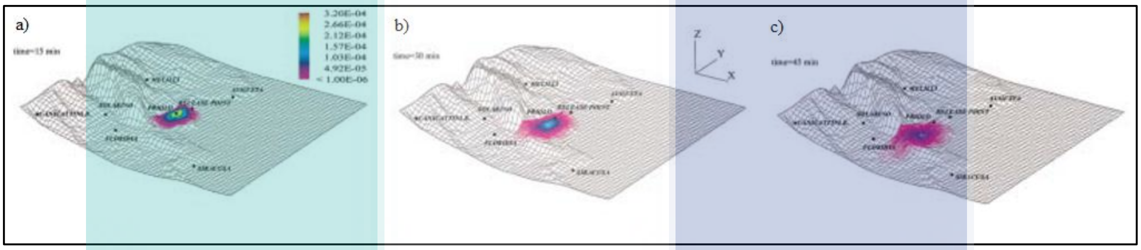

Figure 2.3 Contour plot of ground level chlorine mass fraction (x 10^{6}) a) 15, b) 30 and c) 45 minutes after release at 08.00 hours

Source: Scargiali et al. (2005)

It can be concluded that the study about the noxious chemical accidental releases from industrial area not as much as other study. So, this is more focus on releasing noxious gas in industrial area where the most sources of pollutant emit and disperse to surrounding accidentally. In chemical industry, there are much equipment with open and closed structure such as vessels, piping, buildings and etc. The accidental releases of noxious gases may happen from any equipment in plant at any elevation. Since the same case studies was not applied in Malaysia yet, this studies may use as a guidance in future if any accidental releases of any noxious chemical in industry. Table 2.3 summarized the previous air pollutant dispersion in industrial sector. To complete this research, suitable and right tools is needed to carry out the simulation of dispersion of pollutant emission around Gebeng industrial area.

Table 2.3 Previous study on air pollutant dispersion in industrial sector

Author	Study area	Purpose of study
Cai et al. (2019)	China coal mining industry	To study the effects of air flowrate on pollutant dispersion pattern of coal dust particles
Ma et al. (2017)	Nanjing Sample Industrial Park, China	To investigate the effects of plant canopy on wind field and pollutant dispersion under various weather conditions.
Scargiali et al. (2005)	Priolo-Gargalo/Augusta industrial site	To investigate the setting up a tool able to produce a realistic description of such dispersion processes by considering atmospheric stability and meteorological factors

2.4 Turbulence Modelling

Earlier studies on the prediction of flow and pollutant dispersion within street canyons were performed using two-dimensional steady-state Reynolds-averaged Navier-Stokes (RANS) equations and their corresponding turbulence closure schemes (Baik and Kim, 1999; Chan et al., 2002; Assimakopoulos et al., 2003). Subsequent to these initial studies, the investigations were extended to three-dimensional modelling in order to capture the inherent nature of turbulence, and improved predictions were observed (Hsieh et al., 2007, Di Sabatino et al., 2008, Xie et al., 2006).

The approach of the standard k-ε model (Launder and Spalding, 1974) is widely and practically useful, is adopted for solutions. Although the standard k-ε model shows some problem in the prediction of the wake phenomenon around buildings, such as the overestimate of turbulent kinetic energy around windward corner (Murakami et al., 1988), it still has a good reputation for reliability in the field of wind engineering (Murakami et al., 1990) and air pollutant diffusion analysis (Huang et al., 2000).

An interest has risen in employing Large eddy simulation (LES) to address the shortcomings of RANS, i.e. its inability to capture the unsteady and inherent fluctuations of the flow field within the street canyon on which the dispersion of pollutants depends (So et al., 2005; Cai et al., 2008; Letzel et al., 2008; Tominaga and

Stathopoulos, 2010). But this simulation requires high cost and sensitive to computational grid.

Maliska et al. (2012) studied the comparison of turbulence models for the computation of a detached flow around a square cylinder. The findings show that the LES turbulence model was unable to adequately compute the flow in boundary layer regions. The truth is this limitation arises not from the model itself, but from the relationship between the turbulent scales and smallest grid size. In detached region, largest turbulent scales are considered to be of order of main geometry scale, as a diameter or wing cord length. On the other side, within the boundary layer, the largest turbulent scales are of order of the boundary layer thickness. Then, the minimum mesh size required to capture turbulent structures which satisfy LES criteria could be impracticable within the boundary layers.

Table 2.4 summarizes the previous study on turbulence modelling of turbulent flow around a hill terrain. Although LES turbulence model was proven to be the most accurate model, it is not affordable to run for a complex topography modelling, because the amount of mesh required will be too much and thus time consuming to model. In addition, RANS based model cannot give a good prediction of the flow field around the hill terrain. Thus, a hydrid LES-RANS model i.e. Scale adaptive simulation (SAS) was chosen in this work to minimise the computational time needed without compromising on the prediction accuracy. The SAS uses a RANS approach within non-detached region and LES in detached ones. SAS model need lesser refined grid near the walls and thus the total CPU requirement is much lower than the standard LES.

Table 2.4 Previous study on the turbulence modelling

Author	Turbulence Model	Findings	Remarks
Hong et al. (2011)	Std k-ε RNG k-ε RSM LES	The LES turbulent model was proven to be the most appropriate.	Limited research on complex topography modelling.
Liu and Ishihara (2014)	LES	The distortion of the flow due to the hill especially in the wake region is well captured, but the turbulence in the region of reverse slope is overestimated.	Due to the not enough grid resolution in the wake where the eddies smaller than the grid size may have important mixing effect to reduce the turbulence. So, the tall hills near the measured points should be included in the model.
Chow and Street (2009)	LES	Standard LES model has a limitations when increase the levels of reconstruction.	An alternative mixed model is proposed to avoid the complexities associated with the dynamic procedure and to allow higher levels of reconstruction. This mixed model combined a standard turbulent kinetic energy (TKE-1.5) eddy viscosity closure with velocity reconstruction to form a simple efficient turbulence model that gives good results for both mean flow and turbulence.

2.5 Measurement Techniques in Topographical Modelling

In the present work, the accuracy of CFD with SAS model to predict the air flow over the hill terrain is validated by comparing with a PIV measurement. The validation is limited to the wind flow across the hill Bukit Pengorak (197 m), which is the only hill in the immediate vicinity of Gebeng industrial area. Most of the area of Gebeng industrial area is flat terrain with approximately 7 m elevation from sea level. As such the effect on flow field is not significant if compared over flat terrain. For the flat terrain, the advection can be neglected and the system can be considered in condition of local equilibrium (Finardi & Morselli, 1997). Thus, the validation was performed on the flow past hill terrain because this work aims to elucidate the effect of hilly terrain on the chlorine dispersion, so it is vital that the effect of the hilly terrain to the flow field is correctly captured.

Many studies performed the measurement by using wind tunnel with different measurement techniques. This method was applied to measure the flow velocity and turbulence (Hong et al., 2010). LDV and PIV systems are the most common tools used for experimentally investigate recirculating flow region nowadays (Pilloni et al., 2000). LDV and PIV produce simultaneous measurements of velocity and concentration, allowing the estimation of instantaneous and turbulent pollutant fluxes, thus giving an important insight into the understanding of turbulence diffusion. This section described the advantages and disadvantages of the measurement techniques chosen.

Hyun et al. (2003) studied the mean velocity and turbulence in a complex open channel flow using LDV and PIV. They reported that PIV is able to provide quantitative information about coherent structure that is not readily measured by LDV. In addition, PIV can measure two-point correlations and make quadrant analysis more accurate compared to LDV.

Deen et al. (2000) studied on multiphase flow using PIV and LDA measurement methods. The results showed that PIV velocity data appeared to be much smoother than LDA data. It is because of the sample period was too short to obtain a steady state time average. This explanation was agreed with the work of Brochers et al. (1999), in which a twice as long averaging period was used. Tamura and Matsui (2002) used PIV, LDV and Particle Tracking Velocimetry (PTV) to monitor wind speed velocity in their wind tunnel test.

Table 2.5 shows the previous studies on flow measurement using various methods. Most of the study explained that PIV is a commonly used in measurement flow field for comparison with CFD simulation. In this study, PIV was used to measure the mean flow velocity since it can offer measurement on a larger interrogation window compared to LDV. PIV can reveal the global structures in a two-dimensional or three-dimensional flow field instantaneously and quantitatively, without disturbing the flow which are very useful and necessary for the research of flow mechanism, in particular for the study of unsteady flow (Saga et al., 1999).

Table 2.5 Measurement Techniques in previous studies

Author	Measurement Techniques	Objectives	Findings	Remarks
Nakiboglu et al. (2009)	LS-PIV AP LST	To manage simultaneous of velocity and concentration in large cross sections by recording and processing images of cloud structure to provide more detailed information for validation of CFD simulations.	LS-PIV was successfully implemented to obtain the velocity except for the region close to the stack. Comparison between AP measurements and CFD revealed that there is good agreement when using a turbulent Schmidt number of 0.4.	Correction function need to be applied to obtain a close agreement between CFD and LST measurements.
Nosek et al. (2013)	LDA FFID	To measure velocity components and concentrations in specific points of vertical and horizontal planes in small scale study.	Both methods showed that the complex terrain topography and surface roughness affect the pollutant dispersion.	The neutrally stratified flow over the model concerning of planned mine expansion should be simulated as well in future study.
Vladut et al. (2016)	PIV	To determine the velocity, turbulence intensity and vorticity contours in a vertical reference plane to compare with URANS numerical simulations.	PIV system could deliver full information on a measuring field for the distribution of absolute average velocity, vorticity and turbulence intensity.	NA
Kamada et al. (2019)	PIV	To accurately predict the wind energy distribution on the terrain for proper selection of suitable sites for installing wind farm.	The PIV system gives the good agreement with the power-law defined by ground surface roughness.	All the measurement limited on single hill models. Future study recommend to use multiple hill models to evaluate more investigations to understand more on flow field characteristics in the atmospheric boundary layer.

2.6 Summary

It is clear from the literature survey that air pollutant released from industrial area is significantly affected the nearby residential areas. The terrain surface and wind condition also contributed to the air dispersion. It is important to study the air pollutant dispersion around GIE in the event accidental release of chlorine gas since there are many processing chemical plant existed. By considering the economy and environmental concern, CFD method is chosen for the evaluation of chlorine gas dispersion around GIE. SAS turbulence model was used due to its prediction accuracy, less sensitive to computational grid and reduced computational demand compared to the LES. This work contributes on the air pollution dispersion around GIE under influence of terrain surface and monsoon wind, whereby the CFD model can be used to simulate the air dispersion and the PIV data can be used for validation. It is clear from the literature review that research gaps exist on the pollution study in GIE. The existing knowledge gaps are listed as follow:

i. Chlorine gas may affect human health depending on its concentration in the atmosphere.

ii. No previous study on the accidental release of chlorine in Gebeng industrial area, despite the existence of chlorine tank in various processing plant.

iii. No previous study using SAS to simulate pollutant dispersion around complex terrain with hills with height up to 215 m. The selected area consists of three hills which is above 20 m up to 215 m.

iv. Limited studies concerning the effect of topographical and wind condition on the pollutant dispersion using SAS model.

v. The safety evacuation route for accidental release of chlorine gas is not yet available for Gebeng industrial area. Hence, this proposed route can be used as a guide to evacuate the affected area.

Therefore, this work aims to address the abovementioned research gaps as reflected in the objectives and scopes (sections 1.3 and 1.4). The details of the method used (i.e., topographical modelling, turbulence modelling, and experimental measurement) to address the identified research gaps are explained in chapter 3.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the CFD and experimental methods used to study the dispersion of chlorine gas around Gebeng industrial area. Figure 3.1 shows the flow chart for the CFD modelling and PIV measurement performed in this study. At first, SketchUp is used to create the contour map, then the SketchUp file exported into Rhinoceros to create a solid object as demanded by Gambit. The detail of geometry was presented in section 3.3.1. The computational mesh of the Gebeng industrial area was created using Ansys Mesher. The quality of mesh prepared is checked to ensure the accuracy of simulation. The detail of meshing was discussed in section 3.3.2. The initial meteorological information, boundary condition and models were set in Ansys Fluent R18.2. The detail of simulation setup and solution convergence was presented in section 3.3.5. The wind flow past a hill in Gebeng industrial area was compared with the PIV measurement. The measurement was conducted on a scaled-down terrain model. The detail of PIV measurement was described in section 3.2.3. The models used was then applied to simulate the combined effect of meteorological and topographical condition on the dispersion of chlorine gas around Gebeng industrial area.

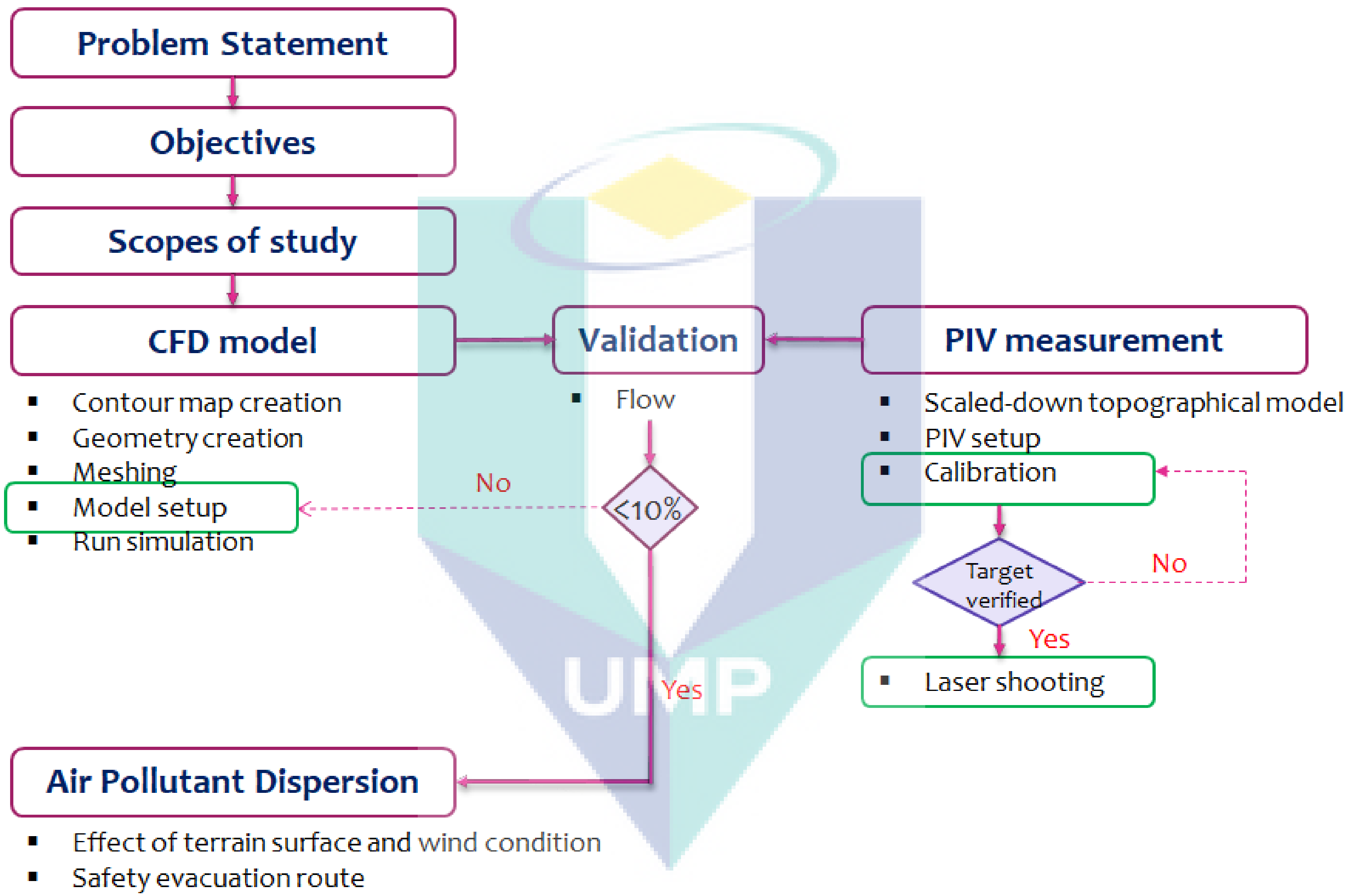

Figure 3.1 Flow chart for the research methodology

3.2 Experimental Measurement

3.2.1 Topography and environmental conditions of the study area

The study area is located in Gebeng Industrial Estate, Kuantan as shown in Figure 3.2. In this study, Gebeng, Kuantan was chosen as the study area because of high potential of high risk pollutant dispersion company operated in GIE area. In last decades, industries were small factories that only produced smoke as the main pollutant. However, when these factories became full scale industries and manufacturing units, the issue of industrial pollution started to take on more importance. The GIE is also have many residential nearby. Taman Balok Perdana, Taman Balok Makmur, Kampung Berahi are the nearest residential south of the GIE along the Kuantan-Pelabuhan bypass road. At north, Kampung Sungai Ular is located about 2.5 km from Kampung Gebeng whilst Kampung Hulu Balok is located at south–east of GIE. Another population nearby include Kampung Selamat, Kampung Seberang Balok, Kampung Balok, and Kampung Balok Baru. The majority of the areas are sparsely populated.

The yellow lined area indicates the possibility of the accidental release of noxious gases marked by S1 and S2 whilst red lined area represent the residential area nearby marked by R1 where Kampung Sungai Ular, Kampung Gebeng, Tanjung Rhu located and R2 includes Kampung Berahi, Balok Perdana, Kampung Seberang Balok. H1 and H2 represents the hills located in the study area whilst H3 is the hill located along the border of Terengganu and Pahang states. H1 is the hill located at the south of Gebeng which is called Bukit Tanjung Gelang with 105 m elevation above sea level. H2 represents two hills, Bukit Pengorak with elevation 197 m and Bukit Cerung Kelubi with elevation of 38 m whilst H3 has an elevation of 109 m up until 215 m along the Terengganu and Pahang border.

There are many potential of chemical plants that may lead to the accidental release of noxious gases. In this study, a hypothetical chlorine gas is chosen as a pollutant that can dispersed into the atmosphere during the accidents from two source points, S1 and S2. The point are the sources that have the high possibility of the chlorine gas release where the petrochemical company situated. 10 m x 10 m source point S1 was created where the petrochemical plant such as Lynas Advanced Material Plant and Polyplastics are situated. The second source S2 was set where MTBE

Malaysia and RP Chemicals Malaysia plant located. This two source is located in between hill H2 and H3.

Figure 3.2 Study area in Gebeng Industrial Estate
Source: Google Map (2016)

Malaysia is known to have two monsoons season and two inter-monsoon season. In the present study, two monsoon seasons was chosen because the rate of the wind speed may higher than normal wind speed. Southwest monsoon season occurs on the latter half of May or early June and ends in September. Wind flow generally South-Westerly (SW) and almost below 15 knots (7.7 m/s). Another monsoon season is Northeast monsoon season that occurs on the early of November and ends in March. During this monsoon, the wind flow generally Easterly (E) or sometimes North-Easterly (NE). The wind speed during this monsoon ranges from 10 up to 20 knots (5 to 10 m/s). Figure 3.3 and Figure 3.4 shows the wind rose of mean wind speed and directions by monthly in 2014.

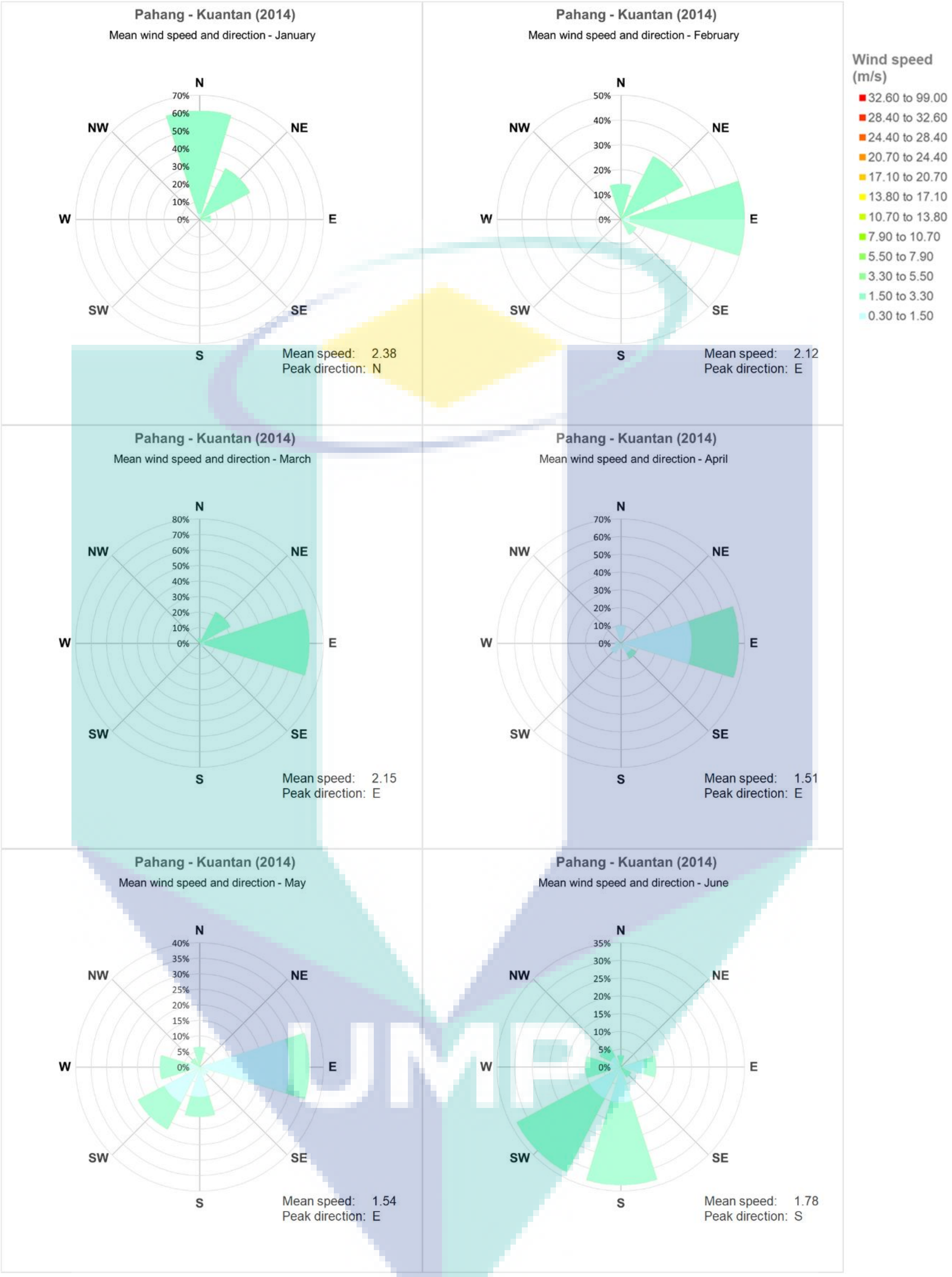

Figure 3.3 Windrose for Gebeng on January until June 2014

Source: Malaysia Meteorological Department (2014)

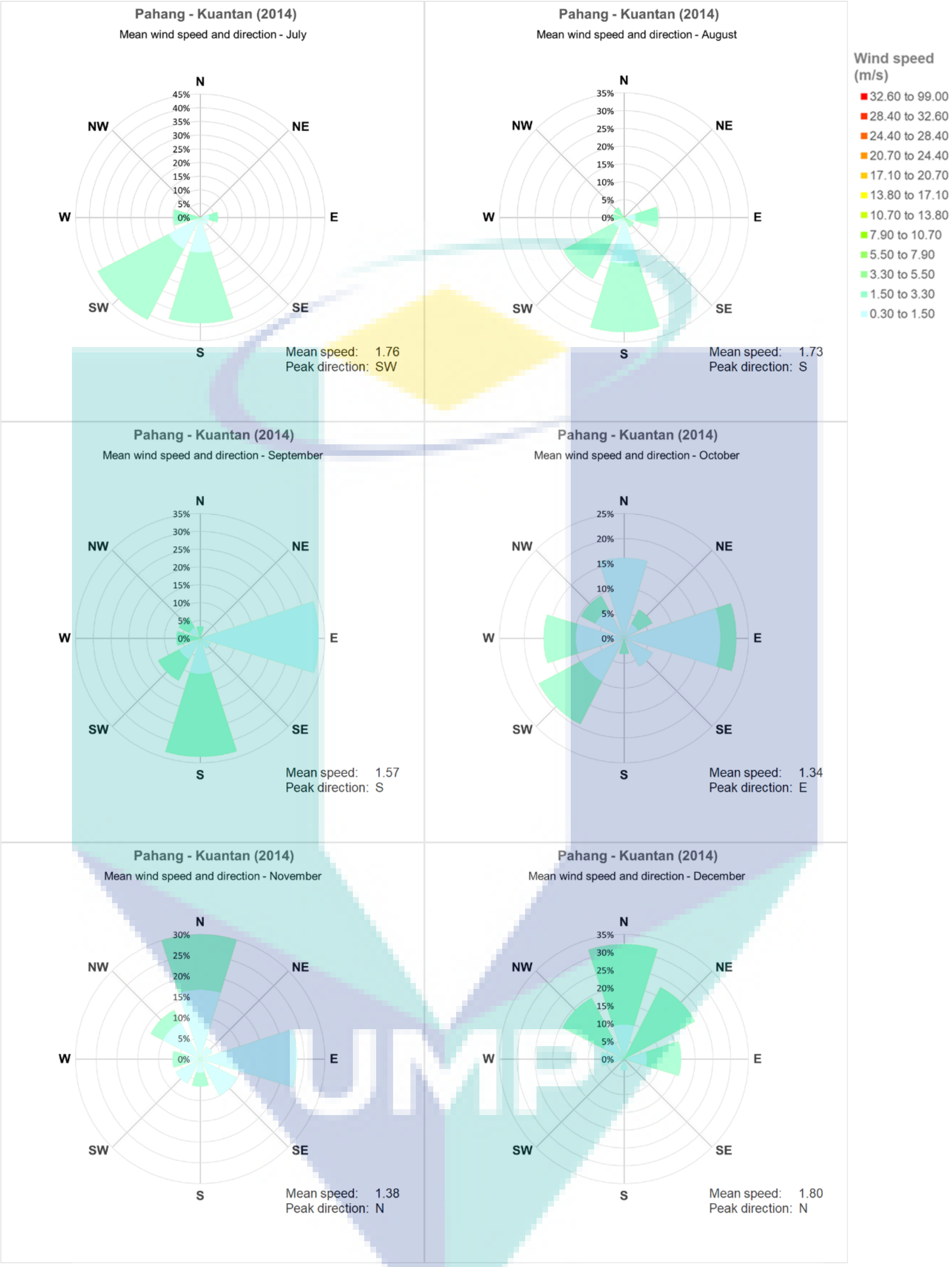

Figure 3.4 Windrose for Gebeng on July until December 2014

Source: Malaysia Meteorological Department (2014)

Table 3.1 shows the data for wind speed and wind direction obtained from Meteorological Department in Kuantan. The coordinate for the station is at Latitude 3° 46' N and Longitude 103° 13' E. The station located at 15.2 m height above mean sea level.

Table 3.1 Mean wind speed and direction in each month of 2014

Month	**Mean Temperature (°C)**	**Mean Wind Speed (m/s)**	**Mean Maximum Wind Speed (m/s)**	**Wind Direction (°)**	**Wind Direction**
January	24.9	2.4	8.6	020	North-Northeast
February	25.9	2.1	8.2	090	East
March	27.1	2.2	8.5	090	East
April	28.5	1.5	8.2	100	East
May	28.2	1.5	8.8	090	East
June	28.6	1.8	9.5	210	South-Southwest
July	28.1	1.8	8.3	210	South-Southwest
August	27.5	1.7	8.2	200	South-Southwest
September	27.4	1.6	8.3	200	South-Southwest
October	27.2	1.3	8.4	090	East
November	26.5	1.4	7.2	350	North
December	25.6	1.8	8.0	340	North-Northwest

Source: Malaysia Meteorological Department (2014)

This study is limited to study the wind data on the year 2014 obtained from Malaysia Meteorological Department. This is due to the similarity of wind pattern in Gebeng industrial area for over 10 years of measurement. As shown in Figure 3.5, until July 2019 the wind rose shows the similar pattern of wind direction for ten years (Jan 2008) to that data in the year 2014. Four month was chosen to represent each monsoon season, i.e., Southwest monsoon (July), Northeast monsoon (January), inter-monsoon (May and October). The wind pattern in each monsoon seasons including the inter-monsoon is comparable for both the 10 years' data and to the data in 2014 alone. Therefore, the use of year 2014 is appropriate for this work.

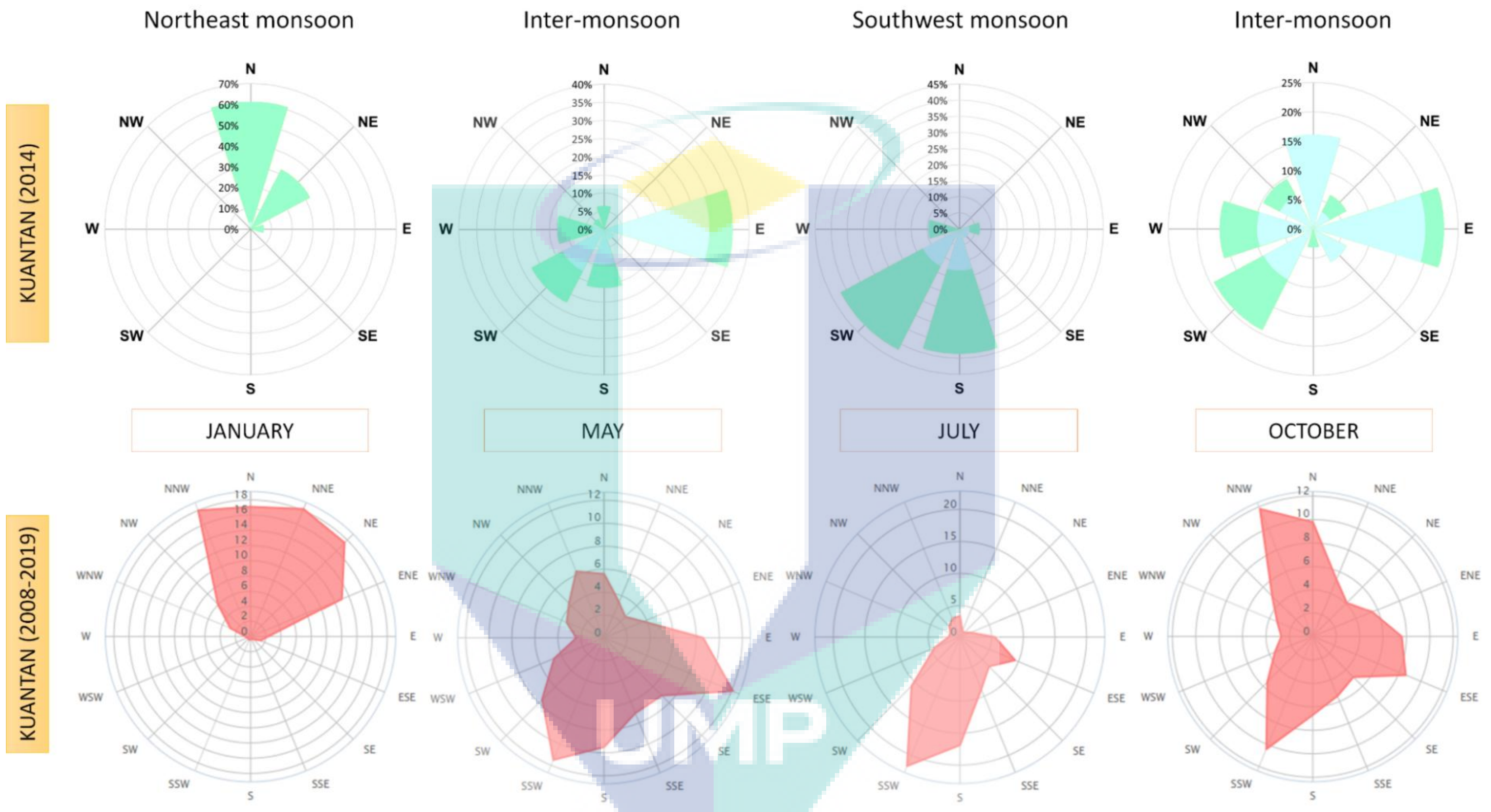

Figure 3.5 Wind direction distribution in (%) for around Gebeng industrial area. Meterological weather station for Gebeng is located in Kuantan.

Source: Winfinder.com (2019)

3.2.2 Scaled-down Model Creation

The scaled–down model (1:4500) was prepared by using Sightline Map to be export in three-dimensional printable version. By the limitation of three dimensional printer platform's size, four parts of scaled – down terrain map is used to be assembled. All parts are chosen at hilly area where Bukit Pengorak is located to be validated with CFD model as shown in Figure 3.6. All four parts is printed by using UP Plus 3D printer. Each parts took up to 2 to 3 hours to be printed. The material used is 1.75 mm acrylonitrile butadiene styrene (ABS).

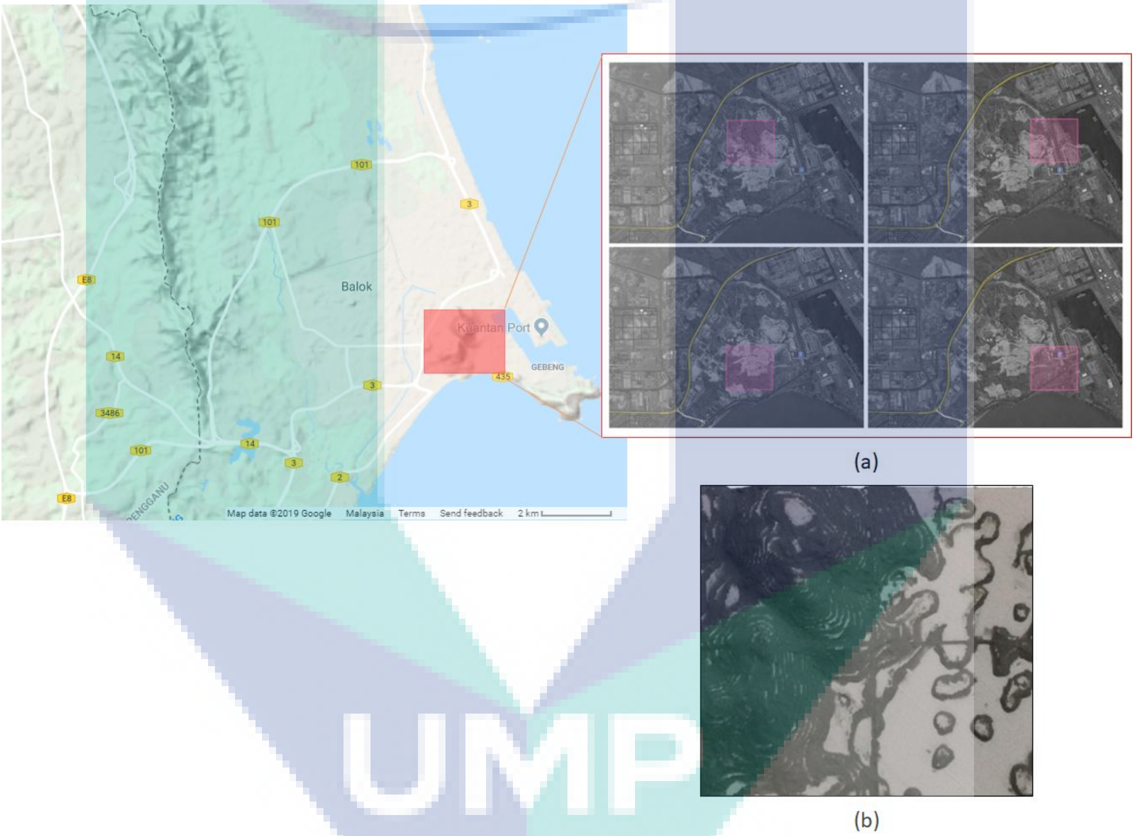

Figure 3.6 Parts of scaled-down model from (a) Sightline maps and (b) printed 3D topography model

3.2.3 Experimental Rig

The velocity flow measurement around the scaled–down terrain model was performed by using PIV. A wind tunnel with a 0.31 m x 0.31 m of testing area was prepared for the experiment. The PIV system consisted of laser, CCD camera, traverse system, synchronizer and processing software. The schematic diagram of experimental setup is shown in Figure 3.7. First step is the flow was seeded with Safex fog into the lab–scale wind tunnel driven by an axial fan. The fog liquid has a droplet size of 1.068 µm and the fog is generated using a fog generator (FOG 2010). The inlet flow was set around 1.78 m/s. The double pulsed Nd:Yag laser (MicroVec, Singapore) was triggered to deliver a thin laser sheer to define the measurement plane. The laser model used in this PIV system is Vlite-200 with a wavelength 532 nm. The particles movements in a specific measurement plane were captured by the CCD camera (Dantec Dynamics, Denmark). Calibration was performed in the measurement plane using the calibration target. A time interval of 400 µs was set for the measurement. The camera and laser system was synchronized by a MicroPulse725 processor. The velocity data was then processing using MicroVec software. The velocity profile obtained was used for comparison with the CFD simulation.

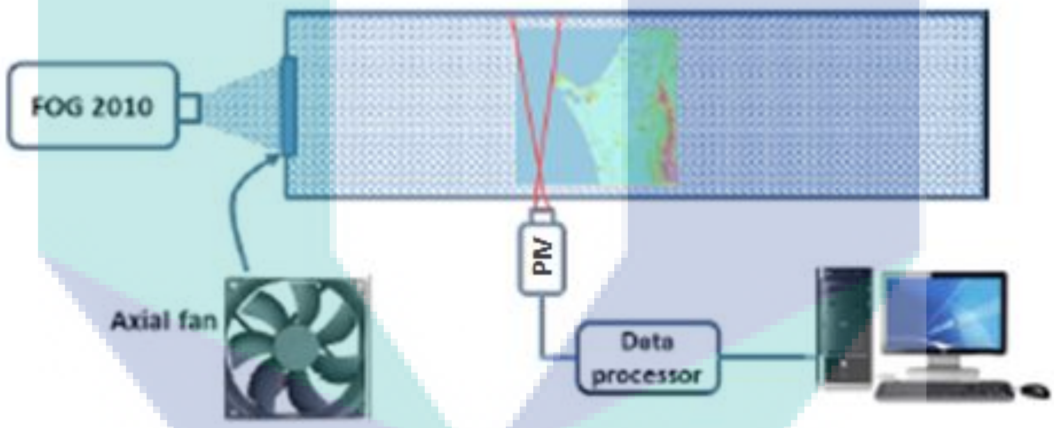

Figure 3.7 Schematic diagram of PIV measurement setup

3.3 Numerical Approach

3.3.1 Topographical Modelling

This present work used modelling using contour lines in topographical modelling for generating a 3D ground surface in GAMBIT, the pre-processor of the FLUENT CFD package. This purpose is to investigate their convenience for unstructured grid creation and practical applications (Hong et. al., 2011). The contour map was obtained from forty (40) topographical maps. The map was arranged in a 4 x 10 overlapped that gives the total size of study area is 15 km x 14 km. In SketchUp, the contour map has been modified such that unnecessary information and re-link broken lines is deleted as shown in Figure 3.8 (a). This method used a triangulate irregular network (TIN) structure which can be said like a group comprised of triangle by using sandbox tool. However, although this structure may resemble a surface, it still not a real solid object, which is demanded by GAMBIT (Hong et. al., 2011). Therefore, a SketchUp file (*.skp) is exported into Rhinoceros to create a solid object by creating a drape surface over the TIN structure by using the “drape surface over objects” command as shown Figure 3.8 (b). Figure 3.8 (c) shows the real solid surface that has been created in Rhinoceros.

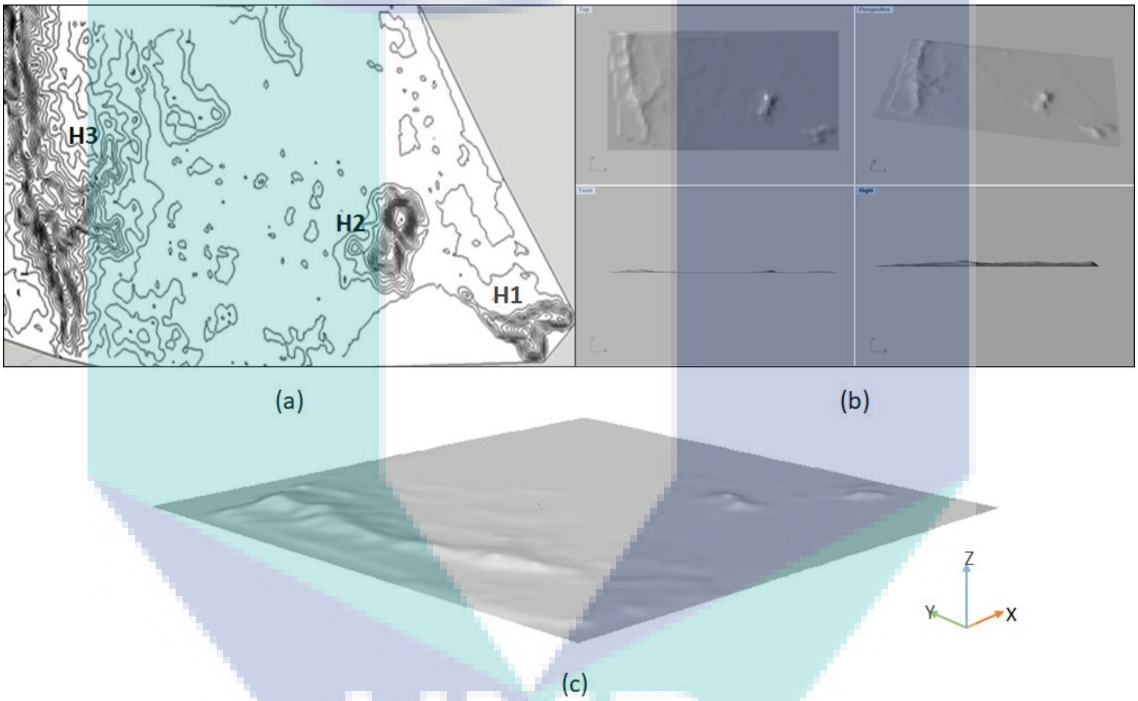

Figure 3.8 Model creation of (a) contour map in SketchUp, (b) drape surface in Rhinoceros and (c) real solid surface in Rhinoceros

3.3.2 Meshing

The terrain surface was meshed using Ansys Workbench Mesher, as shown in Figure 3.9. The mesh was prepared using a well-structured cut-cell method, which offers a robust and faster convergence in comparison with the traditional meshing technique (Ingram et al., 2003) while retaining the boundary conforming mesh. Finer mesh was applied to the region of terrain surface where turbulence may exist while the rest of domain used a coarser mesh to reduce the computational demand. The flat sky is extruded up to 5000 m to reduce the effect of the ground when the velocity is slightly increased near the high mountain compared to the inlet boundary. The effects can be reduced to 2.3% from 5.9% compared to the height below 2500 m (Hong et al., 2011). 1,292,230 cells were employed to the whole domain. The element quality, orthogonal quality and skewness of the domain are 0.84, 0.94 and 0.09, respectively. The mesh is of good quality according to Andersson et al. (2011), i.e., the orthogonal quality should be above 0.7 and the skewness should below 0.5.

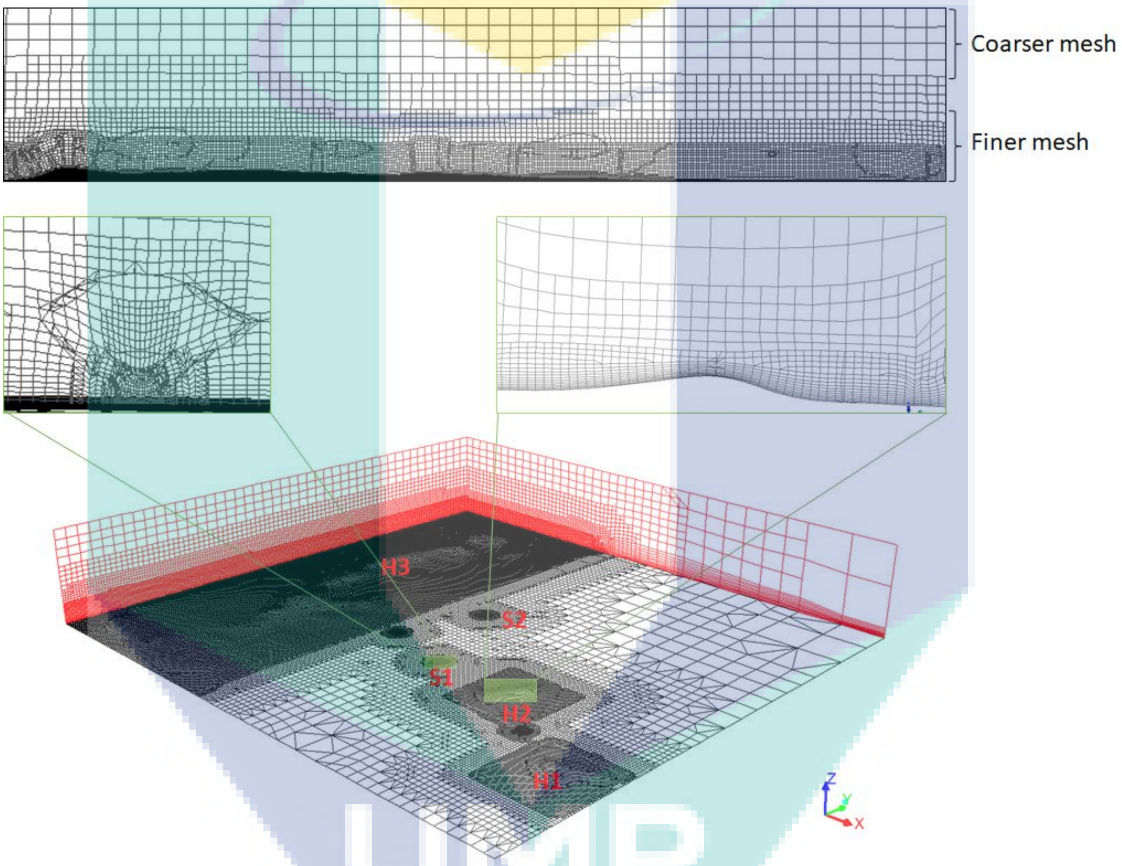

Figure 3.9 Surface mesh of Gebeng industrial area (Note: H1, H2 and H3 represent the hills and S1 and S2 represent the source of leakage).

3.3.3 Turbulence Modelling

3.3.3.1 Standard *k-ε*

According to Huang et al., the conventional and still most widely–used approach is time averaging, also described as Reynolds averaging, in which the Navier–Stokes equations transformed as the Reynolds–Average Navier-Stokes (RANS) set (Gosman 1999). This model is the most widely used engineering turbulence model for industrial applications. The k-epsilon (k-ε) model for turbulence is the most common to simulate the mean flow characteristics for turbulent flow conditions. This model computed two separate transport equations which allow the turbulent velocity and length scales to be independently determined. The first transported variable is turbulent kinetic energy, k as shown in Equation 3.1.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\epsilon - Y_M \qquad 3.1$$

The turbulent viscosity, μ_t is computed by combining k and ϵ as follows:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \qquad 3.2$$

In this equation, C_μ and σ_k has a constant value of 0.09 and 1.0. σ_k is the turbulent Prandtl numbers for k. In Equation 3.1, G_k and G_b represents the generation of turbulence kinetic energy due to the mean velocity gradients and buoyancy respectively. Both are calculated as follow:

$$G_k = -\overline{\rho u_i' u_j'}\frac{\partial u_j}{\partial x_i} \qquad 3.3$$

$$G_b = \beta g_i \frac{u_t}{\mathrm{Pr}_t}\frac{\partial T}{\partial x_i} \qquad 3.4$$

where Pr_t is the turbulent Prandtl number for energy with a constant value of 0.85 and g_i is the component of the gravitational vector in the i-th direction. The coefficient of thermal expansion, β, is defined as:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \qquad 3.5$$

where Y_M represents the dilatation dissipation term that modelled according to a proposal by Sarkar and Balakrishnan (1990):

$$Y_M = 2\rho\epsilon M_t^2 \qquad 3.6$$

where M_t is the turbulent Mach number, computed as:

$$M_t = \sqrt{\frac{k}{a^2}} \quad 3.7$$

α is define as the speed of sound.

$$\alpha = \sqrt{\gamma RT} \quad 3.8$$

The second transported variable in this case is the turbulent dissipation, ϵ and computed in following equation:

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial\epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \quad 3.9$$

where σ_ϵ is the turbulent Prandtl number for ϵ with a constant value of 1.3. $C_{1\epsilon}$ and $C_{2\epsilon}$ are also constant with value 1.44 and 1.92 respectively. $C_{3\epsilon}$ is also constant and derived from:

$$C_{3\epsilon} = tanh\left|\frac{v}{u}\right| \quad 3.10$$

where v is the component of the flow velocity parallel to the gravitational vector and u is the component of the flow velocity perpendicular to the gravitational vector. However, this turbulence model could not produce the unsteady turbulent wake behind the structures (Beyers and Waechter 2008). Thus, SAS simulation is introduced to overcome the limitation of SKE model.

3.3.3.2 Scale Adaptive Simulation

Scale Adaptive Simulation (SAS) is an improved URANS formulation, which allows the resolution of the turbulent spectrum in unstable flow conditions. SAS models adapt the length scale automatically to the resolved scales of the flow field. Rotta, 1972 has proposed the exact transport equation for the turbulent length-scale. In 2004, Menter and Egorov presented a two-equation turbulence model using a $k-v_t$ formulation which can be operated in RANS and SAS mode. The final SAS two-equation model are:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho U_j k)}{\partial x_j}=P_k-c_\mu^{\frac{3}{4}}\rho\frac{k^2}{\Phi}+\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] \qquad 3.11$$

$$\frac{\partial(\rho\Phi)}{\partial t}+\frac{\partial(\rho U_j\Phi)}{\partial x_j}=\frac{\Phi}{k}P_k\left(\zeta_1-\zeta_3\left(\frac{L}{L_{vK}}\right)^2\right)-\zeta_3\rho k+\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\Phi}\frac{\partial\Phi}{\partial x_j}\right] \qquad 3.12$$

The Φ coefficient and the turbulent viscosity, μ_t are respectively given as:

$$\Phi=\sqrt{k}L \qquad 3.13$$

$$\mu_t=c_\mu^{\frac{1}{4}}\rho\Phi \qquad 3.14$$

where another new term added are:

$$L_{vK}=\kappa\left|\frac{U'}{U''}\right| \qquad 3.15$$

$$U''=\sqrt{\frac{\partial^2 U_i}{\partial x_k^2}\frac{\partial^2 U_i}{\partial x_j^2}} \qquad 3.16$$

$$U'=S=\sqrt{2S_{ij}S_{ij}} \qquad 3.17$$

$$S_{ij}=\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right) \qquad 3.18$$

The model constant from Equation 3.11 and 3.12 are ζ_1 =0.8, ζ_2 =1.47, ζ_3=0.0288,$\sigma_k=\frac{2}{3}$, $\sigma_\Phi=\frac{2}{3}$, $c_\mu=0.09$, $\kappa=0.041$.

3.3.4 Species Transport Modelling

The dispersion of air pollution was solved by the species transport equation as shown in Equation 3.19. The air pollutant was assumed to be a polluted gases parcel mixture that consists of pollutants and air (Hong et al., 2011).

$$\frac{\partial}{\partial t}(\rho Y_j) + \nabla.(\rho \vec{u} Y_j) = -\nabla.\vec{J_j} + S_j \qquad 3.19$$

where ρ is the density; t is the time; $\vec{u}$ is the velocity; Y_j is the mass fraction of species j; $\vec{J_j}$ is the diffusion flux of species j and S_j is the source term of species j by an additional reaction. The diffusion flux can be computed as Equation 3.20:

$$\vec{J_j} = -\left(\rho D_{mj} + \frac{\mu_t}{Sc_t}\right)\nabla Y_j - D_{tj}\frac{\nabla T}{T} \qquad 3.20$$

where: D_{mj} is the mass diffusion coefficient for species j; μ_t is the turbulent viscosity; Sc_t is the turbulent Schmidt number; D_{tj} is the thermal diffusion coefficient for species j; and T is the temperature.

3.3.5 Simulation Setup

The simulation of dispersion of chlorine gas was performed using ANSYS Fluent R18.2. The Ansys software was installed on Dell Precision Tower 3620 workstations with Intel Xeon E3-1240 v6 processor (3.70 GHz) and 16.0 GB RAM. The CPU time for each simulation iteration is about 1.22 s. Initially, the simulation was performed using a steady-state solver, first-order upwind discretization and SKE turbulence model. A second-order discretization scheme was then enabled after an initial stable solution was obtained. SAS turbulence model was then employed and the bounded central differencing was used for the momentum discretization. The time step size was set at 0.05 s. The initial conditions used ambient pressure at 101.325 kPa as a standard atmospheric pressure and the ambient temperature is 293 K. The inlet velocity was set at 1.78 m/s in the eastern direction. The data was recorded for over 1000 time steps once a pseudo-steady solution was achieved. The solution convergence was determined by two criteria. First is to ensure all absolute residuals of solved equations fall below the specified thresholds set at 1 x 10^{-5} for all variables. Second, monitor the statistical convergence of the velocities in x, y and z direction at the specified spatial position (x = -4510 m, y = -12000 m, z = 500 m). The simulation is only considered converged when the monitored statistics is no longer changing with the iterations. The simulation data was compared with the PIV result. Once the CFD prediction is validated, the similar models was employed and the species transport model was enabled to simulate the dispersion of chlorine gas from two leaks sources (i.e. S1 and S2) at different wind direction and speed.

In the present study, chlorine gas was used as air pollutant which dispersed into the atmosphere by the incident of the pipeline leaks connected to a 1000 L horizontal cylindrical tank which is commercialized in industrial plants. The liquefied chlorine of capacity 1.30 T is stored at ambient temperature. The chlorine leakage rate was calculate using ALOHA heavy gas model. The time step size used changed to 5 s to reduce computational demand since time step size below 1 is not applicable in this case because it requires too much computational time, more than a month per case (Hong et al, 2011). Four different concentration of chlorine is marked as a guide to how it can disperse during the leakage. The concentration of chlorine in the threat zone analysis was set to 0.014 ppm (tickling effect), 0.35 ppm (burning effect), 1 ppm (mild irritation), and 30 ppm (life threatening effect).

The diffusion process of chlorine leakage is relatively complex, some basic assumptions have been applied to the simulation to simplify the analysis:

i. Chlorine leakage rate is constant, e.g. it does not change with chlorine leak pressure, temperature and humidity without heat exchange between chorine gas and the environment. The chlorine leak is assumed to be from a storage tank.

ii. The atmospheric condition such as the atmospheric stability is resolved directly by the scale-adaptive modelling, which provides a LES-like unsteady prediction.

iii. Chlorine gas in atmosphere is not involving any phase change, chemical reactions and droplet deposition.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the findings on the validation of velocity profile and the prediction of noxious gas dispersion around Gebeng industrial area. At first, a study on a wind flow past a hill was performed to ensure the suitability of turbulence model used. The velocity profile was compared with the PIV measurement done in this work, as presented in section 4.2. Then, the model used was employed to simulate the chlorine gas dispersion around the Gebeng industrial area. The effect of terrain surface, wind direction and speed on the chlorine gas dispersion was evaluated, as discussed in section 4.3. Lastly, a suitable safety evacuation plan based on the direction of noxious gas dispersion was proposed, as presented in section 4.4.

4.2 Validation of Velocity Profile

The study of wind flow past the hill in the Gebeng industrial area was performed to ensure the turbulent flow is well resolved. Figure 4.1 shows the velocity vector for the air flow past the hill H2. The wind velocity increases due to Venturi phenomenon on top of hill area. When the wind blows above the top of hills, the air pressure decreases and wind velocity increases. The wind velocity on top of hills exhibits higher values compared to those in lower altitudes. This is due to the fact that the wind becomes compressed on the windy side of the hill, and once the air reaches the ridge it can expand again as it soars down into the low pressure area on the lee side of the hill. From the findings, the wind bending some time before it reaches the hill. This is because of the high pressure area extends quite some distance out in front of the hill. The velocity profile from this model is then validated with PIV measurement to ensure the valid model for further study.

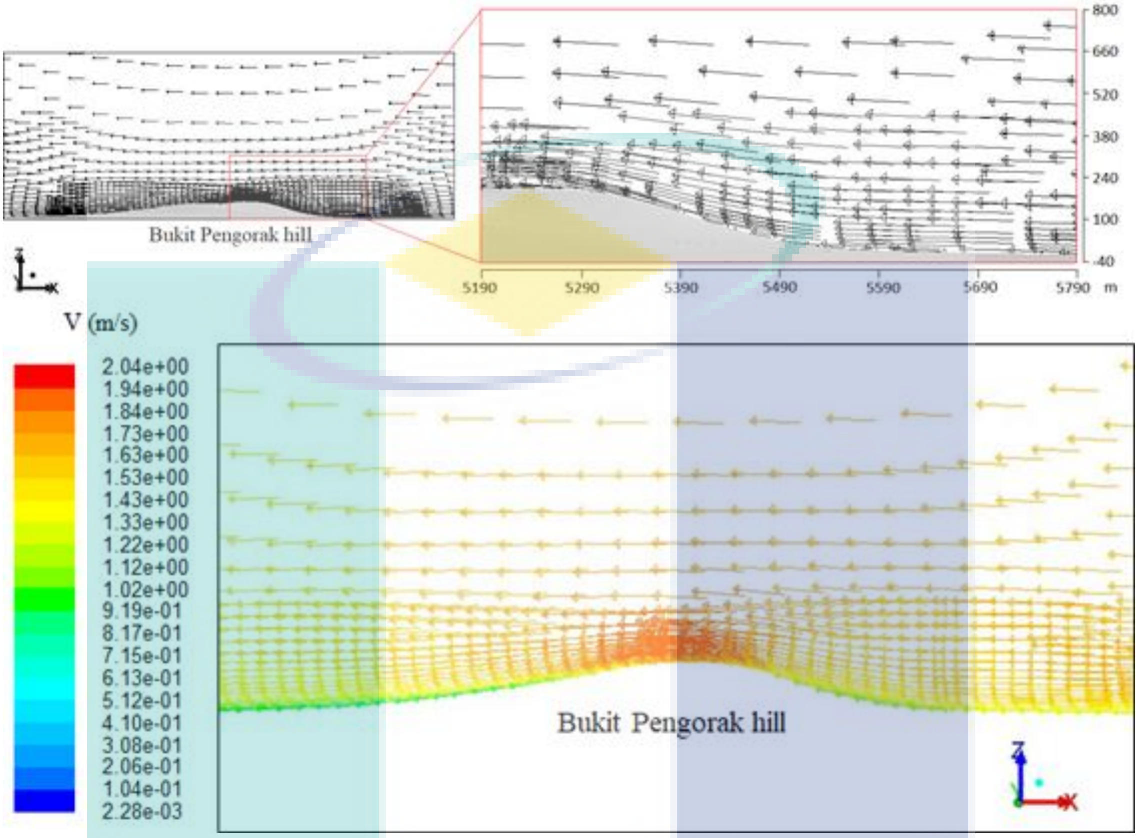

Figure 4.1 Vector plot for air flow past Bukit Pengorak hill

The predicted streamwise velocity profile past the hill H2 (i.e. Bukit Pengorak) using SAS model was compared with the PIV measurement, as shown in Figure 4.2. The velocity profile was taken from an eastern wind direction along the length, x* (refer Figure 4.2 a) and height, z* (refer Figure 4.2 b) of the hill. The streamwise velocity is normalized with the freestream velocity ($u^* = u/u_{in}$) to ensure a fair comparison between the measurement using a scaled down model and the actual terrain scale by CFD simulation can be performed. The length and height in the flow direction is also normalized with the total length and total height of the subject area respectively so that the result can be matched in a correct perspective of the actual terrain and the scaled-down model. The result shows that the measured velocity data was excellently predicted by the CFD simulation using SAS model, with the error ranging 1.5 to 2.6% from the PIV measured data. A correct flow features around the hill H2 was obtained. The flow of topographic factors along terrain has identical pattern with terrain feature (Maharani et al., 2009). Hence, the model chosen can be used to evaluate the combined effect of surface terrain, wind direction and speed on the pollution dispersion around Gebeng industrial area.

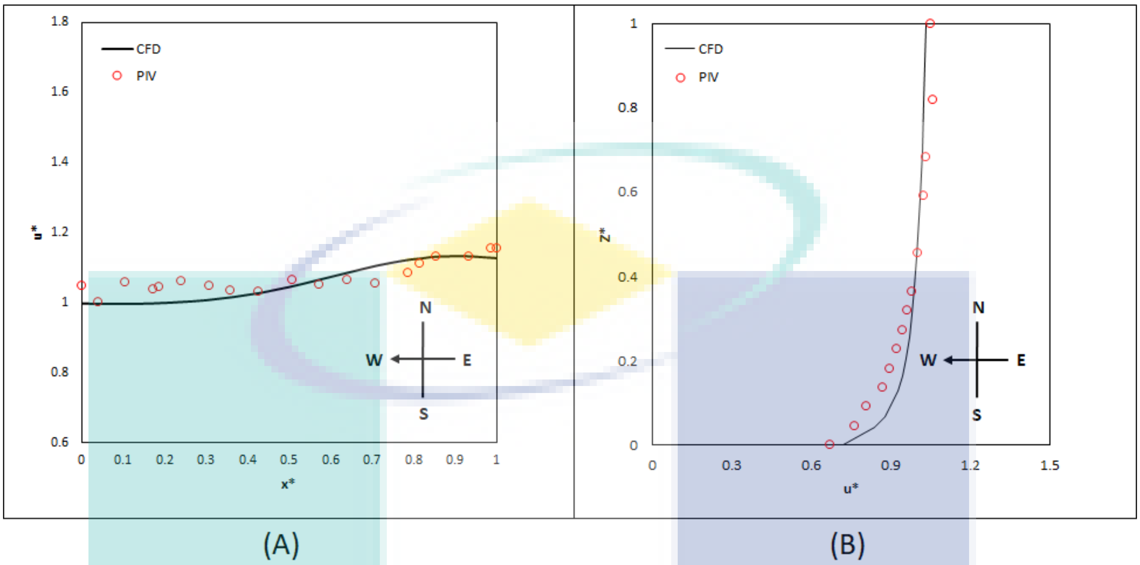

Figure 4.2 Comparison of CFD and PIV data for, A) u* along x*, B) u* along z*

4.3 Prediction of Chlorine Gas Dispersion around Gebeng Industrial Area

The CFD topography model was developed to predict the chlorine gas dispersion around Gebeng industrial area. This model was validated by the wind flows past a scaled-down model using PIV measurement in field experiment to be routinely used as the correct air flow was obtained. A potential chlorine gas leak from a chemical plant at Gebeng industrial area was modelled for the case of wind from various directions within a year of 2014 wind data, as shown in Table 4.1. The mean wind speed is in the range of 1.3 to 2.4 m/s and the higher wind speed is between 7.2 to 9.5 m/s. The first leak source S1 was set at a position between hill H2 and residential area R1 where many chemical plants are located, e.g., Lynas Advanced Material Plant, BASF Petronas Chemicals, Polyplastics Asia Pacific and Petronas Chemicals PDH. Another leak source S2 was set at a position nearby the hill H2 and residential area R2 where the chemical plant situated at this source is MTBE. This potential of leak sources S1 and S2 marked with yellow colour in a yellow dotted line area. The residential area R1 and R2 marked with red colour in a red dotted line area. The concentration of chlorine gas plume at 0.014, 0.35, 1 and 30 ppm was labelled with light blue, purple, dark blue and red iso-surface contour plot, respectively.

4.3.1 Effect of wind speed

The findings showed that the crosswise dispersion of chlorine plume is larger when the wind is weaker, for instance in Figure 4.3 (a and b). In contrast, the hazard plume becomes smaller when the wind is stronger, as shown in Figure 4.3 (c and d). This is because a higher wind speed is sufficiently strong to push and dilute the heavy gas like the chlorine and hence the hazard region is reduced. The result also showed that the chlorine gas dispersed by a stronger wind took a shorter time to reach the residential area, as shown in Table 4.1. Residential area can be affected within 3.3 to 10.0 min when the wind speed is above 7.2 m/s. Whereas, the chlorine plume dispersed by weaker wind below 2.4 m/s took duration of 11.7 to 49.2 min to reach the residential area.

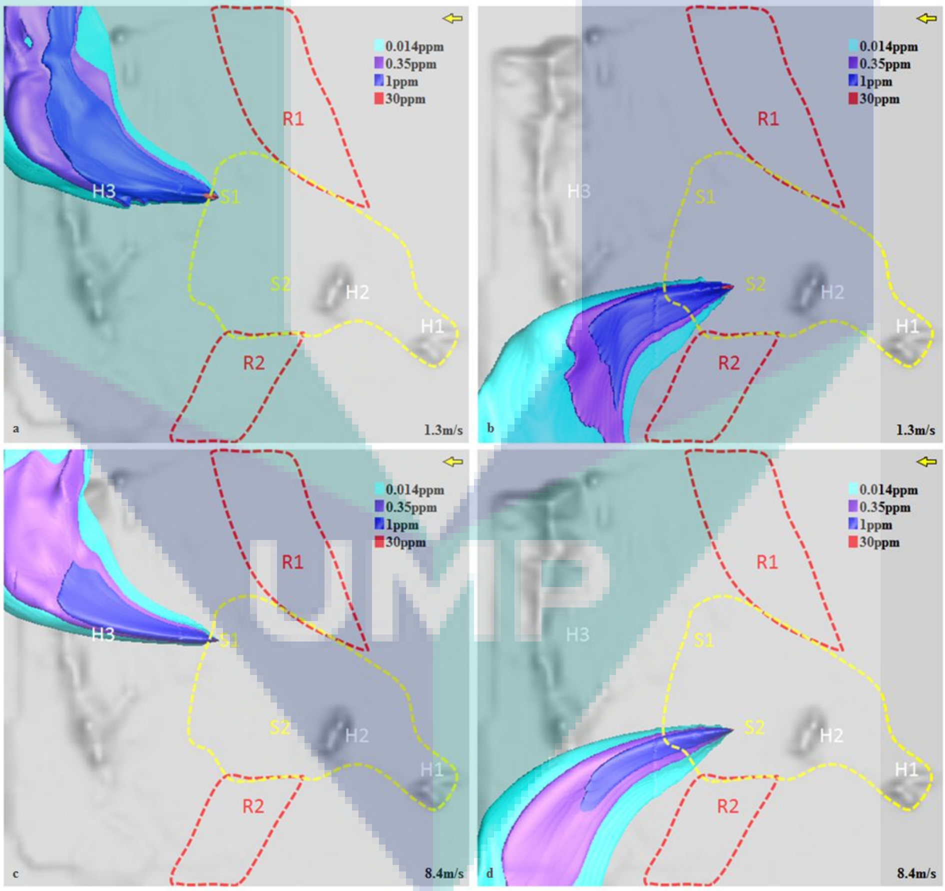

Figure 4.3 Air pollutant from points S1 and S2 dispersed by eastern wind, 1.3 m/s (a and b) and 8.4 m/s (c and d) on October.

Table 4.1 Duration for the chlorine plume to reach residential area in each month of 2014 at different wind speed and wind direction (Note: (a) is mean wind speed and (b) is high wind speed)

Month	Wind Direction (°)	Wind Speed (m/s)	Leak from S1 (min)	Leak from S2 (min)
January	020	2.4 [a]	-	11.7
		8.6 [b]	-	4.2
February	090	2.1 [a]	-	-
		8.2 [b]	-	-
March	090	2.2 [a]	-	-
		8.5 [b]	-	-
April	100	1.5 [a]	-	-
		8.2 [b]	-	-
May	090	1.5 [a]	-	-
		8.8 [b]	-	-
June	210	1.8 [a]	16.7	24.2
		9.5 [b]	4.2	5.8
July	210	1.8 [a]	16.7	24.2
		8.3 [b]	5.0	6.7
August	200	1.7 [a]	17.5	25.8
		8.2 [b]	5.0	6.7
September	200	1.6 [a]	20.8	27.5
		8.3 [b]	5.0	6.7
October	090	1.3 [a]	-	-
		8.4 [b]	-	-
November	350	1.4 [a]	49.2	15.8
		7.2 [b]	10.0	4.2
December	340	1.8 [a]	34.9	13.3
		8.0 [b]	9.1	3.3

4.3.2 Effect of wind direction

It can be seen that the residential area either R1 or R2 are not affected by the noxious gas during February to May and October (refer Figure 4.4). The residential area R1 and R2 studied in this work are located at north and south of the Gebeng industrial area, respectively. During these months, the seasonal monsoon is inter-monsoon that mostly eastern wind (i.e. 90 to 100°), and hence the residential area is escaped from the noxious gas.

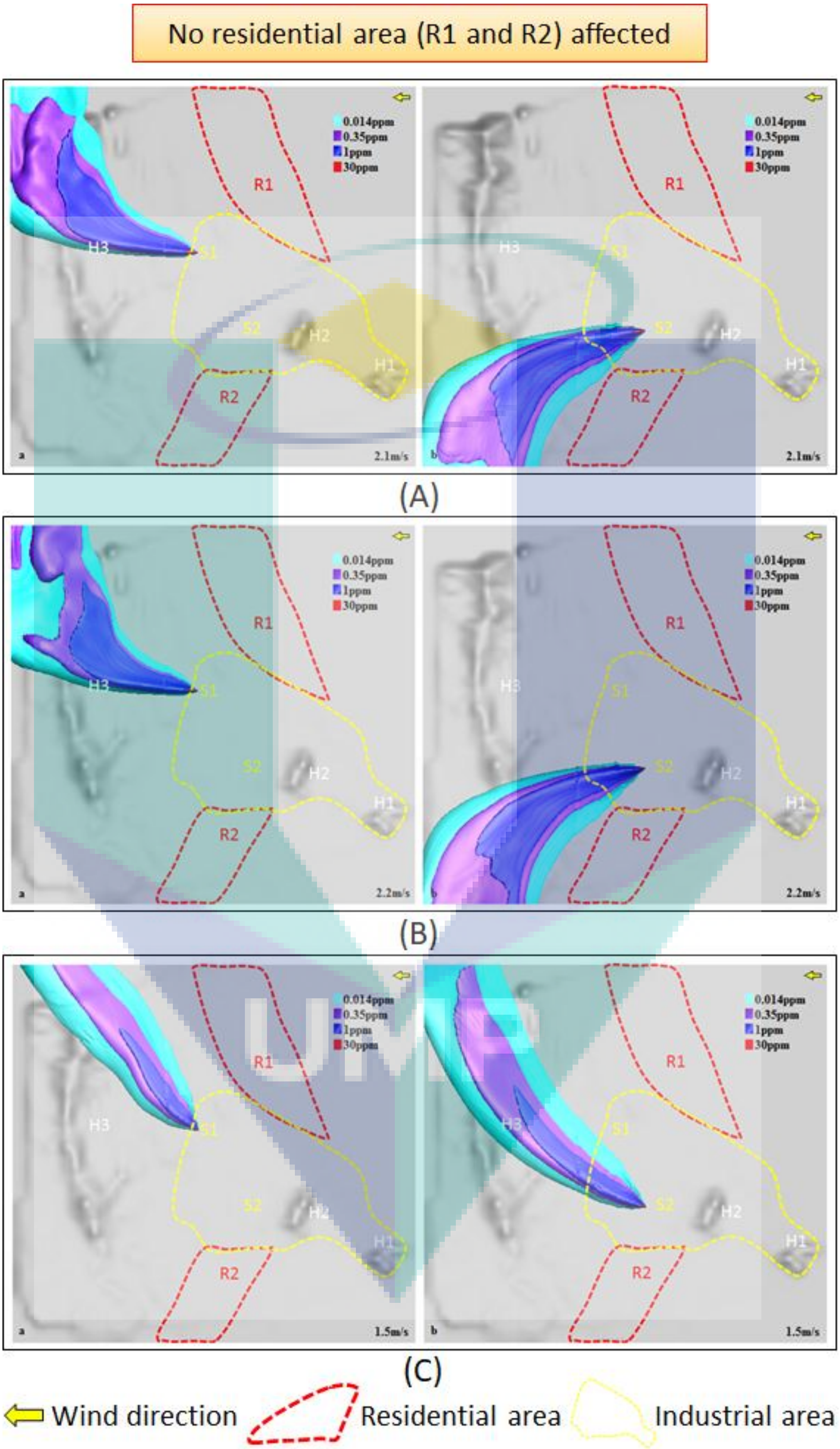

Figure 4.4 Chlorine plume disperse by mean wind speed from leak source a) S1 and b) S2 on the month of A) February, B) March, C) April, D) May, E) October.

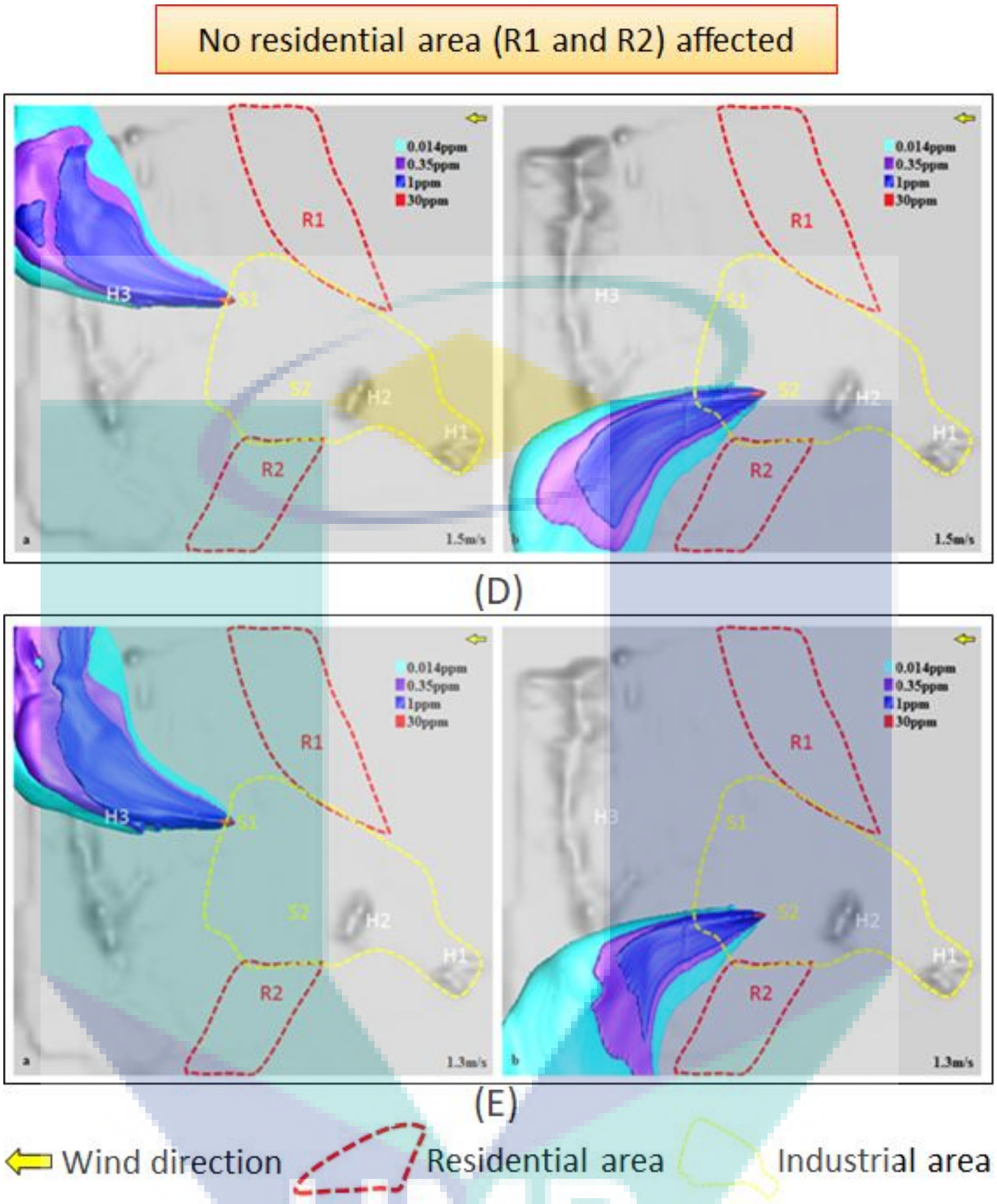

Figure 4.4 Continued.

However, the residents around the Gebeng industrial area should be alert with the chlorine gas plume if the leaks happen during Southwest and Northeast monsoon season on June to September (refer Figure 4.5) and November to January (refer Figure 4.6) respectively. This is because the monsoon wind is mostly in the direction of southwest and northwest, and therefore the chlorine gas plume is forced to move to northern and southeast, respectively. As the result, part of the residential area is affected. For instance from June to September, the south-westerly wind may lead to the air pollution on the residential area R1 where the location is included Kampung Gebeng, Tanjung Rhu, Kampung Sungai Ular and Cherating if the leakage happened from both sources S1 and S2. During November to January, northern wind may affects the residential area R2 where the Balok Baru Secondary School, Balok Perdana, Kampung Berahi and Kampung Selamat are situated. In facts lower wind speeds cause a larger plume formation and hence affecting a larger residential area. Hence, necessary evacuation procedure is needed in the event of noxious gas leaks from the position S1 and S2 for the affected area R1 and R2. The proposed evacuation route is discussed in the session 4.4.

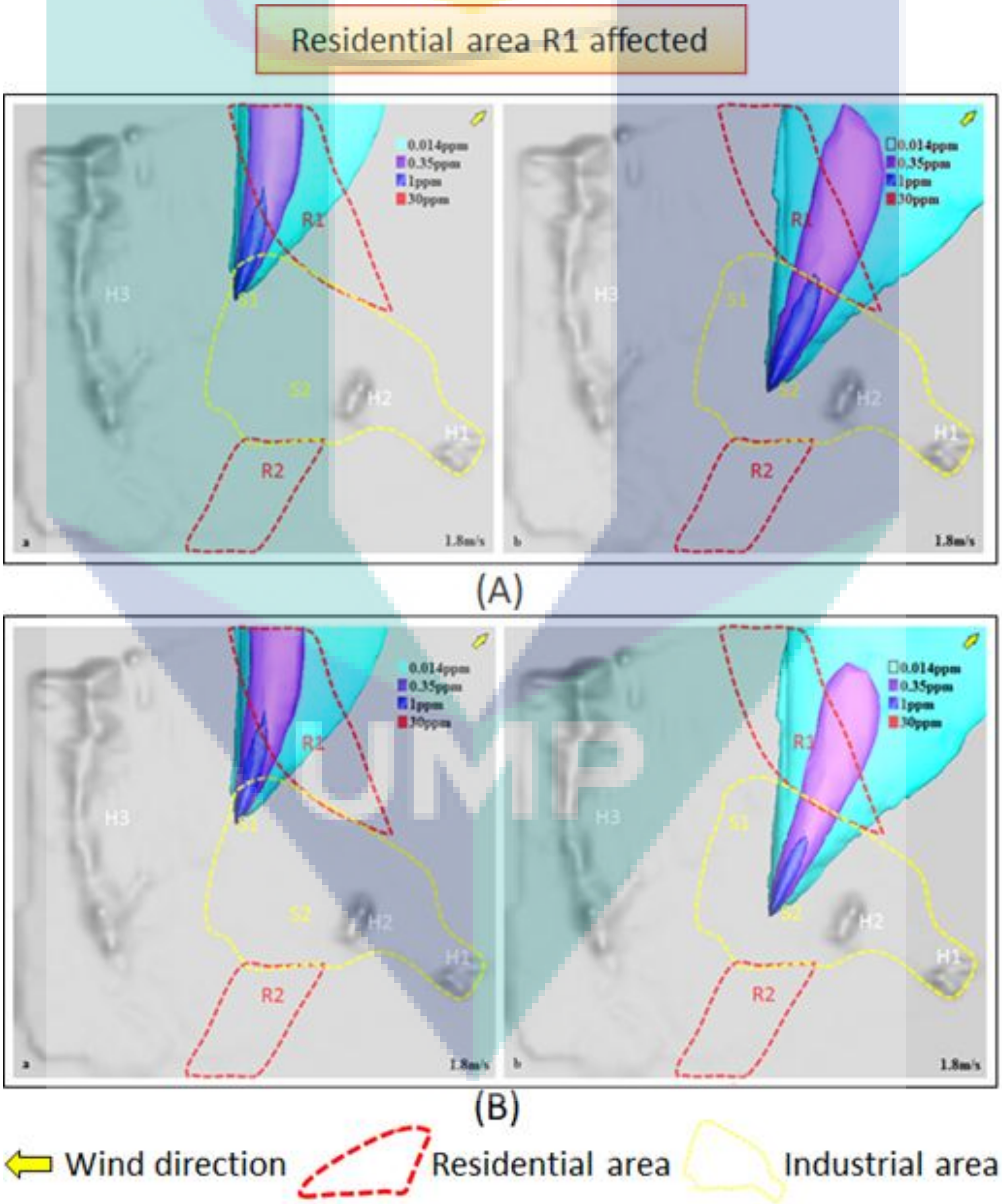

Figure 4.5 Chlorine plume disperse by mean wind speed from leak source a) S1 and b) S2 on the month of A) June, B) July, C) Augutst, D) September.

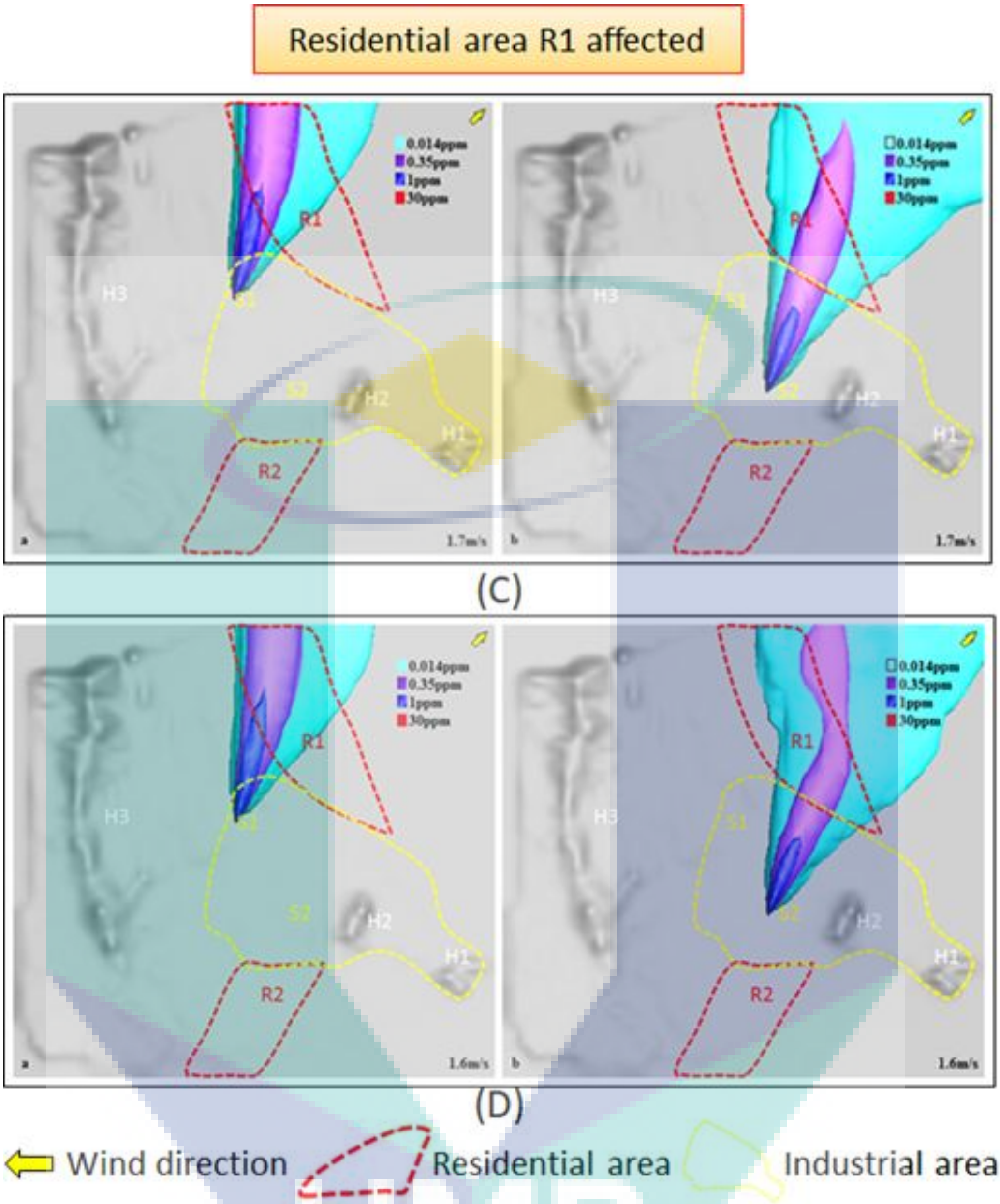

Figure 4.5 Continued.

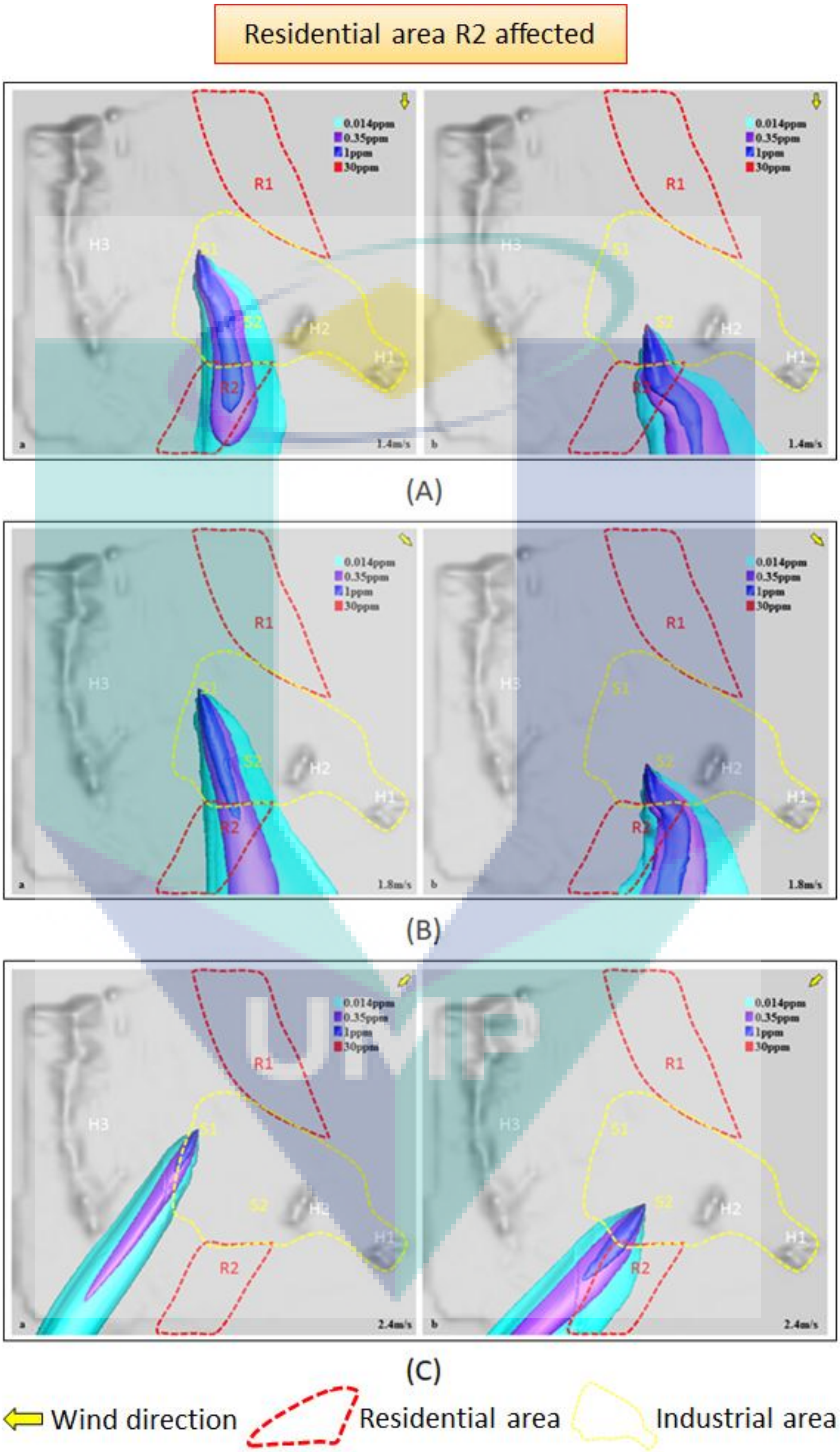

Figure 4.6 Chlorine plume disperse by mean wind speed from leak source a) S1 and b) S2 on the month of A) November, B) December, C) January.

4.3.3 Effect of surface terrain

Meanwhile, during the months in February, March, May and October (refer Figure 4.4 A, B, D and E), the chlorine plume is dispersed by an eastern wind. Figure 4.7 showed the vector plot for chlorine plume disperse from the leak sources S1 and S2. The vectors are slightly being moving toward northwest and southwest, respectively, when the plume approaching hill H3 driven by the mean wind speed ranging from 1.32 to 2.2 m/s. This is because the hill H3 with a height from 109 to 215 m becomes an obstacle for the plume to across it, especially for the higher concentration plume at 1 ppm. The plume at level of 1 ppm difficult to lift up and majority of it accumulates at the windward side of hill. The most dangerous level of 30 ppm plume only moves less than 1 km from the leaks source. Nevertheless, the chlorine plume with lower concentration level of 0.014 and 0.35 ppm was found not affected by the hill. The lower concentration plume is easily pushed by the wind flow due to its lower density. Therefore, the plume can engulf the hill H3 and then move further.

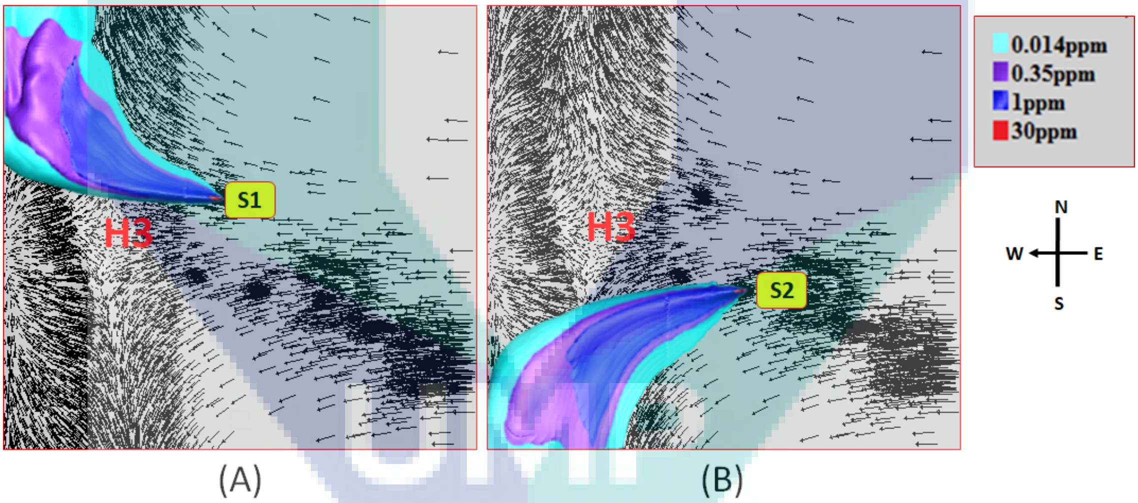

Figure 4.7 Vector plot for chlorine plume disperse from leak source A) S1, B) S2 towards hill H3 by eastern wind.

4.4 Safety Evacuation Route

From the findings in previous section 4.3, the risk of exposure to hazard plume during inter-monsoon season from February to May and October is negligible for the residential area nearby. Meanwhile, the residential area R1 and R2 are affected when the chlorine leakage occurs during Southwest and Northeast monsoon season on June to

September and November to January, respectively. Hence, the suitable safety evacuation route is proposed in the event of the residential area R1 and R2 are affected, as shown in Figure 4.8 (A and B) and Figure 4.9 (A and B), respectively. In Malaysia, the school and public hall are usually used as the safety and emergency evacuation points when incidents occurred such as natural disasters, industrial accidents, fire and sometimes from the structural failure. The summary of the potential affected area and proposed evacuation point in the event accidental chlorine leaks in different seasonal monsoon on 2014 is showed in Table 4.2.

The findings showed that a weaker wind resulted in a larger hazard zone in comparison with a stronger wind, although the chlorine plume dispersed by a weaker wind took longer time to reach the residential area. The following works are more emphasized on the particular areas that are highly affected instead of the time required to reach the residential area, hence the effect of the chlorine dispersion at lower wind speed was discussed. During Southwest monsoon season which is from June to September, the wind flows from south-southwest wind (200 to 210° in direction) with the mean wind speed ranging from 1.6 to 1.8 m/s. It was observed that the chlorine plume released from both source S1 and S2 affecting the residents live within R1 area extremely as the leak source is located at 1.5 and 6 km southwest of R1, respectively. However, residential area R2 is not affected.

The safety evacuation route and points in the event of the accidental release of chlorine during June to September is shown in Figure 4.8 (A and B), whereby the residents in R1 area should move towards the south or southwest of the residential area R1 for safety purpose. The suitable evacuation locations such as the school in evacuation point E1 are located around 12.6 to 24.6 km from the affected area. The residents will be forced to evacuate within less than one hour since at the 0.014 ppm chlorine leakage, they may feel tickling of the nose. They might be at risk to feel the effect since the gas can reach the residential area within 16 min from the leak source if the wind flows in the mean wind speed.

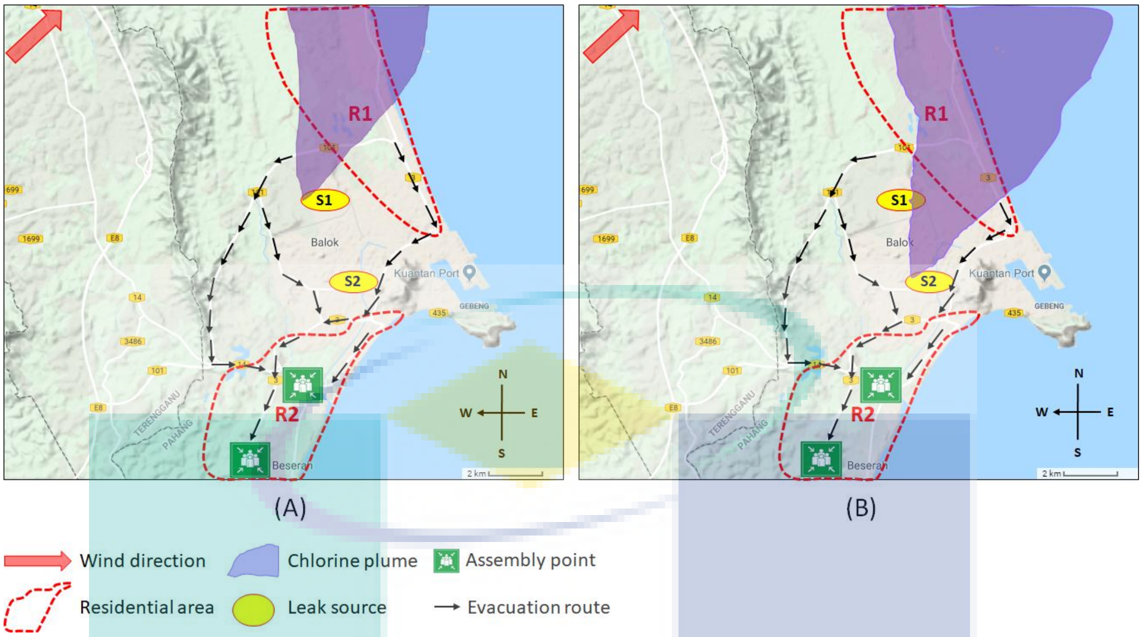

Figure 4.8 Proposed safety evacuation route if residential area R1 is affected from source A) S1 and B) S2.

During Northeast monsoon season from November to January, the wind flows from the northern wind (340 to 20° in direction) with mean wind speed ranging from 1.4 to 2.4 m/s. The findings show the plume released from sources S1 and S2 move slightly towards a southeast direction and hence affecting a major part of residential area R2 during November and December. In January, there is no residential area affected in the event of chlorine plume release from source S1. Meanwhile, minor part of R2 residential area is affected when the chlorine plume is released from S2. A safety evacuation route is needed in the event of chlorine leaks from either source S1 or S2 during the month of November to January.

The proposed safety evacuation points are towards the southwest, west and north of the affected area as shown in Figure 4.9 (A and B). The evacuation points are located approximately more than 5 km in radius respectively from the affected area. Since the mean wind speed during January is higher than November and December, it took only 11.7 minutes for chlorine plume to reach residential area R2 which is located southern direction from leak source S2. So, the residents live in residential area R2 might feel the tickling of nose as the chlorine leakage at 0.014 ppm if they failed to evacuate their residents. The authorities must take charge to ensure all the residents within the affected area to move towards the evacuation point proposed as the chlorine leakage is continuing.

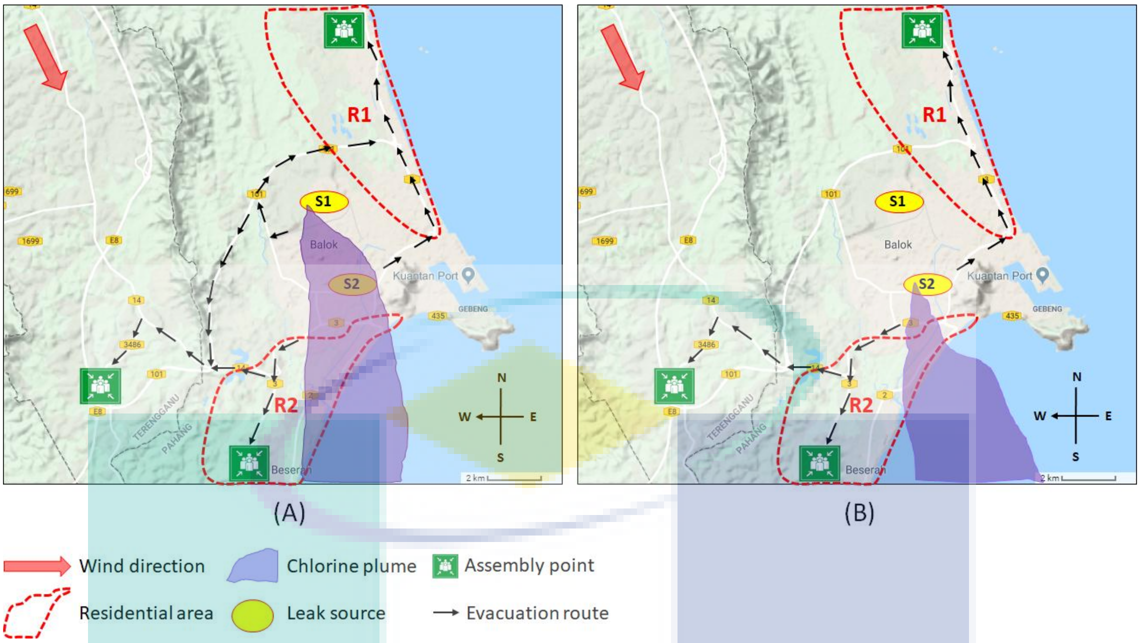

Figure 4.9 Proposed safety evacuation route if residential area R2 is affected from leak sources A) S1 and B) S2.

Table 4.2 below summarized the potential affected area and proposed evacuation point in the event accidental chlorine leaks in different seasonal monsoon on 2014. In the event of residential area R1 affected during June to September, the safer place chose as an evacuation point E1 located on south-southwest of the both leak sources since the location of residential area R1 affected is on north-northeast area of leak sources S1 and S2. During November to January, the safer place as evacuation points E2 and E3 located on southwest, west and north respectively from the leak sources S1 and S2. Mostly the evacuation points represent the schools and public hall located in the free pollutant region.

Table 4.2 Potential affected area and proposed evacuation point in the event accidental chlorine leaks in different seasonal monsoon in 2014

Month	**Wind direction (°)**	**Mean wind speed (m/s)**	**Chlorine leak source**	**Affected area**	**Evacuation point**
June-September	200-210	1.6-1.8	S1	R1 residential area, i.e. Kampung Sungai Ular, Kampung Darat Sungai Ular, Kampung Baging	E1: Schools (Sekolah Kebangsaan Balok Baru, Sekolah Kebangsaan Balok Makmur, Sekolah Kebangsaan Pelabuhan)
			S2	R1 residential area, i.e. Kampung Baru Gebeng, Tanjung Rhu, Kampung Sungai Ular, Kampung Darat Sungai Ular, Kampung Baging	
November-January	340-20	1.4-2.4	S1	R2 residential area, i.e. Kampung Balok, Kampung Balok Perdana, Kampung Seberang Balok, Kampung Berahi, Kampung Selamat, Kampung Balok Baru	E2: Schools (Sekolah Kebangsaan Sungai Ular, Sekolah Menengah Kebangsaan Sungai Baging, Sekolah Kebangsaan Cherating, Sekolah Kebangsaan Lembah Jabor) and public hall Dewan Orang Ramai Balok
			S2	R2 residential area, i.e. Kampung Berahi, Kampung Selamat, Balok Perdana, Kampung Seberang Balok	E3: Schools (Sekolah Kebangsaan Sungai Ular, Sekolah Kebangsaan Lembah Jabor, Sekolah Kebangsaan Balok Makmur)

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The CFD prediction with SAS model on the air flow over hill terrain was successfully performed. An experimental measurement of wind flows past the scaled-down terrain model was carried out using PIV and compared with the CFD simulation. The effect of terrain surface and wind condition (i.e. wind speed and directions) to the chlorine gas dispersion was successfully studied. The safety evacuation route in the event of the accidental release of chlorine was well identified. The major findings of this work are outlined as follows:

i. The velocity data was excellently predicted by using SAS model with the error ranging 1.5 to 2.6% from the PIV measured data. A correct flow features around the hill H2 (Bukit Pengorak) was successfully obtained. In addition, the effect of hill terrain was successfully captured by the SAS model, as shown in the vector plot map. Hence, the validated topographical model can be used to evaluate the combined effect of surface terrain, wind direction and speed on the pollutant dispersion around Gebeng industrial area.

ii. The terrain surface and wind condition (i.e., wind speed and direction) gave significant effect to the chlorine dispersion around Gebeng industrial area. The lower concentration level of the chlorine plume (i.e., 0.014 and 0.35 ppm) was not affected by the hill because it can easily push by the wind flow due to its lower density. Whereas, the chlorine plume concentration level at 1 ppm was accumulated at the windward side of hill and the plume (30 ppm) only moves less than 1 km from the leak sources. The chlorine plume is larger when the wind is weaker meanwhile in the stronger wind, the chlorine plume is getting smaller. The plume took shorter time to reach the residential area when it dispersed by the stronger wind. In the effect of wind directions, residential area R1 (i.e., Kampung Baru Gebeng, Tanjung Rhu, Kampung Sungai Ular, Kampung Darat Sungai Ular and Kampung Baging) was affected during June to September where the wind is in southwest directions meanwhile the residential area R2 (i.e., Kampung Selamat, Kampung Berahi, Kampung Balok, Kampung Seberang Balok Kampung Balok Baru and Kampung Balok Perdana) was affected by the northern wind during November to January.

iii. The safety evacuation route in the event of accidental chlorine leak was proposed based on the prediction results. In the event of leakage happened during south-westerly wind where R1 was mostly affected, Sekolah Kebangsaan Balok Baru, Sekolah Kebangsaan Balok Makmur, Sekolah Kebangsaan Pelabuhan was proposed as an evacuation point. During November to January, Sekolah Kebangsaan Sungai Ular, Sekolah Menengah Kebangsaan Sungai Baging, Sekolah Kebangsaan Cherating, Sekolah Kebangsaan Lembah Jabor and also Sekolah Kebangsaan Balok Makmur was proposed as an evacuation point for the residents in area R2.

5.2 Recommendation

This work used the terrain that created by using Sandbox from contours tools. The terrain generated on TIN structure can be study by using different tools (i.e., smoove, stamp, add detail, flip edge) to sculpt or do some minor adjustments on terrain to be the most accurate model to the actual terrain. The study on this different model will focus more on the best tools for designing the terrain.

The present work emphasized on the effect of terrain surface and wind condition on the chlorine gas dispersion. Other factors such as the atmospheric stability, temperature, humidity and ground roughness should be studied for better understanding on flow field measurement.

The wind flow moving over a complex terrain is subjected to a highly turbulent flows consisting of trapped lee waves, vertically propagating wave and rotors. All these waves may affect the chlorine gas dispersion mechanism. Rotor is a low level vortex generated in the lee side of hill. It can lead to a potential aeronautical risk due to the strong lower tropospheric (up to 10 km from the earth surface) turbulence and shear. Hence, it is important to study the detail mechanism of chlorine gas dispersion under influence of terrain surface induced turbulence.

REFERENCES

Abdullah, M. Z., Ismail, A., & Mahammad, N. I. (2014). Statistical analysis of heavy metal concentration in moss and soil as indicator of industrial pollution. *International Journal of Science, Environment and Technology*, *3*(3), 762–775.

Abdullah, M. Z., Azhar, N. F., & Abdul Kadir, S. M. (2015). Deposition Of Heavy Metals In Soil And Higher Plant Related To Rare-Earth Processing Activities. *Jr. of Industrial Pollution Control*, *31*(2), 315–321.

Alhassan, M., & Jimoh, A. (2006). Modeling and Simulation of Air Pollutant Dispartion a Case Study of an Industrial Area in Nigeria. *Leonardo Journal of Sciences*, *9*(9), 137–148.

Andersson, B., Andersson, R., Hakansson, L., Mortensen, M., Sudiyo, R., & Wachem, B. V. (2011). Computational Fluid Dynamics for Engineers. *Cambridge University Press*. New York.

Assimakopoulos, V. D., ApSimon, H. M., & Moussiopoulos, N. (2003). A numerical study of atmospheric pollutant dispersion in different two-dimensional street canyon configurations. *Atmospheric Environment*, *37*(29), 4037–4049.

Austin, A. (2005, May). Preventing chlorine gas accidents. Retrieved from http://ohsoline.com/

Baik, J. J. & Kim, J. J. (1999) A numerical study of flow and pollutant dispersion characteristics in urban street canyons. *Journal of Applied Meteorology*, 38**,** 1576-1589.

Beyers, M., & Waechter, B. (2008). Modeling transient snowdrift development around complex three-dimensional structures. *Journal of Wind Engineering and Industrial Aerodynamics*, *96*, 1603–1615.

Blocken, B., Stathopoulos, T., & Carmeliet, J. (2007). CFD simulation of the atmospheric boundary layer: wall function problems. *Atmospheric Environment*, *41*(2), 238–252.

Balogh, M., Parente, A., & Benocci, C. (2012). RANS simulation of ABL flow over complex terrains applying an Enhanced k-ε model and wall function formulation: Implementation and comparison for fluent and OpenFOAM. *Journal of Wind Engineering and Industrial Aerodynamics*, *104–106*, 360–368.

Borchers, O., Busch, C., Sokolichin, A. and Eigenberger, G. (1999) "Applicability of the standard k-ε turbulence model to the dynamic simulation of bubble columns. Part II: Comparison of detailed experiments and flow simulations", *Chem. Eng. Sci.*, *54*, pp.5927-5935

Cai, X. M., Barlow, J. F., & Belcher, S. E. (2008). Dispersion and transfer of passive scalars in and above street canyons-Large-eddy simulations. *Atmospheric Environment*, *42*(23), 5885–5895.

Cai, P., Nie, W., Chen, D., Yang, S., & Liu, Z. (2019). Effect of air flowrate on pollutant dispersion pattern of coal dust particles at fully mechanized mining face based on numerical simulation. *Fuel*, *239* (May 2018), 623–635.

Calabrese, E. J., & Kenyon, E. M. (1991). Air toxics and risk assessment.

Chan, T. L., Dong, G., Leung, C. W., Cheung, C. S., & Hung, W. T. (2002). Validation of a two-dimensional pollutant dispersion model in an isolated street canyon. *Atmospheric Environment*, *36*(5), 861–872.

Chow, F. K., & Street, R. L. (2009). Evaluation of Turbulence Closure Models for Large-Eddy Simulation over Complex Terrain: Flow over Askervein Hill. *Journal of Applied Meteorology and Climatology*, *48*, 1050–1065.

Corsmeier, U., Behrendt, R., Drobinski, Ph., Kottmeier, Ch. (2005). The mistral and its effect on air pollution transport and vertical mixing. *Atmospheric Research*, *74*, 275-302.

De la Torre, A., Pessano, H., Hierro, R., Santos, J. R., Llamedo, P., & Alexander, P. (2015). The influence of topography on vertical velocity of air in relation to severe storms near the Southern Andes Mountains. *Atmospheric Research*, *156*, 91–101.

Deen, N. G., Hjertager, B. H., & Solberg, T. (2000). Comparison of PIV and LDA Measurement Methods Applied to the Gas-Liquid Flow in a Bubble Column. *10th Int. Symp. on Appl. of Laser Techniques to Fluid Mech*, Lisbon, Portugal: 10-13 July.

Deng, Y., Hu, H., Yu, B., Sun, D., Hou, L., & Liang, Y. (2018). A method for simulating the release of natural gas from the rupture of high-pressure pipelines in any terrain. *Journal of Hazardous Materials*, *342*, 418–428.

Dharmawan and Hanna. (2007). Computational Fluid Dynamic (CFD) modelling of toxic gas dispersion in the vicinity of complex buildings, structures, and topography. *ICheme Symposium Series No.153*.

Di Sabatino, S., Buccolieri, R., Pulvirenti, B., & Britter, R. E. (2008). Flow and pollutant dispersion in street canyons using FLUENT and ADMS-Urban. *Environmental Modeling and Assessment*, *13*(3), 369–381.

Diebold, M., Higgins, C., Fang, J., Bechmann, A., & Parlange, M. B. (2013). Flow over Hills: A Large-Eddy Simulation of the Bolund Case. *Boundary-Layer Meteorology*, *148*(1), 177–194.

Dominick, D., Latif, M. T., Juahir, H., Aris, A. Z., & Zain, S. M. (2013). An assessment on influence of meteorological factors on PM10 and NO_2 at selected stations in Malaysia. *Sustainable Environment Research*, *22*(5), 305–315.

EPA (Environmental Protection Agency), U. S. (1999). Chlorine gas. Prevention, Pesticides and Toxic Substances.

Fesquet, C., Drobinski, P., Barthlott, C., & Dubos, T. (2009). Impact of terrain heterogeneity on near-surface turbulence structure. *Atmospheric Research*, *94*(2), 254–269.

Finardi, S., & Morselli, M. G. (1997). Wind flow models over complex terrain for dispersion calculations. *Working Group*, (May 1997), 1–51.

Gilham, S., Deaves, D. M., & Woodburn, P. (2000). Mitigation of dense gas releases within buildings: Validation of CFD modelling. *Journal of Hazardous Materials*, *71*(1–3), 193–218.

Goh, J. (2017, July). Gas leak at KB Water Dept. Retrieved from http://www.dailyexpress.com.my/

Gosman, A. D. (1999). Developments in CFD for industrial and environmental applications in wind engineering. *Journal of Wind Engineering and Industrial Aerodynamics*, *81*, 21–39.

Gousseau, P., Blocken, B., Stathopoulos, T., & van Heijst, G. J. F. (2011). CFD simulation of near-field pollutant dispersion on a high-resolution grid: A case study by LES and RANS for a building group in downtown Montreal. *Atmospheric Environment*, *45*(2), 428–438.

Grigoras, G., Cuculeanu, V., Ene, G., Mocioaca, G., & Deneanu, A. (2012). Air pollution dispersion modeling in a polluted industrial area of complex terrain from Romania. *Romanian Reports in Physics*, *64*(1), 173–186.

Ha, T., Lee, I. Bok, Kwon, K. Seok, & Lee, S. J. (2018). Development of a micro-scale CFD model to predict wind environment on mountainous terrain. *Computers and Electronics in Agriculture*, *149*(November 2017), 110–120.

HHS (Department of Health and Human Services), U. S. (1993). Hazardous Substances Data Bank (HSDB, online database). National Toxicology Information Program, National Library of Medicine, Bethesda, M. D.

Holmes, N. S., & Morawska, L. (2006). A review of dispersion modelling and its application to the dispersion of particles: an overview of different dispersion models available. *Atmospheric Environment*, 40, 5902-5928.

Hong, S., Lee, I., Hwang, H., Seo, I., Bitog, J., Kwon, K., Song, J., Moon, O., Kim, K., Ko, H. (2011). CFD modelling of livestock odour dispersion over complex terrain, part I: Topographical modelling. *Biosystems Engineering*, *108*(3), 253–264.

Hong, S., Lee, I., Hwang, H., Seo, I., Bitog, J., Kwon, K., Song, J., Moon, O., Kim, K., Ko, H. (2011). CFD modelling of livestock odour dispersion over complex terrain, part II: Dispersion modelling. *Biosystems Engineering*, *108*(3), 265–279.

Hsieh, K.-J., Lien, F.-S. & Yee, E. (2007) Numerical modeling of passive scalar dispersion in an urban canopy layer. *Journal of Wind Engineering and Industrial Aerodynamics,* 95**,** 1611-1636.

Huang, H., Akutsu, Y., Arai, M., & Tamura, M. (2000). A two-dimensional air quality model in an urban street canyon: Evaluation and sensitivity analysis. *Atmospheric Environment*, *34*(5), 689–698.

Hyun, B.-S., Balachandar, R., Yu, K., & Patel, V. C. (2003). Piv/Ldv Measurements of Mean Velocity and Turbulence in a Complex Open Channel Flow. (424).

Ingram, D. M., Causon, D. M., & Mingham, C. G. (2003). Developments in Cartesian cut cell methods. *Mathematics and Computers in Simulation*, *61*, 561–572.

Institution of Occupational Safety and Health (IOSH), 2008. Chlorine equipment. In: Material Safety Data Sheets SDS-E-002, 0005, http://www.iosh.gov.tw/

Jadidi, M., Bazdidi-Tehrani, F., & Kiamansouri, M. (2018). Scale-adaptive simulation of unsteady flow and dispersion around a model building: spectral and POD analyses. *Journal of Building Performance Simulation*, *11*(2), 241–260.

Jayamurugan, R., Kumaravel, B., Palanivelraja, S., & Chockalingam, M. P. (2013). Influence of Temperature, Relative Humidity and Seasonal Variability on Ambient Air Quality in a Coastal Urban Area. *International Journal of Atmospheric Sciences*, *2013*, 1–7.

Kamada, Y., Li, Q., Maeda, T., & Yamada, K. (2019). Wind tunnel experimental investigation of flow field around two-dimensional single hill models. *Renewable Energy*, *136*, 1107–1118.

Katsaprakakis, D. A. & Christakakis, D. G. (2012). Wind Energy. *Comprehensive Renewable Energy*.

Koh, K. (2017, September). Melaka chlorine gas leak: Residents return home after removal of cylinders from neighborhood. *Nst*. Retrieved from https://www.nst.com.my/

Kumar, P., Singh, S. K., Ngae, P., Feiz, A. A., & Turbelin, G. (2017). Assessment of a CFD model for short-range plume dispersion: Applications to the Fusion Field Trial 2007 (FFT-07) diffusion experiment. *Atmospheric Research*, *197*(June), 84–93.

Laeng, J. (2018). Nine people rushed to hospital for suspected inhalation of poisonous gas. Retrieved from http://www.theborneopost.com/ (accessed 30 July 2019).

Launder, B. E., & Spalding, D. B. (1974). The Numerical Computation of Turbulent Flows. *Computer Methods in Applied Mechanics and Engineering*, *3*, 269–289.

Letzel, M. O., Krane, M. & Raasch, S. (2008) High resolution urban large-eddy simulation studies from street canyon to neighbourhood scale. *Atmospheric Environment*, 42**,** 8770-8784.

Linfield, K. W., & Mudry, R. G. (2008). Pros and Cons of CFD and Physical Flow Modeling. *Airflow Sciences Corporation*.

Liu, Y., Chen, D., Kahn, R. A., & He, K. Bin. (2009). Review of the applications of Multiangle Imaging SpectroRadiometer to air quality research. *Science in China, Series D: Earth Sciences*, *52*(1), 132–144.

Liu, Z., & Ishihara, T. (2014). Numerical study of turbulent flow over complex topography by LES model. 1–8.

Liu, B., Liu, X., Lu, C., Godbole, A., Michal, G., & Tieu, A. K. (2016). Computational fluid dynamics simulation of carbon dioxide dispersion in a complex environment. *Journal of Loss Prevention in the Process Industries*, *40*, 419–432.

Ma, X., Zhong, W., Feng, W., & Li, G. (2017). Modelling of pollutant dispersion with atmospheric instabilities in an industrial park. *Powder Technology*, *314*, 577–588.

Maharani, Y. N., Lee, S., & Lee, Y. (2009). Topographical Effect on Wind Speed over Various Terrains: A Case Study for Korean Peninsula. *The Seventh Asia-Pacific Conference on Wind Engineering, Taipei, Taiwan*.

Maliska, C. R., Paladino, E. E., Saltara, F., Contessi, B. A., & Ataides, R. (2012). A Comparison of Turbulence Models for the Computation of a Detached Flow around a Square Cylinder.

McBride, M. A., Reeves, A. B., Vanderheyden, M. D., Lea, C. J., & Zhou, X. X. (2001). Use of advanced techniques to model the dispersion of chlorine in complex terrain. *Process Safety and Environmental Protection*, *79*(2), 89–102.

Michálek, P., & Zacho, D. (2015). Wind tunnel studies of gas dispersion over complex terrain. In *EPJ Web of Conferences* (Vol. 114).

Malaysian Investment Development Authority (MIDA). (2013). Petrochemical Industry.

Menter, F. R., & Egorov, Y. (2006). SAS Turbulence Modelling of Technical Flows. *Direct and Large-Eddy Simulation VI*, 687–694.

Murakami, S. (1990). Numerical simulation of turbulent flowfield around cubic model current status and applications of k-ε model and LES. *Journal of Wind Engineering and Industrial Aerodynamics*, *33*(1–2), 139–152.

Murakami, S., Mochida, A. and Hayashi, Y., 1988: Modification of production terms in k-ε Model to remove overestimate of k value around windward corner. *10th Wind Engineering Symposium*, 199-204.

Murena, F., & Mele, B. (2016). Effect of balconies on air quality in deep street canyons. *Atmospheric Pollution Research*, *7*(6), 1004–1012.

Nakiboglu, G., Gorle, C., Horvath, I., Beeck, J. Van, & Blocken, B. (2009). Stack gas dispersion measurements with Large Scale-PIV, Aspiration Probes and Light Scattering Techniques and comparison with CFD. *Atmospheric Environment*, *43*, 3396–3406.

Nosek, S., Janour, Z., Kukacka, L., Jurcakova, K., Kellnerova, R., & Gulikova, E. (2013). Atmospheric dispersion modelling over complex terrain at small scale. *EPJ Web of Conferences*.

Onianwa, P. C., Ajayi, S. O., Osibanjo, O., & Egunyomi, A. (1986). Accumulation patterns of heavy metals in forest mosses from the south-west region of Nigeria. *Environmental Pollution Series B, Chemical and Physical*, *11*(1), 67–78.

Pilloni, M. T., Schram®, C., & Riethmulle, M. L. (2000). PIV and LDV measurements behind a backward facing step. *Air Pollution VIII*, 633–642.

Rasouli, A., Hangan, H., & Siddiqui, K. (2009). PIV measurements for a complex topographic terrain. *Journal of Wind Engineering and Industrial Aerodynamics*, *97*(5–6), 242–254.

Riddle, A., Carruthers, D., Sharpe, A., McHugh, C., & Stocker, J. (2004). Comparisons between FLUENT and ADMS for atmospheric dispersion modelling. *Atmospheric Environment*, 38, 1029-1038.

Rotta, J. C., (1972). Turbulent Flows (Turbulente Stromungen). Teubner-Verlag, Stuttgart.

Saga, T., Hu, H., Kobayashi, T., Segawa, S., Taniguchi, N., Measuring, F., & Division, I. (1999). A Comparative Study of the PIV and LDV Measurements on a Self-induced Sloshing Flow. *3rd International Workshop on PIV*. Santa Barbara, USA: 16-18 September.

Salim, S. M., Buccolieri, R., Chan, A., & Di Sabatino, S. (2011). Numerical simulation of atmospheric pollutant dispersion in an urban street canyon: Comparison between RANS and LES. *Journal of Wind Engineering and Industrial Aerodynamics*, *99*(2–3), 103–113.

Sarkar, S., & Balakrishnan, L. (1990). Application of a Reynolds Stress Turbulence Model to the Compressible Shear Layer. In *AIAA journal* (Vol. 29).

Scargiali, F., Di Rienzo, E., Ciofalo, M., Grisafi, F., & Brucato, A. (2005). Heavy gas dispersion modelling over a topographically complex mesoscale a cfd based approach. *Process Safety and Environmental Protection*, *83*(3 B), 242–256.

Scargiali, F., Grisafi, F., Busciglio, A., & Brucato, A. (2011). Modeling and simulation of dense cloud dispersion in urban areas by means of computational fluid dynamics. *Journal of Hazardous Materials*, *197*, 285–293.

So, E. S. P., Chan, A. T. Y. & Wong, A. Y. T. (2005) Large-eddy simulations of wind flow and pollutant dispersion in a street canyon. *Atmospheric Environment*, 39**,** 3573-3582.

Sobahan, M. A., & Islam, M. S. (2015). Integrated Assessment of Heavy Metal Contamination in Sediments from. *Research Journal of Recent Sciences*, *4*(11), 26–35.

Spalart, P. R. (2000). Strategies for turbulence modelling and simulations. *International Journal of Heat and Fluid Flow*, *21*(3), 252–263.

Sudarsan, J. S., Thattai, D., Shah, U. K., & Mitra, A. (2016). Micrometeorological tower observations and their importance in atmospheric modelling and space technology. *Indian Journal of Science and Technology, 9*(42), 1-6.

Sujaul, I. M., Hossain, M. A., Nasly, M. A., & Sobahan, M. A. (2013). Effect of Industrial Pollution on the Spatial Variation of Surface Water Quality. *American Journal of Environmental Science*, *9*(2), 120–129.

Tamura, Y., & Matsui, M. (2002). - Recent topics in wind engineering focusing on monitoring techniques. In M. Anson, J. M. Ko, & E. S. S. Lam (Eds.), *Advances in Building Technology* (pp. 65–74).

Teneler, G. (2011). Wind Flow Analysis on a Complex Terrain. *Master of Science Thesis*. Gotland University.

Tominaga, Y. & Stathopoulos, T. (2010) Numerical simulation of dispersion around an isolated cubic building: Model evaluation of RANS and LES. *Building and Environment*, 45**,** 2231-2239.

Tominaga, Y., & Stathopoulos, T. (2011). CFD modeling of pollution dispersion in a street canyon: Comparison between LES and RANS. *Journal of Wind Engineering and Industrial Aerodynamics*, *99*(4), 340–348.

Vladut, A. C., Cosoiu, C. I., Georgescu, A. M., Degeratu, M., & Damian, R. M. (2016). Wind Tunnel and Numerical Modeling of Atmospheric Boundary Layer Flow over Bolund Island. *Energy Procedia*, *85* (November 2015), 603–611.

Warner P.O. 1976. Analysis of Air Pollutions. John Wiley and Son, New York. 329.

White, C. W., & Martin, J. G. (2010). Chlorine Gas Inhalation: Human Clinical Evidence of Toxicity and Experience in Animal Models. *Proceedings of the American Thoracic Society*, *7*(4), 257–263.

Xie, X., Huang, H. & Wang, J. (2006). The impact of urban street layout on local atmospheric environment. *Building and Environment*, 41**,** 1352-1363.

Yeap, A. (2016, September). Chlorine gas causes scare around plant. Retrieved from https://www.thestar.com.my/

Zaharim, A., Shaharuddin, M., Nor, M. J. M., Karim, O. A., & Sopian, K. (2009). Relationships between airborne particulate matter and meteorological variables using non-decimated wavelet transform. *European Journal of Scientific Research, 27*(2)**,** 308-312.

Zhang, H., Xu, T., Zong, Y., Tang, H., Liu, X., & Wang, Y. (2015). Influence of Meteorological Conditions on Pollutant Dispersion in Street Canyon. *Procedia Engineering*, *121*, 899–905.

APPENDIX A
PIV MEASUREMENT SETUP

Figure A.1 shows the real figure for the PIV measurement setup and Figure A.2 shows the Fog generator in the field experiment.

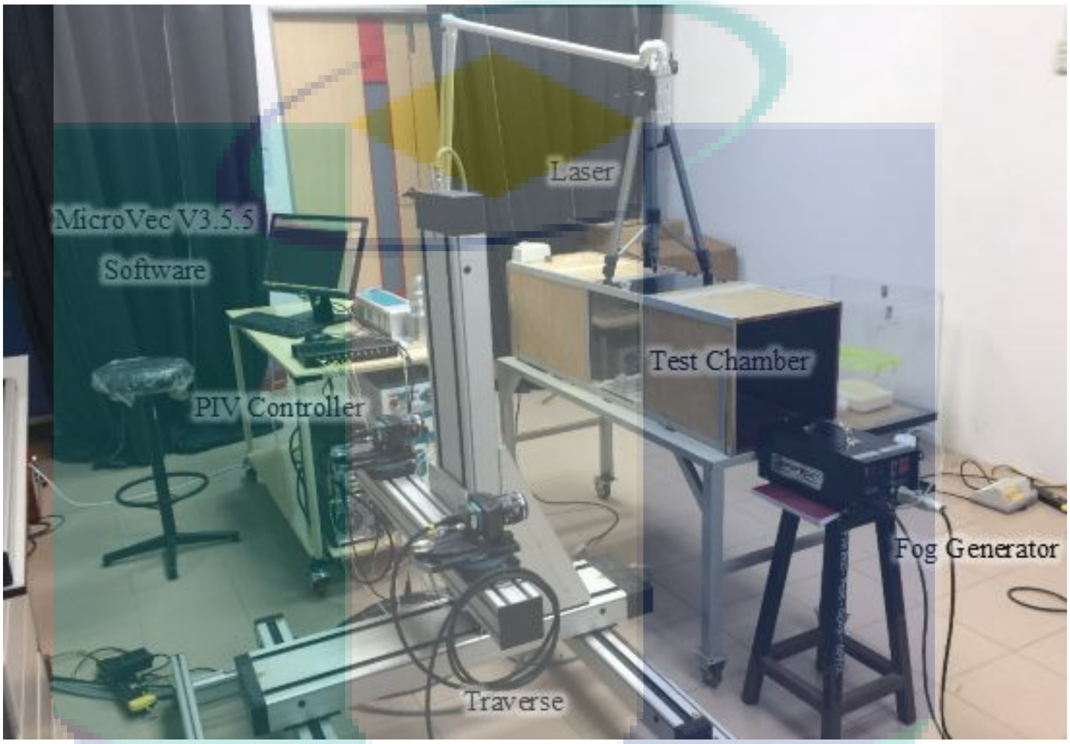

Figure A.1 PIV measurement setup

Figure A.2 Fog generator

LIST OF PUBLICATIONS

Journal

1. Law, W. P., Erain, N., Ramli, N. I., & Gimbun, J. (2019). Assessment of chlorine leak dispersion around Gebeng industrial area and potential evacuation route. *Atmospheric Research*, 216, 117-129. Q1 ISI IF 4.114

2. Erain, N., Law, W. P., Ramli, N., Chin, S. C., & Gimbun, J. (2017). Understanding the Effect of Surface Terrain on Pollution Transport around Gebeng Industrial Area. *Indian Journal of Science and Technology*, 10:2, 1-5.

Conference

1. Erain, N., Law, W.P., Ramli, N., & Gimbun, J. (2017). Understanding the Effect of Surface Topology on Wind Speed and Atmospheric Turbulent around Gebeng Industrial Park. *FluidsChe*, 4-6 April, Sabah.

Award

1. Best paper award, N. Erain, W.P. Law, N.I. Ramli, J. Gimbun. (2017). Understanding the Effect of Surface Topology on Wind Speed and Atmospheric Turbulent around Gebeng Industrial Park. *FluidsChe 2017*, Sabah.