PROGRESS REPORT

UMP GRANT

ASSESSMENT OF POLLUTION DISPERSION FROM GEBENG INDUSTRIAL AREA (RDU150314)

By,

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b) The reported analyses, opinion, conclusions are limited only by the reported assumptions and limiting conditions, and are my personal impartial, unbiased professional analyses, opinions and conclusions.
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Assoc. Prof. Dr. Jolius Gimbun
Project Leader

Abstract

Air pollution dispersion is greatly affected by the wind speed and direction. Most often the pollution dispersion from industrial area is not fully understood. In the present work, the effect of surface topology on the wind speed and atmospheric turbulent around the Gebeng industrial area in Pahang was studied using a computational fluid dynamics (CFD) method. The typical southeastern wind with a speed of about 1.3003 m/s corresponding to the actual speed of approximately 5 km/h was considered for validation. The turbulent flow was modelled using k-ε model. The model was compared with the laser Doppler velocimetry (LDV) measurement on the scale-down rig. The CFD prediction showed good agreement within 10% deviation with the experimental measurement via LDV. It was found that the plume of noxious gas driven by the eastern wind can affect the nearby residential area R2, whereas the western wind is affecting the residential area R1. In the presence of hill obstacle, the gas plume moves southward into the flat terrain. In addition to the CFD simulation, gas dispersion analysis using ALOHA software is also studied. The chlorine dispersion was modelled using the heavy gas cloud model and the incident zone area is plotted accurately from the point of release with the aid of GPS coordinate and google map. The risk zone and the affected residential area were identified and the safety evacuation route in the event of accidental chlorine leak is also suggested. Results from this work may be useful to understand the risk of air pollutant dispersion around Gebeng industrial area.

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Table of Content

1 INTRODUCTION

1.1 Background

Air pollution affects human health, ecosystems and materials in a variety of ways, and deserves appropriate attention. The atmosphere can act as a medium for transporting local pollution to other locations. Pollutant dispersion at different area has been studied extensively. For instance, Varma and Manjula (2016) studied the nitrogen oxide dispersion and its concentration level around the Rayalaseema Thermal Power plant. Sudarsan et al. (2016) showed that the atmospheric fluctuation strongly depends on the wind speed, direction and temperature. Saravankumar et al. (2016) investigated the concentration of air pollutants (i.e., particulate matter, sulfur dioxide and nitrogen dioxide) at residential, commercial and industrial areas at different seasons. They found that the pollutant level during monsoon is lesser than that during winter and summer due to the wind fluctuation. All the aforementioned works reported that pollutant dispersion is significantly affected by the emission source and meteorological condition, e.g., wind speed and direction, atmospheric humidity and temperature, pollutant temperature and emission rate. Other than the meteorological condition the dispersion of air pollution are also significantly affected by the terrain type. Air flow and dispersion around the different hills has been studied experimentally and numerically (Hunt et al., 1984; Chow and Street, 2009). However, limited study on the effect of wind speed, direction and terrain map on the air pollutant transport around Gebeng industrial area in Kuantan, Malaysia. It is important to study the effect of surface topography on the air dispersion in Gebeng industrial area as a precautionary guide for evacuation during emergency and hence this is the aim of this work.

Ideally, experimental techniques like the satellite photography is the best method to observe and understand the air flow in a complex terrain. However, experimental technique has limitations to provide detailed information of turbulent flow. In addition, the satellite photography experiment is very costly. Hence, computational fluid dynamics (CFD) is used, although they require more computing time and costs compared to the other numerical techniques (Holmes and Morawska, 2006; Rillde et al., 2004). Reynolds-averaged Navier-Stokes (RANS) and large eddy simulation (LES) are commonly used to model air flow and pollutant dispersion around the complex terrain (Hong et al., 2011; Liu et al., 2016). RANS-based turbulence models such as k-ε models are easier and economical to run. However, these models suffer from the isotropic eddy viscosity assumption, thus may not provide an accurate measure of turbulent kinetic energy, but may provide a good prediction of the mean velocity. In the case of atmospheric pollutant dispersion, mean flow is more important than the turbulent kinetic energy and hence RANS-based model is applicable in this work. LES generally performs well because it resolved directly the large flow structureand modelled the smaller eddies at the region of boundary layers. However, the simulation via LES is costly due to a very fine grid resolution at the boundary layer. A massive number of grids required for a large terrain (14 km x 7 km) in the present work when LES was used. Therefore, RANS-based models were used in the present work to study the effect of surface terrain on pollutant transport around Gebeng industrial area.

1.2 Objectives

The main objectives of this program are:

- To fabricate a scaled-down model of Gebeng industrial area topography and to develop a measurement platform
- To perform a (laser doppler anemometer) LDV measurement of air flow around Gebeng industrial area
- To study the effect of noxious air pollution release on the residential area around Gebeng industrial area

1.3 Scope of this research

The following are the scope of this research:

i) Fabrication of a scaled-down 3D topographical model of Gebeng industrial area and its surrounding
ii) Measuring the air flow around the scaled down model using LDV
iii) Obtaining a wind and rainfall pattern around Gebeng industrial area from Meteorological Department Malaysia
iv) Performing a CFD simulation of air flow around Gebeng industrial area and comparing with the LDV measurement
v) Performing a CFD simulation of noxious gas release in Gebeng industrial area
vi) Assessing the pollution dispersion to residential area around Gebeng industrial area using CFD and ALOHA

2 Literature review

2.1 Introduction

Air pollution is the presence of high concentration of contamination, various hazardous chemicals, particulate matter, toxic substances and biological organisms into the earth atmosphere. 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. 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, 1985). Major air pollutant were identified, their source, how they cause air pollution, effects and control measures were analyzed (AlHassan M. and Jimoh, 2015)

Many researchers already 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 where 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 (2015) 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. Study about the thorium releases from industrial area not as much as other study. So, this is more focus on releasing thorium gas in industrial area where the most sources of pollutant emit and disperse to surrounding freely. To complete this research, suitable and right tools is needed to carry out the simulation of dispersion of pollutant emission around Gebeng industrial area.

2.2 CFD study on air pollutant dispersion

CFD models can considered to be more appropriate and more effective for applications to complex terrain, although they require more computing time and costs compared to the other models (Holmes & Morawska, 2006; Riddle, Carruthers, Sharpe, McHugh, & Stocker, 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., 2010).

Among the techniques commonly used to predict the dispersion of pollution in cities, Computational Fluid Dynamics (CFD) is increasingly explored and used (Pierre et al., 2010). Same goes other researchers, 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., 2005).

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 modeling 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). Recently, 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).

CFD incorporates empirical models for modeling turbulence based experimentation, as well as the solution of heat, mass and other transport and field equations. There are three phases to CFD, which is pre-processing or creation of geometry, mesh generation of a suitable computational domain to solve the flow equations on and solving with post processing or visualization of a CFD code's predictions.

In my case, FLUENT will be used which is a software that uses the science of predicting fluid flow, heat and mass transfer, chemical reactions, surface elevation, wind speed and directions and related phenomena by solving numerically the sets of governing mathematical equations.

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).

2.3 *Wind tunnel experiment*

In this study, wind tunnel study was presented to be validated mean velocity predicted with CFD results. Many studies use this test but with different measurement techniques. This method was applied to measure the flow velocity and turbulence (Hong et al., 2010). Wind tunnel test was performed to study the correlation between the velocity and concentration fields which is Particle Image Velocimetry (PIV) used to explain the concentration fields (Isao et al., 2006). Laser Doppler Anemometry (LDA) or also called Laser Doppler Velocimetry (LDV) and Fast Flame Ionisation Detector (FFID) devices were coupled in order to 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 (Carpentri and Robins, 2009). Niels et al. (2000) has been studied on both PIV and LDA measurement methods on multiphase flow velocity. The resulted shows that PIV velocity data appears 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. So, for this study, PIV was used to measure mean flow velocity since it can offer many advantages compared to LDV. One of them are 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 (Tetsuo et al., 1999).

3 Methodology

3.1 Overview

This section describes the computational and experimental methods used to study the air pollution dispersion around the Gebeng industrial area. Figure 3.1 shows the flowchart for the terrain map creation, flow simulation and PIV measurement performed in this work. At first, a terrain model of Gebeng industrial area was extracted from the google map using Sketch Up and Rhinoceros. The geometry was then meshed using ANSYS Workbench mesher 16.2. Detail of geometry and mesh was given in section 3.3. The initial condition, boundary condition and models were set in ANSYS Fluent R16.2. The detail of simulation setup was presented in section 3.7. Air pollution dispersion at 2 m/s from west direction was compared with the PIV measurement. The measurement was performed in a scaled-down terrain model, as presented in section 3.8. A prediction error of from the measured data was set for the CFD simulation of velocity flow to ensure the models used are correct. The correct models were then used to evaluate the effect of different wind direction, wind speed and pollutant flowrate on the pollutant dispersion around the Gebeng industrial area.

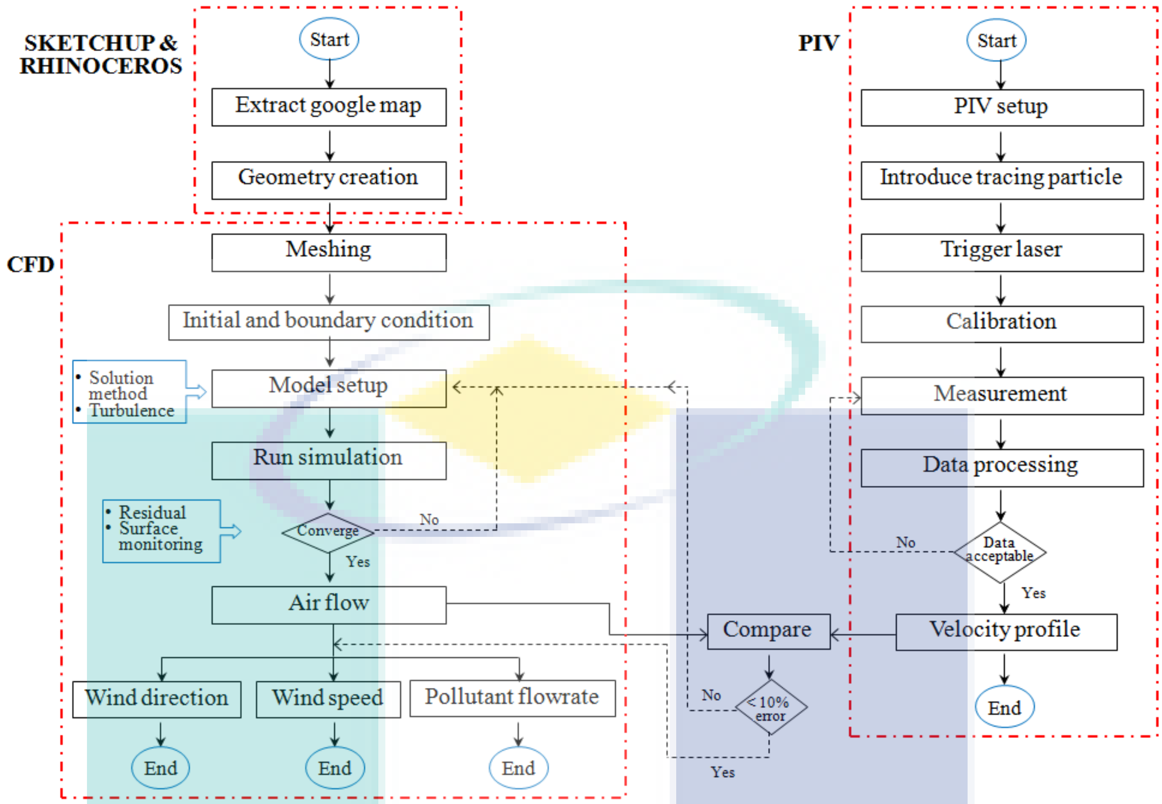

Figure 3.1. Flowchart for the research methodology.

3.2 *Terrain around Gebeng industrial area*

The present work focuses the Gebeng industrial area, Pahang of about 15 km (east-west) x 14 km (north-south), as shown in Figure 3.2. Gebeng industrial area has the two sea–facing hills namely Bukit Tanjung Gelang (H1) and Bukit Pengorak (H2) with the elevation above sea level of 105 m and 197 m, respectively. Another hill (H3) is located along the border of Pahang and Terengganu states. The height of this hill is ranging from 109 m up to 215 m. Residential area marked as R1 and R2 is situated in the north and south of the industrial area, respectively. The potential noxious gas source was marked as S1, S2 and S3 where the chemical plant is situated. The wind speed and wind direction around Gebeng industrial area varies from time to time, and hence the air dispersion from the pollutant source to the residential areas is the major concern. The pollutant dispersion around the Gebeng industrial area was investigated via PIV and CFD techniques.

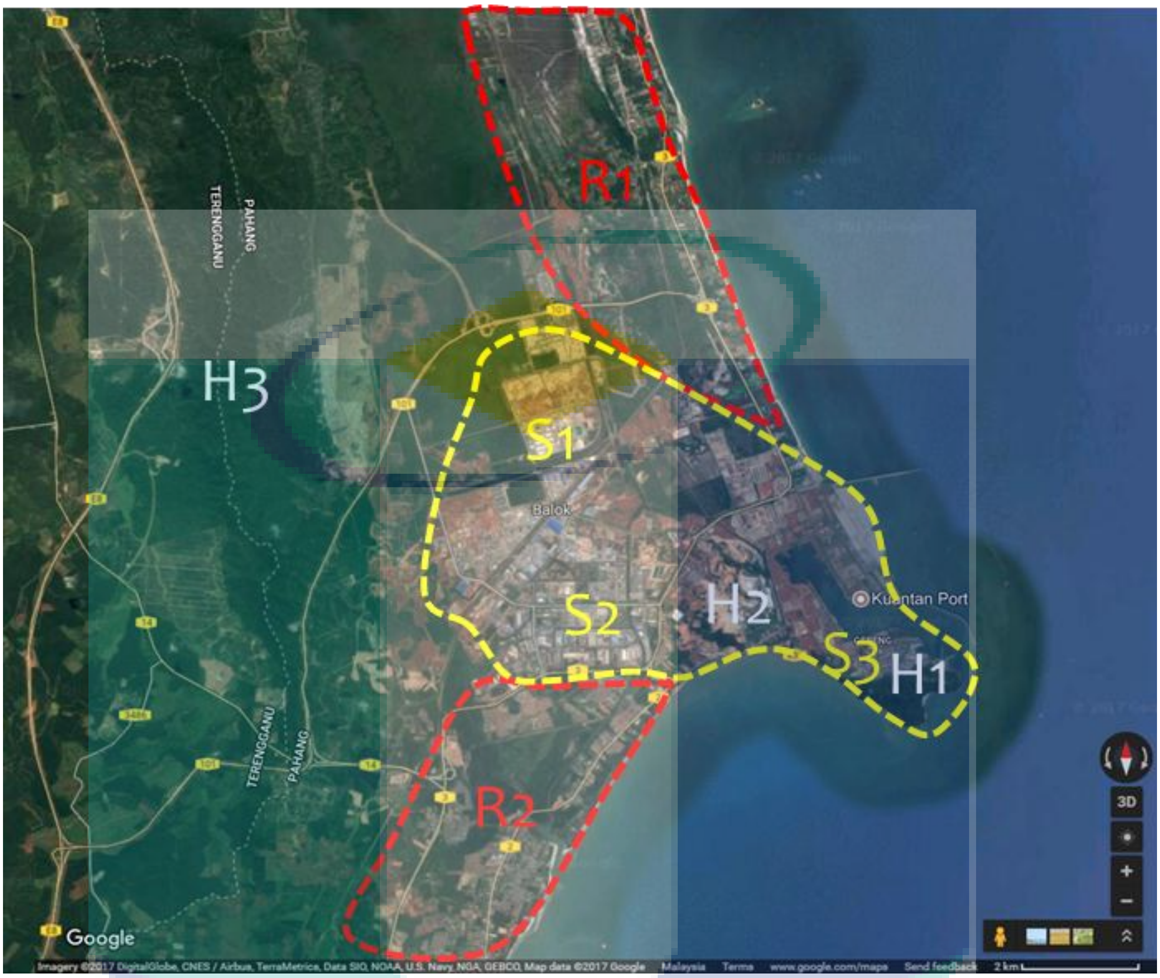

Figure 3.2. Modelled hills location around Gebeng industrial area. Square box indicates the study area, Gebeng industrial area and Kuantan port is located inside the yellow line area.

3.3 *Computational geometry and mesh*

The detail dimension of the terrain and location of pollutant sources around Gebeng industrial area is presented in prior section 3.2. The terrain was obtained from Google map using Sketch Up and the TIN surface splitting was done using Rhinoceros software, as shown in Figure 3.3. The area of study was taken from up to 42 topographical maps which represent about 15 km (east-west) x 14 km (north-south). The height of the flat sky face is 2.5 km above the ground to ensure the flow at the earth surface is independence to that of the sky (Hong et al., 2011). The terrain surface was then meshed using ANSYS Workbench Mesher 16.2, as shown in Figure 3.4. Refined mesh was used for the region around the hills. The grid resolution around the hills surface was set at 6 x 10^{-2} m and 5 m at the bulk region, respectively. The entire domain of the terrain model containing 1292k grid nodes.

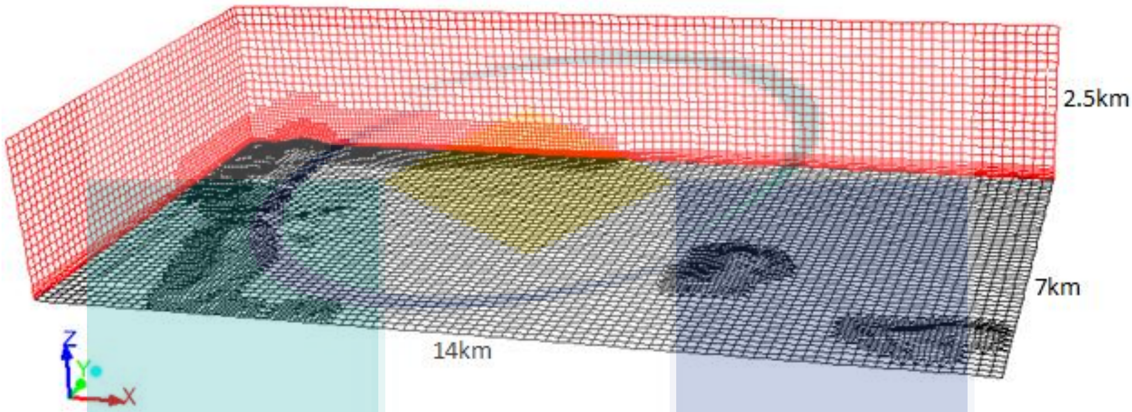

Figure 3.3. Terrain model of Gebeng industrial area.

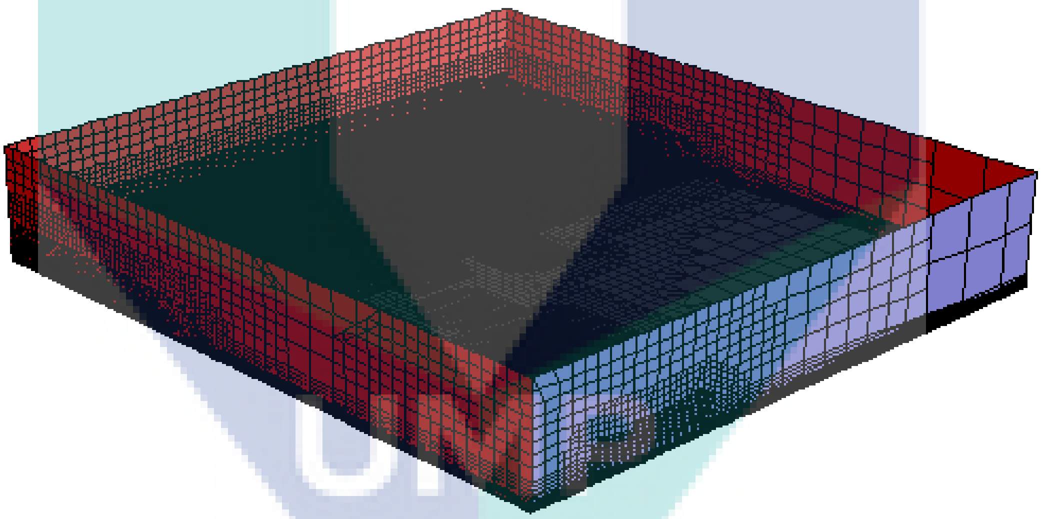

Figure 3.4. Computational grid of the terrain around Gebeng industrial area.

3.4 Conservation equations

The mass of control volume is assumed to be conserved. For a single particle in fluid, the rate of mass change equals to the net rate of mass flow normal to its surface (Versteeg and Malalasekera, 1995). The mass flow of control volume is typically measured by its density, velocity and size. The resulting mass balance is given as:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (3.1)$$

where u, v and w are denoted as the velocity in x, y, and z direction, respectively and ρ is the density of fluid.

According to the Newton's second law, the rate of momentum change is equals to the net force acting on a control volume. Generally, the total force on a control volume is the product of surface forces, i.e., pressure (P) and viscous stresses (τ). The momentum conservation equations for x, y, and z-components are given as:

$$\rho\frac{\partial u}{\partial t}=\frac{\partial(\tau_{xx}-P)}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}+S_{Mx} \qquad (3.2)$$

$$\rho\frac{\partial v}{\partial t}=\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial(\tau_{yy}-P)}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+S_{My} \qquad (3.3)$$

$$\rho\frac{\partial w}{\partial t}=\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial(\tau_{zz}-P)}{\partial z}+S_{Mz} \qquad (3.4)$$

where S_M is the source term due to body force, e.g., gravitational force. The negative sign in pressure term represented as compressive stress.

3.5 Turbulence modelling

The dispersion of air pollution is affected by the terrain surface, wind speed and wind direction. Hence, air flow around the Gebeng industrial area was modelled using turbulence model such as RANS model. Standard *k-ε* (SKE) is the most-used two-equation RANS model to account for the kinetic energy and the dissipation rate due to its simplicity, robustness and has a relatively low computational demand (Launder and Spalding, 1974). SKE solves the mean flow quantities, while the majority of the turbulence spectrum is modelled. The turbulence kinetic energy equation is modelled as:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M \quad (3.5)$$

The turbulence diffusive transport term is modelled by assuming a gradient-diffusion transport mechanism (Andersson et al., 2012). σ_k is known as Prandtl-Schmidt number of k with a constant value of 1.0 while μ_t is turbulence viscosity. Turbulence viscosity is computed as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (3.6)$$

where C_μ is given as 0.09. A production rate term describes the production of turbulence kinetic energy due to mean velocity gradient (G_k) and turbulence buoyancy effect (G_b), respectively. Both production terms are computed as follows:

$$G_k = -\rho\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_i} \quad (3.7)$$

$$G_b = \beta g_i \frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i} \quad (3.8)$$

where Pr_t is the turbulence Prandtl number with a constant value of 0.85 and g_i is the component of gravitational vector in *i*-th direction. The model coefficient for G_b (β) is given by:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \quad (3.9)$$

Turbulence dissipation rate is modelled as:

$$\varepsilon = \nu \overline{\frac{\partial u_i''}{\partial x_j} \frac{\partial u_i''}{\partial x_j}} \tag{3.10}$$

The additional term in Eq. (3.5) is the dilatation dissipation term. Y_M is accounts for compressibility effect on turbulence flows and given as:

$$Y_M = 2\rho\varepsilon M_t^2 \tag{3.11}$$

The dissipation rate is modelled as a second transport equation in the SKE model as follows:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{3.12}$$

$C_{3\varepsilon}$ is computed from:

$$C_{3\varepsilon} = \tanh\left|\frac{v}{u}\right| \tag{3.13}$$

where v is the component of flow velocity parallel to the gravitational vector and u is the component of flow velocity perpendicular to the gravitational vector (Fluent, 2006). Turbulent Prandtl number for ε is σ_ε=1.3. The model constants are $C_{1\varepsilon}$=1.44 and $C_{2\varepsilon}$=1.92. Nevertheless, SKE is known to perform poorly for the flows containing large adverse pressure gradients, unconfined flows, curved streamlines, swirling and rotating flows due to the isotropic eddy viscosity formulation which could lead to a negative normal stresses computation under certain circumstances. Hence, a hybrid model like the SAS was introduced to overcome the limitation of SKE.

Scale-adaptive simulation (SAS) is a two-equation model which was first proposed by Rotta (1972), which is based on exact transport equation for length scale. The SAS was then modified by Menter et al. (2006) which became known as the KSKL (K-square-root-K-L) model. The Φ coefficient in the KSKL model is directly proportional to the eddy viscosity and allows the formulation of the one-equation model in addition to the proposed two-equation model. The inclusion of von Karman length scale enables the SAS to model the steady flow using RANS method and switch to LES-like mode to resolve the turbulence spectrum in unstable flows by allowing the formation of a broadband of the turbulence spectrum (Menter et al., 2006). At the grid limit, different limiters can be employed to ensure the proper turbulence dissipation. In SAS, the limiters do not affect the RANS behaviour of the model and hence the model is not sensitive to grid resolution, unlike the LES. The two equations in KSKL model are given as:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho u_i k) = P_k - C_\mu^{\frac{3}{4}} \rho \frac{k^2}{\Phi} + \frac{\partial}{\partial x_i}\left[\left(\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] \tag{3.14}$$

$$\frac{\partial}{\partial t}(\rho \Phi) + \frac{\partial}{\partial x_i}(\rho u_i \Phi) = \frac{\Phi}{k} P_k \left[\zeta_1 - \zeta_2 \left(\frac{L}{L_{vk}}\right)^2\right] - \zeta_3 \rho k + \frac{\partial}{\partial x_i}\left[\left(\frac{\mu_t}{\sigma_\Phi}\right)\frac{\partial \Phi}{\partial x_i}\right] \tag{3.15}$$

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

$$\Phi = \sqrt{k}L \tag{3.16}$$

$$\mu_t = C_\mu^{\frac{1}{4}} \rho \Phi \tag{3.17}$$

The new term added into KSKL model is von Karman length scale, L_{vk} which is obtained from:

$$L_{vk} = \mathcal{K}\left|\frac{U'}{U''}\right| \tag{3.18}$$

$$U' = \sqrt{2S_{ij}S_{ij}} \tag{3.19}$$

$$U'' = \sqrt{\frac{\partial^2 u_i}{\partial x_k^2}\frac{\partial^2 u_i}{\partial x_j^2}} \tag{3.20}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) \quad (3.21)$$

Given that U' is the invariant of strain rate tensor. The model constants C_μ is 0.09, σ_k is $\frac{2}{3}$, σ_Φ is $\frac{2}{3}$, $\mathcal{K}$ is 0.41, ζ_1 is 0.8, ζ_2 is 1.47 and ζ_3 is 0.0288.

3.6 *Species transport equation*

The non-reacting species mixing was solved using species transport approach. The mass-averaged transport equation without reaction is given by:

$$\frac{\partial}{\partial x_j}(\rho \bar{u}_j \bar{Y}_i) = -\vec{J}_i + S_i \quad (3.22)$$

where $\bar{u}_j$ is the mass-averaged velocity of mixture, $\bar{Y}_i$ is the local mass fraction of each species, $\vec{J}_i$ is the diffusion flux of species *i* and S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources.

$$\vec{J}_i = -\frac{\partial^2}{\partial x_i^2}\left[\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\bar{Y}_i\right] \quad (3.23)$$

where $D_{i,m}$ is a diffusion coefficient for species *i* in the mixture, μ_t is turbulent viscosity and Sc_t is the turbulent Schmidt number which is computed as a function of turbulent diffusivity, D_t .

$$Sc_t = \mu_t / \rho D_t \quad (3.24)$$

3.7 *CFD simulation setup*

Computational fluid dynamics (CFD) simulation in the present work was performed using ANSYS Fluent R16.2 installed on the HP Compaq Pro 6300 MT workstation with a Quadcore i7-3770 processor (3.40 GHz) and 4 GB RAM. In this work, validation was performed to test the suitability of the model chosen and the grid resolution before used to study the effect of different wind speed, wind direction and pollutant flowrate. The wind direction around Gebeng industrial area varies from time to time, however, only one wind direction (i.e., west wind) was chosen for the validation, as shown in Table 3.1. The hourly highest wind speed and wind direction was obtained from Kuantan Meteorological Department. The ambient air flow was set at 2 m/s in the west direction. The simulation was performed using a steady-state solver and SKE model to fasten the convergence of initial solution. Second-order discretization scheme was used for the scalar equations of turbulence and momentum.

SAS model was then enabled and bounded central differencing was used for the momentum. All residuals were set to fall below specified thresholds at 1×10^{-5}. The statistical convergence of the velocity at x, y and z direction at specified spatial position was monitored to ensure a good convergence. Once a pseudo-steady solution was achieved, data was recorded for over 1000 time steps and averaged. The velocity prediction was compared with the PIV measurement. Once the validation is done, a case study to evaluate the dispersion of chlorine from three hypothetical sources at different wind speed and wind direction is modelled using species transport model. The chlorine flowrate was set at constant 10 kg/h. The wind speed and direction was taken from January to December, as shown in Table 3.1. Then, the effect of different wind speed (2.1 m/s and 11.8 m/s) and pollutant flowrate (10 kg/h and 100 kg/h) released from source S2 in March was studied.

Table 3.1. Wind direction and speed from January to December

Month	Wind direction	Wind speed (m/s)
January	East	11.9
February	North	10.1
March	North	11.8
April	North	8.7
May	North	8.9
June	Southwest	11.7
July	Southwest	12.2
August	West	11.0
September	West	12.1
October	North	10.4
November	East	8.4
December	East	12.4

3.8 PIV measurement

In this experiment, a scaled-down terrain model (1 : 6) was prepared to represent the Gebeng industrial area. The scaled-down terrain model is shown in Figure 3.5. A mini wind tunnel with a transparent window for PIV measurement having a length of 1.23 m, width of 0.31 m and height of 0.31 m was made for the experiment, as shown in Figure 3.6. The wall of the measurement window with thickness of 0.004 m is made of Perspex to enable measurement by PIV. A PIV (MicroVec Pte Ltd) was used to measure the air velocity around the terrain model. The PIV system consists of a CCD camera (FlowSense EO), laser system (Vlite-200 model), synchronizer, electronic traverse and processing software. The dual-laser has a wavelength of 532 nm and energy of 200 mJ. The laser was triggered and delivers a thin light sheet to define the plane of measurement area. The flow was seeded with fog into the mini wind tunnel driven by an axial fan. The axial fan was installed at the outlet of the wind tunnel to provide a homogeneous flow. The Safex fog liquid (Dantec Dynamics, Denmark) has a droplet size of 1.068 µm and converted into fog by the mean of internal heating using a fog generator (FOG 2010 model). The inlet flow was set at 1.3 m/s. CCD camera view was placed perpendicular to the plane of measurement area and used to capture the displacement of particles in a specific plane at a rate of a few frames per second. A calibration was carried out to ensure a correct measurement can be made. Velocity measurement at specified position was performed using MicroVec software. The images are divided into a grid of 32 x 32 pixels interrogation area. An overlap of 50% is used to provide more detail velocity information out of the particle images recorded. The velocity profile obtained was used to compare with the CFD prediction of the air pollutant dispersion around the Gebeng industrial area.

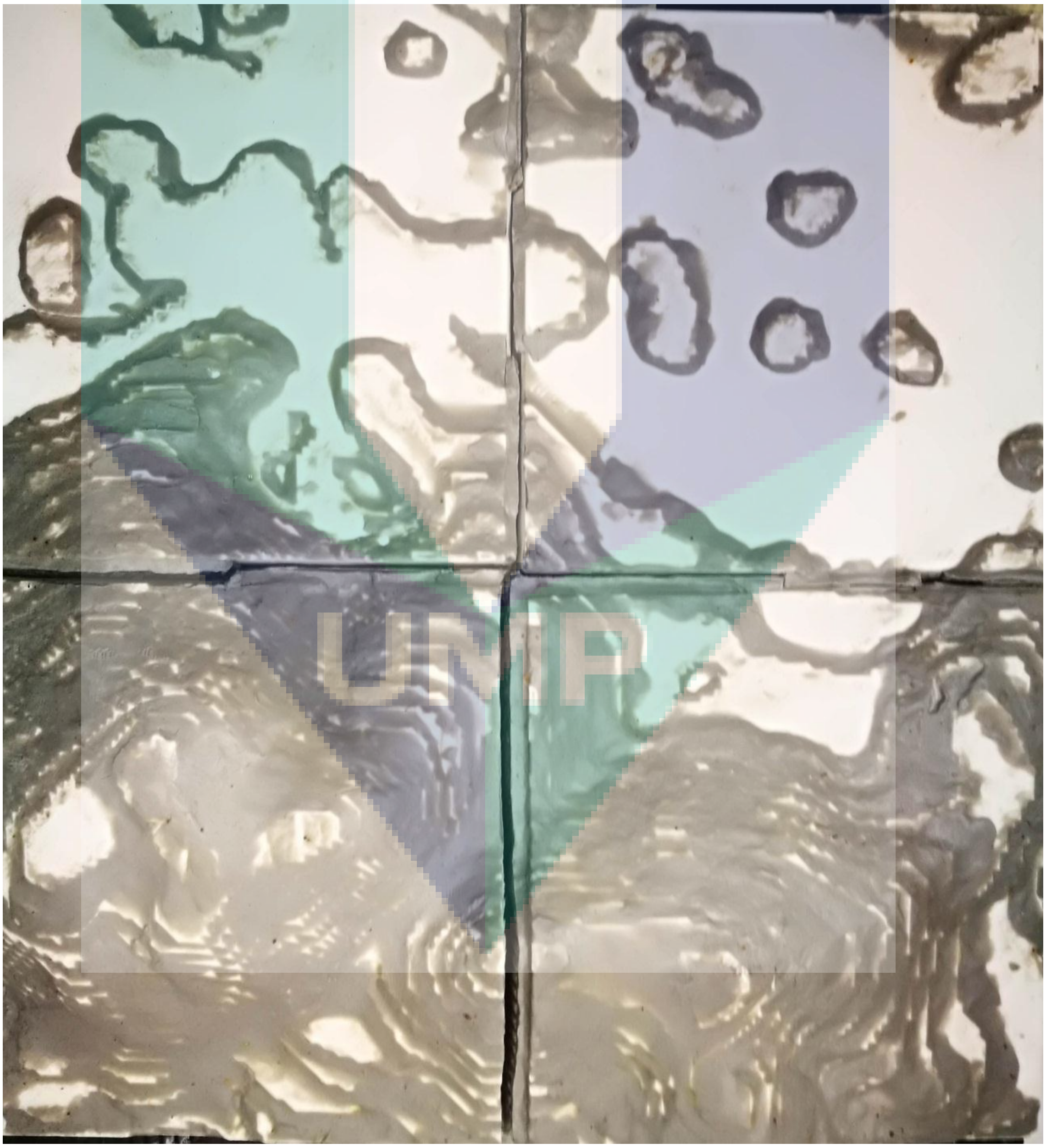

Figure 3.5. Scaled-down terrain model

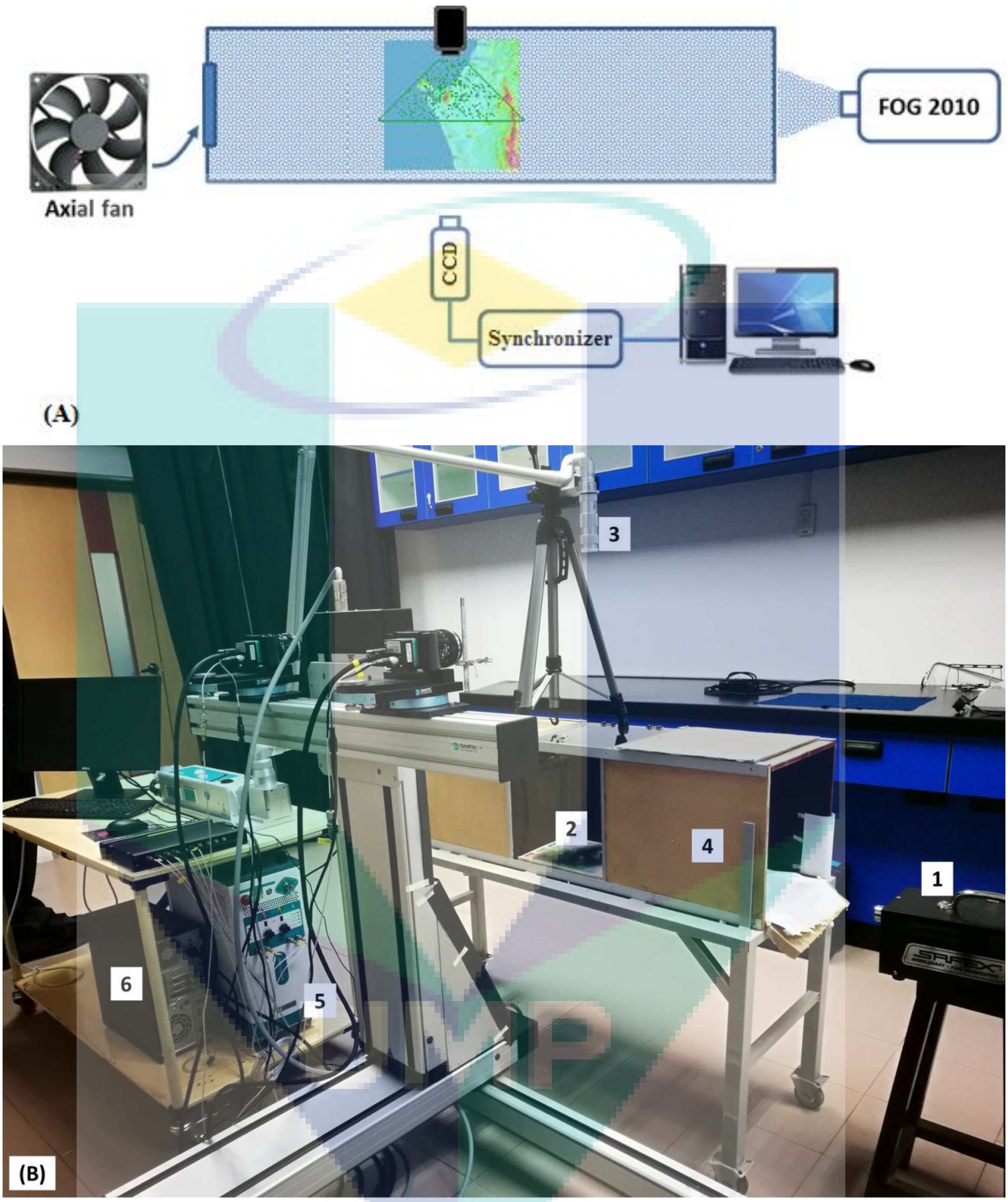

Figure 3.6. A) Schematic diagram, B) Physical image of the experimental setup. 1) Fog generator, 2) Terrain model, 3) Laser beam, 4) Mini wind tunnel, 5) Laser generator, 6) Computer CPU

4 Computational Fluids Dynamics Study

4.1 Wind rose

The wind data such as the mean wind speed and direction was obtained from a local weather station (Kuantan meteorological department) for the whole year in 2014 is shown in Figure 4.1. Based on the data obtained, the southwest monsoon season usually occurs from April until the end of September. The highest wind speed (17.8 m/s) usually occurs in the middle of July. The northeast monsoon season commences in early December and ends in March. The maximum wind speed is in the early December is 12.4 m/s.

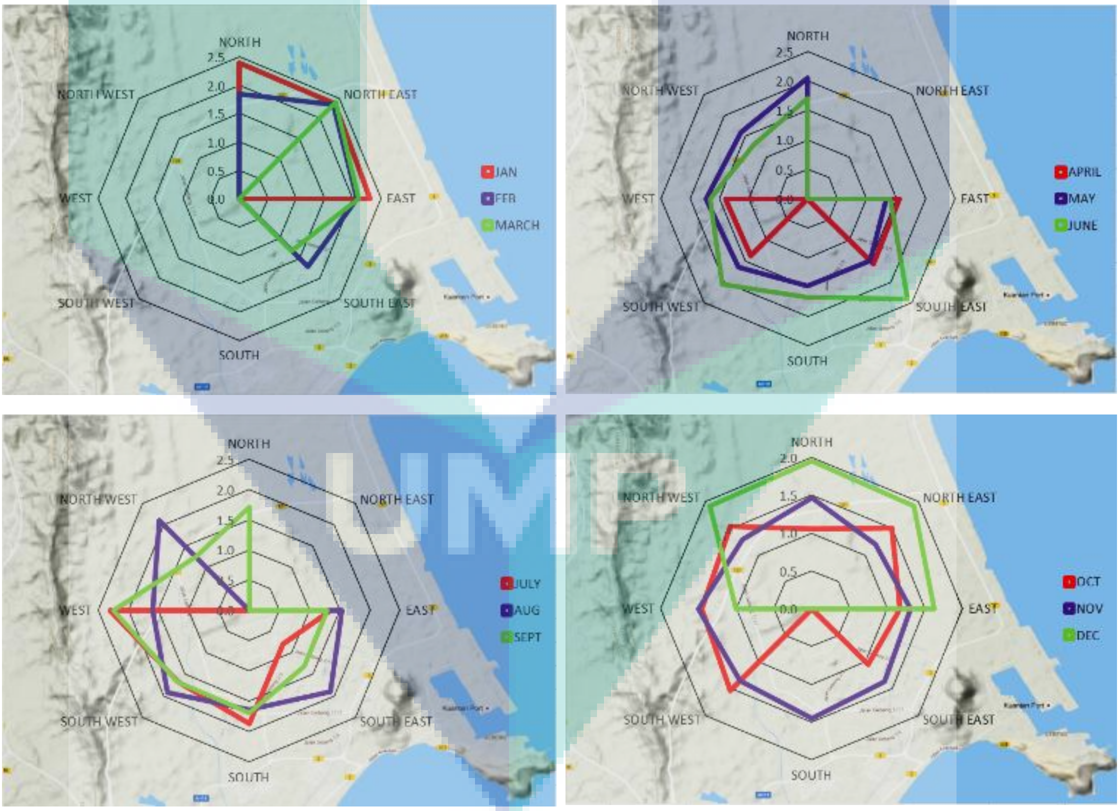

Figure 4.1. Whole year wind speed and direction in Gebeng industrial area.

4.2 Comparison between CFD simulation and LDV measurement

Comparison between the CFD prediction and LDV measurement is shown in Figure 4.2. The stream wise velocity is normalised with the inlet velocity ($u^* = u/u_{in}$) to ensure a fair comparison between the measurement using a scale-down model and actual terrain CFD simulation can be performed. The length in the flow direction is also normalised with the total length of the subject area ($x^* = x/L$) so that the result can be matched in a correct perspective of the actual terrain and the scaled-down model. The result shows that CFD and experimental data are in good agreement with <3% deviation on the measured mean flow. A correct flow features around the hills H1 and H2 was obtained. Hence, this model can be used to evaluate the effect of surface terrain on pollution dispersion.

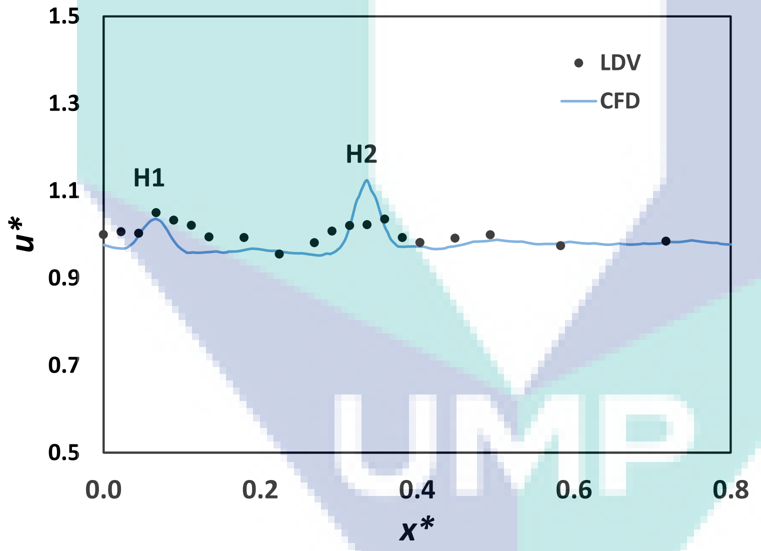

Figure 4.2. CFD and LDV measurement of flow around Gebeng industrial area.

4.3 Chlorine Gas Dispersion in Gebeng industrial area

A hypothetical noxious gas leak from a chemical plant at Gebeng industrial area was modelled for the case of wind from western and eastern direction with the velocity of 17.8 m/s and 6 m/s representing the high and low actual velocity in the area. The wind in the eastern direction usually occurs between October to

March, while wind in western direction occurs from April to September every year in this area (see Figure 4.1). Some of the chemical plants such as DoveChem, Air Products and FPG Oleo chemicals are situated near the Kuantan port, hence one source point S1 of 10 m × 10 m was created in between hill H1 and H2. The second sourceS2 was set at a position between hill H2 and H3 where many chemical plants are located, e.g. Lynas Advanced Material Plant, BASF Petronas Chemicals, Polyplastics and Petronas Chemicals PDH. In this case a hypothetical chlorine gas leakage is assumed.

Result from the CFD simulation is shown in Figures 4.3 and 4.4, whereby the chlorine with concentration of greater than 1×10^{-6} kg/m^3 is marked as iso-surface. Higher wind speed (17.8 m/s) creates a smaller plume than that of slower wind speed (6 m/s). The chlorine gas plume moves slightly southward due to the position of hill H2 (Bukit Pengorak) and H3. The plume moves southward towards the end of hill H3, where the terrain is flat. Thus, the surface terrain actually affects the dispersion of the chlorine gas in addition to the wind speed and direction. It was observed that gas released from S2 is not affecting the residential area in the north (R1) and south (R2) of Gebeng industrial area closed to the coastal area. Therefore, the risk of noxious gas leaks affecting the local population is limited during the period from October to March, if the leaks occur at position S2. However, if gas leakage happens at position S1, the residential area R2 around Balok Baru Secondary School, Balok Perdana, Kampung Berahi and Kampung Selamat will be severely affected regardless the wind speed during the particular incident. In fact 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 during the month from October to March. The safer place will be going southward towards Kuantan city.

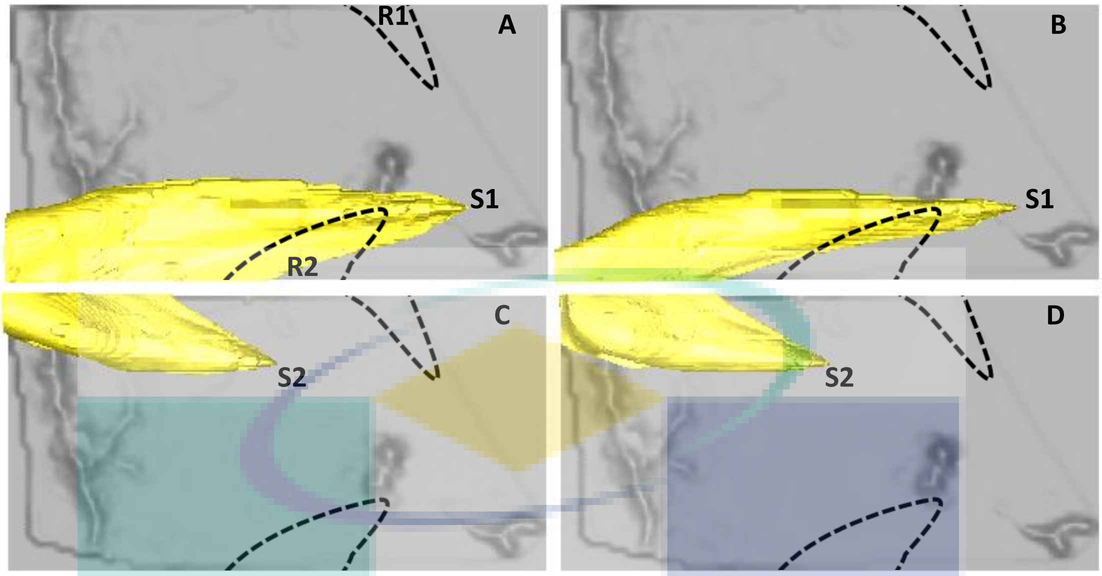

Figure 4.3. Air pollutant from points S1 and S2 dispersed by eastern wind. Residential area marked by R1 and R2. A) 6 m/s, B) 17.8 m/s, C) 6 m/s, D) 17.8 m/s.

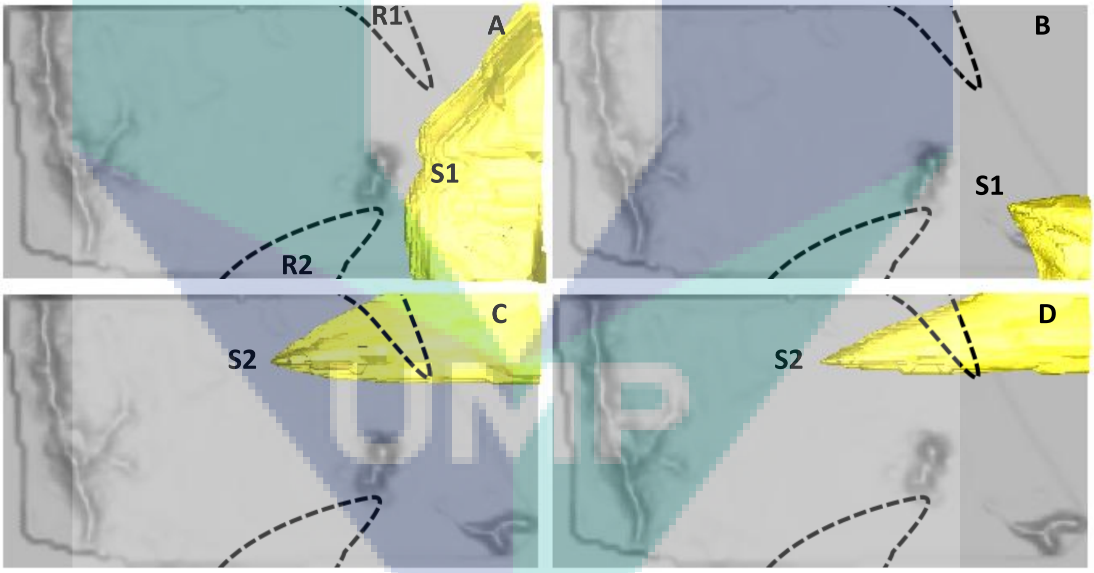

Figure 4.4. Air pollutant from points S1 and S2 dispersed by western wind. Residential area marked by R1 and R2. A) 6 m/s, B) 17.8 m/s, C) 6 m/s, D) 17.8 m/s.

Figure 4.4 shows the gas plume for the case of western direction which is usually occurs during April to September every year. It can be seen that noxious gas release at this time of the year can affect the residential area R1 around

Kampung Gebeng, Rizk Beach Residence and Mermaid Inn if the source come from S2. Leakage of noxious gas from source S1 is not likely to affect the residential area. The larger area is affected if the wind speed is slower (6 m/s), because the pollutant density and the ambient temperature inversion yielded a larger plume size.

Wind past hill creates a recirculation certain wind pattern in the wake of the hill that affect the dispersion of pollutant. For instance the vector plot in Figure 4.5 shows clearly the recirculation behind the hill H3. The pathlines plot also shows the extent of the recirculation zone in the wake region. A smooth deflection of the mean flow over the hills can be observed, with the mean separation streamline emerging from the downstream surface of the hills. This recirculation is due to the difference in air velocity above and at the wake region of the hill. Velocity above the hill is much higher, meanwhile velocity in the hill wake region is moving in the opposite direction, and hence creating the recirculation effect (Almeida et al., 1993).

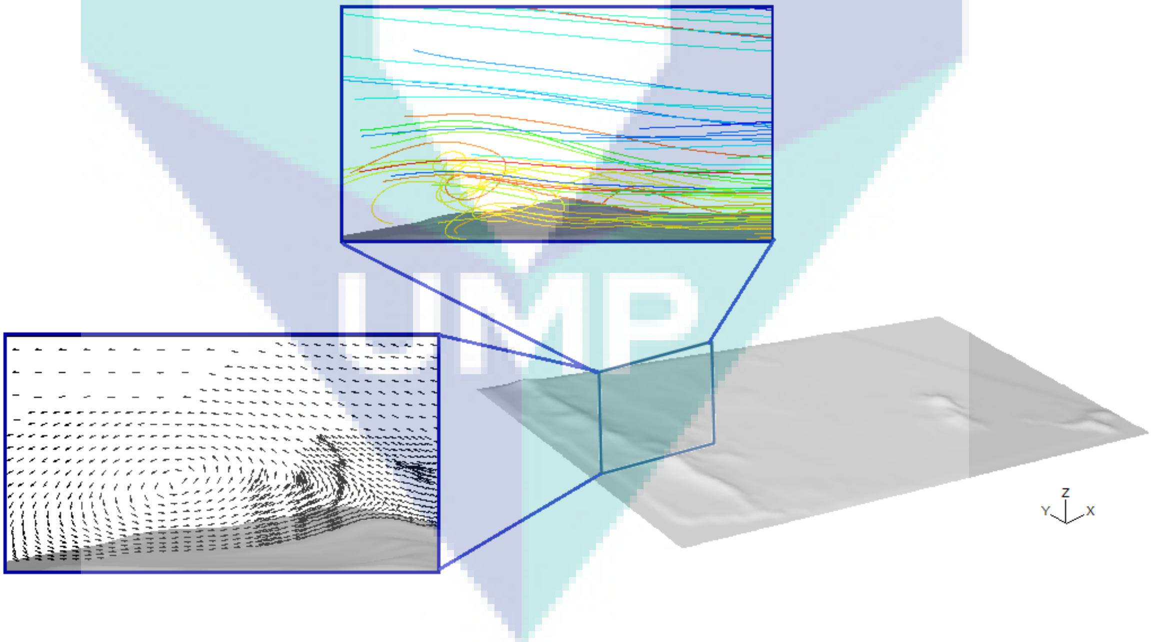

Figure 4.5. Vector and pathlines of flow over hill H3.

4.4 Summary

A CFD simulation of the atmospheric wind pollutant transport in Gebeng industrial area has been successfully assessed. The CFD simulation showed good agreement with the LDV measurement with deviation within 3% of the experimental data. The terrain surface affects the direction of the gas plume, whereby the plume evades the hills H2 and H3. Any potential noxious gas release from chemical plant in Gebeng industrial area can potentially affect the safety of the nearby coastal residential area depending on the source of the gas release and wind direction. During October to March any noxious gas release from the position near the Kuantan port is affecting the residential area R2 around Balok Baru Secondary School, Balok Perdana, Kampung Berahi and Kampung Selamat. While gas release from Gebeng phase 2 (S2) during April to September may affect the residential area R1 around Kampung Gebeng, Rizk Beach Residence and Mermaid Inn

5 Influence of Monsoon Seasons on Accidental Chlorine Leak and Dispersion around Gebeng Industrial Area: ALOHA study

5.1 Overview

This chapter presents the dispersion of a hypothetical chlorine leak around Gebeng industrial area using ALOHA. The effect of a different wind direction and wind speed in the meteorological microscale area was investigated. The wind speed ranging from 1.32 to 10.7 m/s obtained from a local weather station was considered. Heavy gas dispersion model was used to determine the concentration of chlorine plume within an area of concern. The leakage rate was set at 792 kg/h. The result showed that the residential areas R1 and R2 are affected by the plume dispersed by southwest and northern winds, respectively. Greater hazard ranges can be achieved under the wind speed below 2.3 m/s. Meanwhile, the hazard zone reduced to nearly half when the wind speed is above 5.4 m/s. The appropriate evacuation routes were developed to reduce risk of exposure to toxic gas. Finding from this work is useful to understand the risk of noxious gas dispersion around Gebeng industrial area.

5.2 Introduction

Gebeng Pahang is one of the leading industrial areas in Malaysia which supply petrochemical products such as polymers. Chlorine is commonly used in the polymer and petrochemical plants, e.g., Polyplastics Asia Pacific and Petronas-MTBE. Exposure to chlorine can cause acute or chronic effects depending on its concentration. For instance, tickling of the nose and throat can occur at a level of 0.014 ppm (Calabrese and Kenyon, 1991). Above 1 ppm, chlorine can cause a mild irritation of eyes, respiratory system, and headache. Higher level at 30 ppm resulted to chest pain, nausea, dyspnea, and cough (US HSS, 1993). A chlorine leak incident can be dangerous when it occurs nearby the residential area. Furthermore, the wind speed and wind direction affect the dispersion of chlorine gas (Sudarsan et al., 2016). Therefore, it is important to evaluate the risk of chlorine leaks from industrial plant to the residential area which include the identification of a safety evacuation route.

The gas dispersion model such as Areal Location of Hazardous Atmosphere (ALOHA) has been widely employed for the risk assessment of accidental release of hazardous gases. For instance, Gharabagh et al. (2009) employed a heavy gas dispersion model for the assessment of chlorine pipeline failure. Derudi et al. (2014) focused on the liquefied natural gas releases from a regasification plant. ALOHA is easy to use and requires relatively low computational demand. To the best of our knowledge, the risk of chlorine leaks dispersion has yet to be assessed for Gebeng industrial area, Pahang. Hence, the current study aims to predict the effect of wind direction and wind speed on the chlorine leaks dispersion around Gebeng industrial area using ALOHA. In addition, a safe evacuation route for Gebeng industrial area in the event accidental leakage of chlorine is proposed based on the simulation result.

ALOHA 5.4.7 was developed by the National Oceanic and Atmospheric Administration's (NOAA) and U.S. Environmental Protection Agency (EPA) NOAA (1999). It is often used to study the gas dispersion of noxious chemical in the event of an accidental release using either the Gaussian or Heavy gas dispersion models. In the present work, the heavy gas dispersion model was used instead of the Gaussian model since the chlorine is denser than air. ALOHA accounts for the gravitational forces in which the dispersion of heavy gas is affected by the wind and atmospheric turbulence. Approximately 700 pure chemicals are included in the chemical database of ALOHA (Daubert and Danner, 1989; NOAA, 1990). All chemicals are treated as non-reactive chemicals.

In the present work, the incident scene is the pipeline leaks connected to a 1000 L horizontal cylindrical tank which is often used commercially. The liquefied chlorine (1.30 T) is stored at ambient temperature. The maximum chlorine leakage rate of 792 kg/h was calculated by (Fauske and Epstein, 1988):

$$Q_T(t) = \frac{A_h L_c}{v_g - v_l} \sqrt{\frac{1}{N_F T_t c_{pl}}} \quad (5.1)$$

where $Q_T(t)$ is the mass flowrate, A_h is the area of leak source, L_c is the heat of vaporization, v_g and v_l are the specific volume of gas and liquid phases, respectively, T_t is the temperature of the fluid, c_{pl} is the heat capacity of fluid, and N_F is given as:

$$N_F = \frac{v_l L_c^2}{2(P_{eff} - P_a) C_{dis}^2 (v_g - v_l)^2 T_t c_{pl}} + \frac{l_p}{l_c} \quad (5.2)$$

where P_{eff} is the effective pressure, P_a is ambient pressure, C_{dis} is the discharge coefficient at 0.61, l_p is the length of pipe, and l_c is 0.1 m. The concentration of chlorine plume is calculated using the heavy gas dispersion model which is almost similar to Colenbrander's model (1980):

$$C(x,y,z) = C_c(x) \exp\left[-\left(\frac{|y| - b(x)}{S_y(x)} \right)^2 - \left(\frac{z}{S_z} \right)^{1+n} \right] |y| > b(x) \quad (5.3)$$

$$C(x,y,z) = C_c(x) \exp\left[-\left(\frac{z}{S_z} \right)^{1+n} \right] |y| \leq b(x) \quad (5.4)$$

where $C(x,y,z)$ is the concentration of the plume, $C_c(x)$ is the centerline ground-level concentration, $S_y(x)$ is the horizontal dispersion coefficient, $S_z(x)$ is a vertical dispersion coefficient, and $b(x)$ is the half-width of homogeneous core section. $S_y(x)$ and $S_z(x)$ were obtained from the algebraic expressions for a specific atmospheric stability class, which is developed by Briggs (1973). The concentration of chlorine in the threat zone analysis was set at 0.014 ppm (tickling effect), 1 ppm (mild irritation), and 30 ppm (life-threatening effect). The dispersion of chlorine plume was set at a meteorological microscale, which is about 10 km. ALOHA is deemed valid for use in this work because Gebeng industrial area has a mainly flat terrain with 8 to 10 m elevation from sea level.

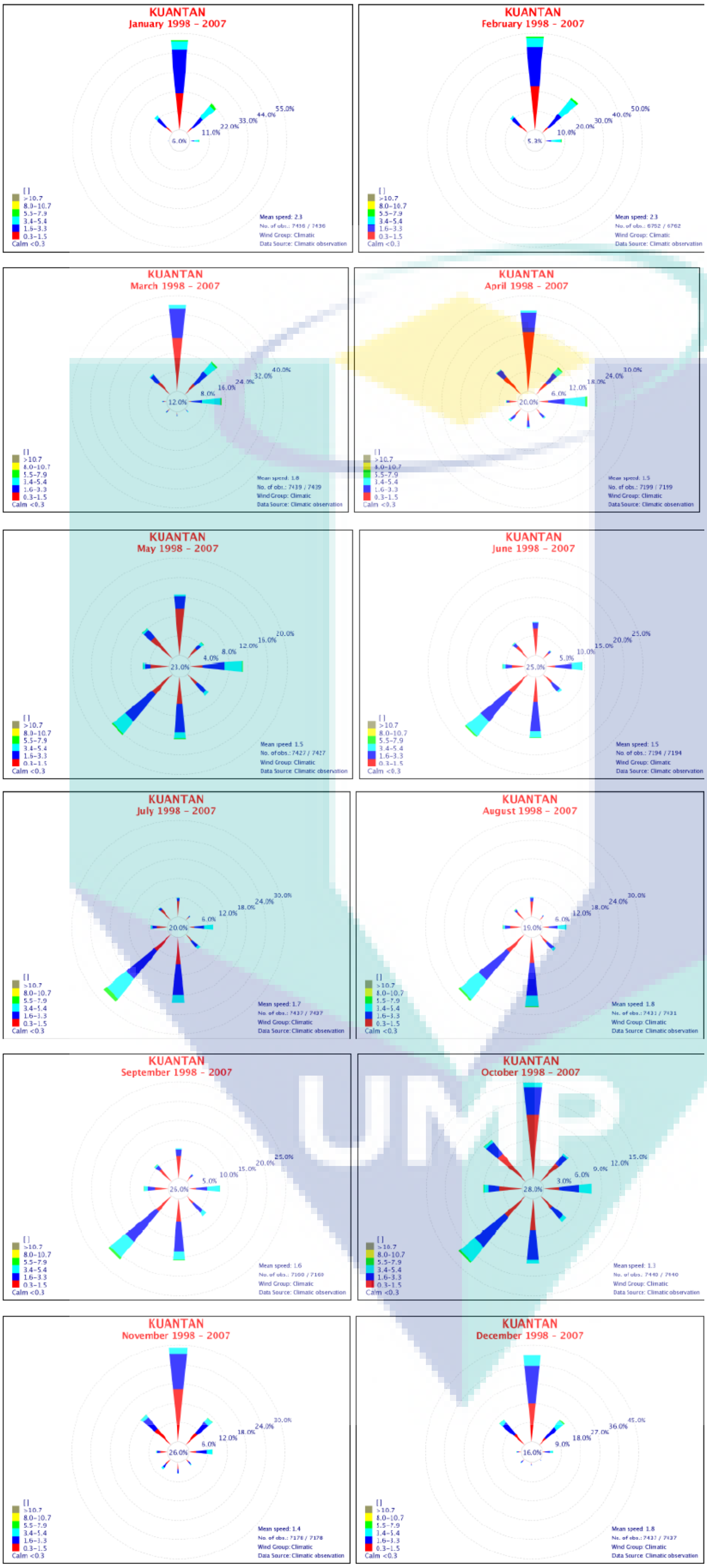

Figure 5.1. Wind rose averaged for 10 years (Abdullah et al., 2011).

The wind direction in Gebeng industrial area is affected by the southwest monsoon usually occurs during the dry season (June to September) and the northeast monsoon occurs during the wet season (November to April). Northern wind dominates the wet season, whereas the dry season is dominated by the southwest wind (Erain et al., 2017). The two inter-monsoon seasons are during May and October, respectively (Fig. 5.1). A partly cloudy model was chosen in the ALOHA setup since Kuantan has over 55% cloudy days annually. The humidity was set at 80% and air temperature was set at 26.9 °C, respectively. Hourly meteorological data were obtained from Kuantan Meteorological Department (Abdullah et al., 2011). Simulation was performed for the mean and maximum wind speed.

5.3 ALOHA Prediction of the Threat Zone in the event of Chlorine Leak

Fig. 5.2 shows the Gebeng industrial area which measures about 15 km (west-east) × 14 km (north-south). The potential chlorine leak is marked where the chemical plants that utilize chlorine are situated. The two residential areas marked as R1 and R2 are located in the north and south of the industrial area, respectively. Residential area R1 covering Kampung Baging, Sanctuary Resort, Kampung Darat Sungai Ular, Kampung Sungai Ular, mosques, resorts, homestays, and Kampung Gebeng. Whereas, R2 includes mosques, Kampung Berahi, Balok Perdana, Kampung Seberang Balok, Kampung Balok, Kampung Balok Baru, Nelayan Balok market, homestays, and schools.

A hypothetical chlorine leakage that occurred in a chemical plant at Gebeng industrial area was predicted for the case of two monsoon winds with varying wind speed. The mean wind speed is between 1.32 to 2.3 m/s and the maximum wind speed is in the range of 5.4 to 10.7 m/s. Figs. 5.2(a) and (b) show the chlorine plume dispersed by the northern wind at mean and maximum wind speed, respectively from November to April. Whereas, Figs. 5.3(a) and (b) show the chlorine plume for the cases of southwest wind (June to September) with the mean and maximum wind speed, respectively.

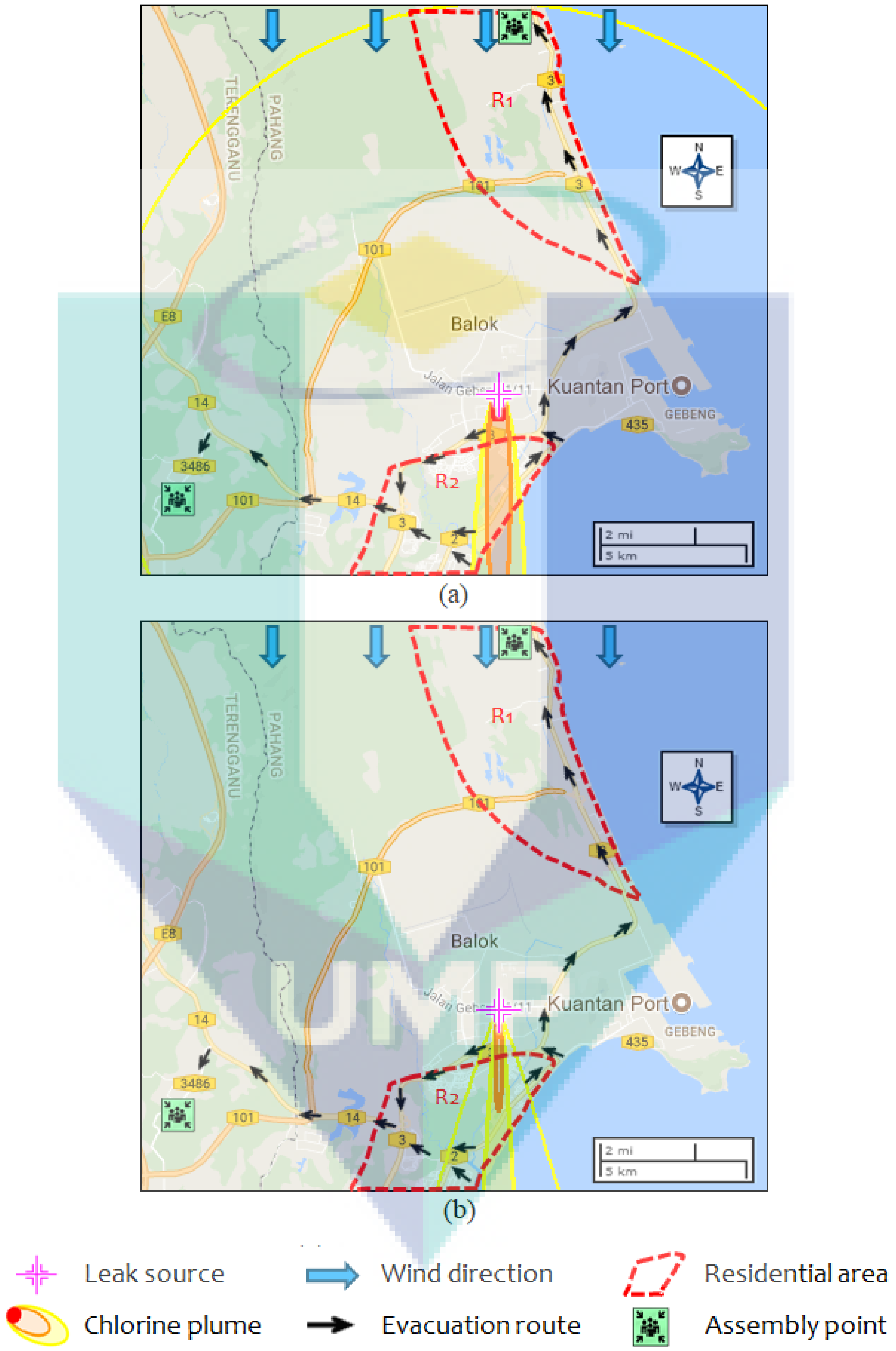

Figure 5.2. Prediction of chlorine plume dispersion and evacuation route around the Gebeng industrial area for the northern wind (November to April) at (a) mean wind speed, (b) maximum wind speed

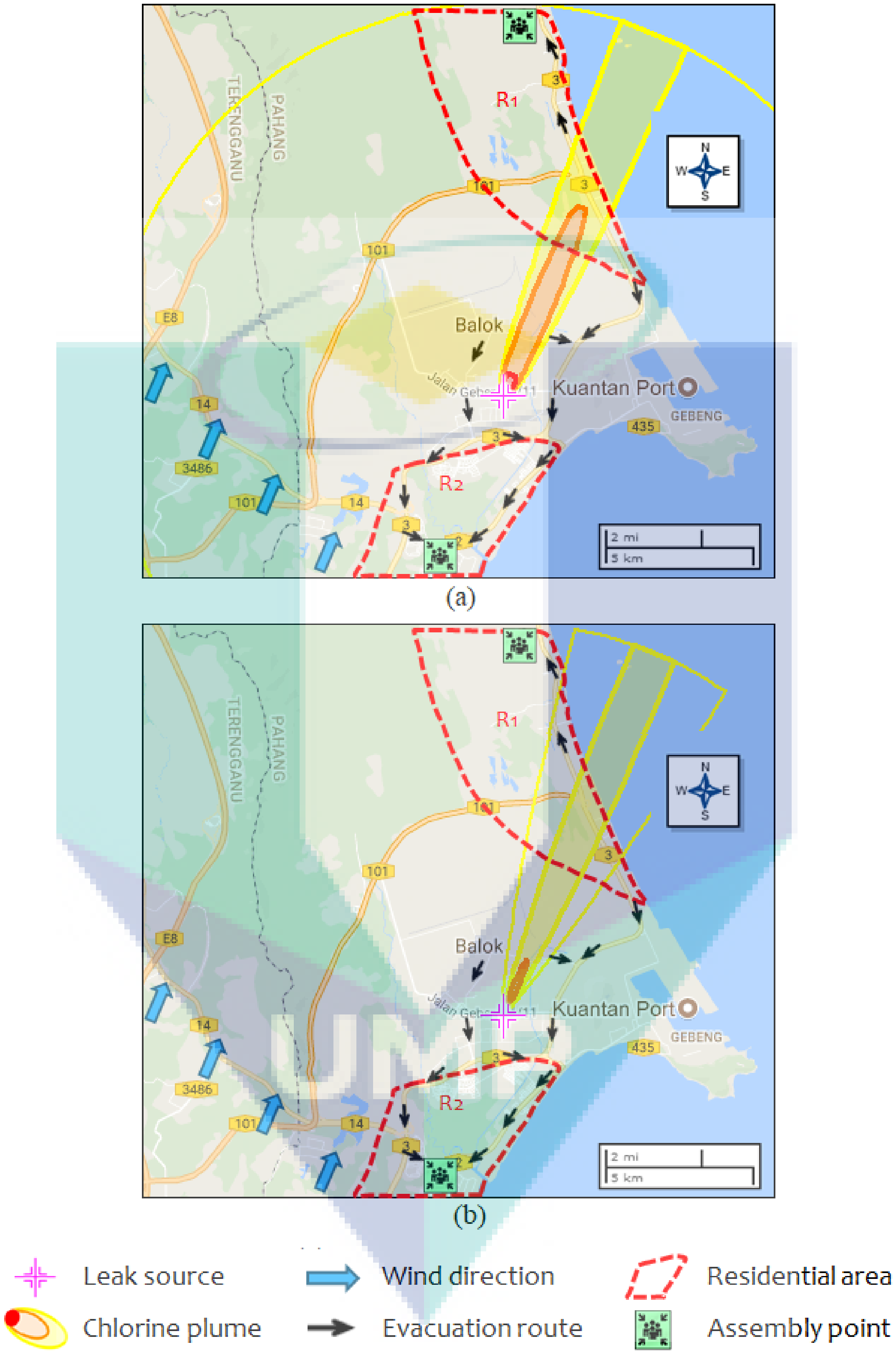

Figure 5.3. Prediction of chlorine plume dispersion and evacuation route around the Gebeng industrial area for the southwest wind (June to September) at (a) mean wind speed, (b) maximum wind speed

The result shows that the plume dispersed by a lower wind speed formed a wider and larger hazard zone. A lower wind speed is not strong enough to push the dense chlorine plume and hence causing the plume to accumulate closer to the leak source. Therefore, the nearby residential area is exposed to a higher hazard risk. At approximately 0.55 km from the leak source, the concentration exceeds 30 ppm for all wind speeds below 2.3 m/s. RP Chemicals (M) Sdn Bhd and the area along Jalan Gebeng 1/10 are affected by the plume dispersed by southwest and northern winds, respectively. In contrast, the plume at a level of 30 ppm only dispersed up to the distance of 0.395 km with the higher wind speed (>5.4 m/s) and there is no residential area affected. During the month of November to April with the lower wind speed (see Fig. 5.2(a)), the area from south of the Balok Makmur mosque until the kindergarten Tadika Seri Zamrud are exposed to the plume at a mild concentration of 1 ppm. Meanwhile, the area from the Seri Makmur petrol station to Villaku Residence is affected by the plume at a concentration of 0.014 ppm. During June to September (see Fig. 5.3(a)), the area within 5 km distance from Eastman Chemical (M) Sdn Bhd to Tenshin Ore Trading Sdn Bhd are affected by the concentration of 1 ppm, while the area from Grandee Biotechnologies Sdn Bhd to Kemaman Seaview Hotel are affected by the level of 0.014 ppm. With the higher wind speed, the residential areas R1 (from Grandee Biotechnologies Sdn Bhd northeastern towards Kemaman Seaview Hotel) and R2 (from Bernas ECMS warehouse southern towards Tanahair Ventures Sdn Bhd) are mostly affected by the plume at the level of 0.014 ppm, as shown in Figs. 5.2(b) and 5.3(b). During the inter-monsoon month in May and October every year, wind mainly comes from the North and Southwest direction. Therefore, both residential areas of R1 and R2 are affected should the accident happens during the inter-monsoon season in a manner to that of combined the effect of both the north and southwest wind.

5.4 Proposed Safety Evacuation Route

The result shows that an accidental chlorine leak from Gebeng industrial area is not causing a life-threatening chlorine concentration in the nearby residential area of all cases evaluated, i.e., high and low wind speed at two different monsoon seasons. However, even at a lower concentration of 0.014 ppm, a safety evacuation is necessary in the event of an accidental chlorine release. A proper emergency preplanning is necessary in the event of accidental chlorine leaks from the chemical plant. School and public hall are often used as an assembly evacuation point in the event of an accident. The proposed assembly evacuation point is towards north or west of the residential area R2 during November to April, as shown in Figs. 5.2(a) and (b). The suitable evacuation locations such as schools, i.e. Sekolah Kebangsaan Cherating and Sekolah Menengah Kebangsaan Sungai Baging, which are located at north of residential area R2 are in 19 to 24 km and 16 to 21 km, respectively, from the affected area. While, the school, Sekolah Kebangsaan Lembah Jabor at the west of residential area R2 is within 12 to 16 km from the affected area.

The evacuation route for the accidental leaks of chlorine during June to September is shown in Figs. 2(c) and (d), whereby the residents should move towards the north or southwest of the residential area R1 for safety purpose. The residents nearby the Kemaman Seaview Hotel should move north towards the schools, i.e., Sekolah Kebangsaan Cherating and Sekolah Menengah Kebangsaan Sungai Baging, which are about 9 to 11 km and approximately 8 km, respectively from the affected area. While, the residents staying around the leak source should move southwest towards the safer locations such as the school Sekolah Kebangsaan Balok and the public hall Dewan Orang Ramai Balok, which are located around 9 and 14 km, respectively from the affected area.

In the event of an accident during the inter-monsoon month in May and October, a combined risk of both the north and southwest wind should be considered due to higher frequency of wind from both directions during this period. Utilization of the school Sekolah Kebangsaan Lembah Jabor at the west of residential area R2 is the best option during the inter-monsoon season.

5.5 Summary

A risk assessment of chlorine leaks dispersion around Gebeng industrial area has been successfully performed using ALOHA heavy gas dispersion model. It was found that the dispersion of chlorine plume is significantly affected by the wind condition. The plume released during June to September affecting the residential area R1. While the residential area R2 is affected by the plume released during November to April. A lower wind speed produced a wider plume and affects a larger area of the residential area in comparison to the higher wind speed. It can be concluded that the risk of exposure to hazardous chlorine concentration is two-fold higher at a wind speed below 2.3 m/s compared the one above 5.4 m/s. The result shows that an accidental chlorine leak from Gebeng industrial area is not causing a life-threatening chlorine concentration in the nearby residential area of all cases evaluated. The result obtained from this work is useful to predict the hazardous zones and potential impact area due to accidental chlorine leakage. The results also provide a guidance to determine a safe emergency evacuation route in the event of accidental chlorine leaks.

6 Conclusion and Recommendation

A simulation of the atmospheric wind pollutant transport in Gebeng industrial area has been successfully assessed. In this work chlorine leak was chosen as a model pollutant because it is actually used in Gebeng industrial area and can pose a health risk to the local resident of Gebeng in the event of gas leak. The following summary of objectives achievement was made in this work.

A scaled-down model of Gebeng industrial area topography was made using a 3D printer and used to perform a laser based measurement (LDV) of flow pattern. This enables us to study the effect of surface terrain on the wind flow around Gebeng. We found that the effect of surface terrain on wind flow around Gebeng is limited due to its relatively flat surface terrain.

Two case studies on the effect of accidental release of noxious gas (chlorine) were performed in this work. It was found that the residential area is affected by the gas dispersion but subject to wind speed and direction. We also proposed a safety evacuation route in the event of accidental chlorine release in Gebeng industrial area.

We recommend the following based on the results obtained in this research.

- Safety evacuation route must be chosen based on the wind direction during the event of accident.
- During the inter-monsoon season, where wind blows from north and southwest, the safest evacuation area is by moving west to Sekolah Kebangsaan Lembah Jabor.

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8 Postgraduate and undergraduate students

The following student works for this project.

Name of Student: ID Matric No: Faculty: Thesis title: Graduation Year: ** *enter for more space*	Norliyana Erain MKC15004 FKKSA Computational Fluid Dynamics Study Of Air Pollutant Dispersion Around Kuantan Expected December 2017 (Delayed due to maternity leave)

9 Publication

Journal

1) Norliyana Erain, Woon Phui Law, Noram Irwan Ramli, Siew Choo Chin and Jolius Gimbun, Understanding the effect of surface terrain on pollution transport around Gebeng industrial area, *Ind J Sci Technol*. 8(2), Indexed by ISI Zoological Record.

2) Woon Phui Law, Norliyana Erain, Noram Irwan Ramli, and Jolius Gimbun, Influence of Monsoon Seasons on Accidental Chlorine Leak and Dispersion around Gebeng Industrial Area, *Engineering Letters*, (submitted). Indexed by ISI ESCI & Scopus.

3) Woon Phui Law, Norliyana Erain, Noram Irwan Ramli, and Jolius Gimbun, Assessment of chlorine leaks dispersion around Gebeng industrial area and potential evacuation route, *Chemosphere*, (submitted). Ranked Q1 ISI SCI & Scopus.

Conference

1) Norliyana Erain, Woon Phui Law, Noram Irwan Ramli, Siew Choo Chin and Jolius Gimbun, Understanding the effect of surface terrain on pollution transport around Gebeng industrial area, international conference in fluids and chemical engineering, Kota Kinabalu Sabah.

Thesis

1) Norliyana Erain, Computational Fluid Dynamics Study of Air Pollutant Dispersion Around Kuantan, MSc Thesis (under-preparation).

11 Financial report

The total amount of budget approved for this project is RM 28000.00. At the end of this project RM 24439.95 was spent representing 87.3% of funding utilisation as shown in Table 1.

Table 1: Budget and spending of each project

Project	Leader	Approved	Spending	% spending
1	Dr. Jolius Gimbun	28000.00	24,439.95	87.3

13 Appendix A

Conference paper

THEORETICAL AND EXPERIMENTAL FLUID FLOW

UNDERSTANDING THE EFFECT OF SURFACE TOPOLOGY ON WIND SPEED AND ATMOSPHERIC TURBULENT AROUND GEBENG INDUSTRIAL PARK
FCE021

Norliyana Erain[1], Woon Phui Law[1], Noram Irwan Ramli[2], Siew Choo Chin[1,2] and Jolius Gimbun[1]*

[1] Centre of Excellence for Advanced Research in Fluid Flow (CARIFF), [2] Faculty of Civil Engineering and Earth Resources, Universiti Malaysia Pahang, 26300 Gambang, Pahang, Malaysia.
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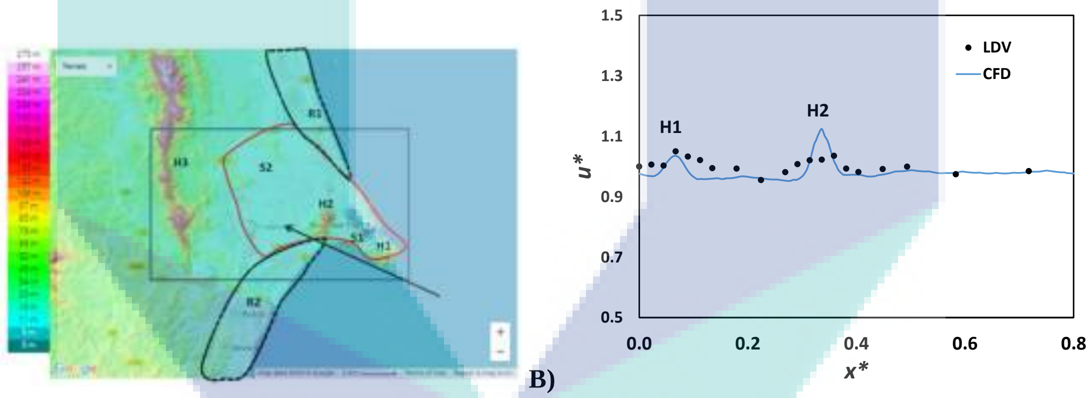
Abstract
Air pollution dispersion is greatly affected by the wind speed and direction. Most often the pollution dispersion from industrial area is not fully understood. In the present work, the effect of surface topology on the wind speed and atmospheric turbulent around the Gebeng industrial area in Pahang was studied using a computational fluid dynamics (CFD) method. The typical southeastern wind with a speed of about 1.3003 m/s corresponding to the actual speed of approximately 5 km/h was considered for validation. The turbulent flow was modelled using k-ε model. The model was compared with the laser doppler velocimetry (LDV) measurement on the scale-down rig. The CFD prediction showed good agreement within 10% deviation with the experimental measurement via LDV (Fig. 1). It was found that the plume of noxious gas driven by the eastern wind can affect the nearby residential area R2, whereas the western wind is affecting the residential area R1. In the presence of hill obstacle, the gas plume moves southward into the flat terrain. Results from this work may be useful to understand the risk of air pollutant dispersion around Gebeng industrial area.

Key words: *Wind speed, atmospheric pollution dispersion, turbulence, CFD, LDV*



A) B)

Fig. 1. A) Wind direction and hills location around Gebeng industrial park. B) CFD vs. LDV measurement.

14 Appendix D

Postgraduate supervision

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Student Particular

Student Name	MKC15004 - Norliyana Binti Erain
Programme	Master Of Science
Mode of Study	Part Time
Registration Date	23/02/2015
No. of Semester	6
Research Title	Computational Fluid Dynamics Study Of Air Pollutant Dispersion Around Kuantan
Research Area	- Environmental Engineering & Hydrodynamic - Fluid Flow - Computational Fluid Dynamic [CFD]
Co Supervisor	Mr. Noram Irwan Bin Ramli

Thesis Details

Date Notification	01/03/2017
Due Date	30/05/2017
Draft Thesis Submit to Supervisor	31/03/2017 ** Change date if necessary* Verify?
Draft Thesis Submit to Faculty	**Draft Thesis Submit to Supervisor** has not verified yet.

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Norliyana Binti Erain
Pt 2910, Pengkalan Cicar 2, Bukit Kuang, Kemaman,
24000 Chukai
Terengganu
Malaysia

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RAJA ALLEN JORDAN IZZUDDIN SHAH BIN RAJA BAHARUDIN
Assistant Registrar

cc Dean
Faculty of Chemical & Natural Resources Engineering
(MS)Assoc. Prof. Dr. Jolius Bin Gimbun, FKKSA
Bursary

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15 Appendix E

Journal

Indian Journal of Science and Technology, Vol 10(1), DOI: 10.17485/ijst/2017/v10i1/110373, January 2017
ISSN (Print) : 0974-6846
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Understanding the Effect of Surface Terrain on Pollution Transport around Gebeng Industrial Area

Norliyana Erain[1], Woon Phui Law[1], Noram Irwan Ramli[2], Siew Choo Chin[1,2] and Jolius Gimbun[1]*

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Abstract

Objectives: Air pollution dispersion is greatly affected by the wind speed and direction. Most often the pollution dispersion from industrial area is not fully understood. In the present work, the effect of surface topology on the wind speed and atmospheric turbulent around the Gebeng industrial area in Pahang was studied using a Computational Fluid Dynamics (CFD) method. **Methods/Statistical Analysis:** The typical southeastern wind with a speed of about 1.3003 m/s corresponding to the actual speed of approximately 5 km/h was considered for validation. The turbulent flow was modelled using *k-ε* model. The model was compared with the Laser Doppler Velocimetry (LDV) measurement on the scale-down rig. **Findings:** The CFD prediction showed good agreement within 10% deviation with the experimental measurement via LDV. It was found that the plume of noxious gas driven by the eastern wind can affect the nearby residential area R2, whereas the western wind is affecting the residential area R1. In the presence of hill obstacle, the gas plume moves southward into the flat terrain. **Application/ Improvements:** Results from this work may be useful to understand the risk of air pollutant dispersion around Gebeng industrial area.

Keywords: CFD, LDV, Atmospheric Pollution Dispersion, Turbulence, Wind Speed

1. Introduction

Air pollution affects human health, ecosystems and materials in a variety of ways, and deserves appropriate attention. The atmosphere can act as a medium for transporting local pollution to other locations. Pollutant dispersion at different area has been studied extensively. For instance, Varma and Manjula[1] studied the nitrogen oxide dispersion and its concentration level around the Rayalaseema Thermal Power plant. Sudarsan et al.[2] showed that the atmospheric fluctuation strongly depends on the wind speed, direction and temperature. Saravankumar et al.[3] investigated the concentration of air pollutants (i.e., particulate matter, sulfur dioxide and nitrogen dioxide) at residential, commercial and industrial areas at different seasons. They found that the pollutant level during monsoon is lesser than that during winter and summer due to the wind fluctuation. All the aforementioned works reported that pollutant dispersion is significantly affected by the emission source and meteorological condition, e.g., wind speed and direction, atmospheric humidity and temperature, pollutant temperature and emission rate. Other than the meteorological condition the dispersion of air pollution are also significantly affected by the terrain type. Air flow and dispersion around the different hills has been studied experimentally and numerically[4,5]. However, limited study on the effect of wind speed, direction and terrain map on the air pollutant transport around Gebeng industrial area in Kuantan, Malaysia. It is important to study the effect of surface topography on the air dispersion in Gebeng industrial area as a precautionary guide for evacuation during emergency and hence this is the aim of this work.

*Author for correspondence

Ideally, experimental techniques like the satellite photography is the best method to observe and understand the air flow in a complex terrain. However, experimental technique has limitations to provide detailed information of turbulent flow. In addition, the satellite photography experiment is very costly. Hence, Computational Fluid Dynamics (CFD) is used, although they require more computing time and costs compared to the other numerical techniques[6,7]. Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) are commonly used to model air flow and pollutant dispersion around the complex terrain[8,9]. RANS-based turbulence models such as k-ε models are easier and economical to run. However, these models suffer from the isotropic eddy viscosity assumption, thus may not provide an accurate measure of turbulent kinetic energy, but may provide a good prediction of the mean velocity. In the case of atmospheric pollutant dispersion, mean flow is more important than the turbulent kinetic energy and hence RANS-based model is applicable in this work. LES generally performs well because it resolved directly the large flow structure-and modelled the smaller eddies at the region of boundary layers. However, the simulation via LES is costly due to a very fine grid resolution at the boundary layer. A massive number of grids required for a large terrain (14 km x 7 km) in the present work when LES was used. Therefore, RANS-based models were used in the present work to study the effect of surface terrain on pollutant transport around Gebeng industrial area.

2. Methodology

The present work focuses the Gebeng industrial area, Pahang of about 14 km x 7 km, as shown in Figure 1. The arrow in Figure 1B represents the wind direction set for LDV experiment, for purpose of CFD validation. Of course the wind direction around Gebeng industrial area varies from time to time, however, only one wind direction was chosen for the validation. The hourly average wind direction and wind speed was obtained from Kuantan Meteorological Department. Gebeng industrial area has the two sea–facing hills namely Bukit Tanjung Gelang (H1) and Bukit Pengorak (H2) with the elevation above sea level of 105 m and 197 m, respectively. Another hill (H3) located along the border of Pahang and Terengganu states. The height of these hills is ranging from 109 m up to 215 m. Residential area marked R1 and R2 is situated in the north and south of the industrial area, respectively. The potential noxious gas source was marked as S1 and S2 where the chemical plant is situated. The air dispersion around the Gebeng industrial area was investigated via LDV and CFD techniques.

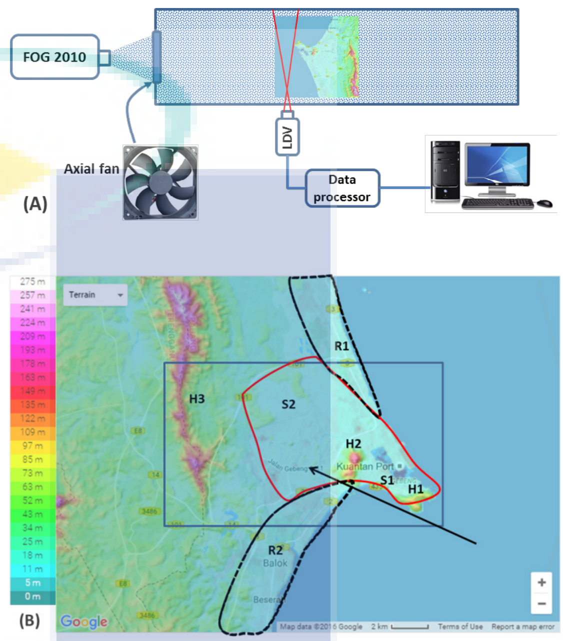

Figure 1. A) Experimental setup, B) Modelled wind direction and hills location around Gebeng industrial area. Square box indicates the study area, Gebeng industrial area and Kuantan port is located inside the red line area, dotted black line marked R1 and R2 is the residential area.

2.1 Experimental Measurement

The velocity flow measurement around the scaled-down terrain model (1:60606) was performed using a mini LDV system. The flow was seeded with 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 at 1.3003 m/s. A mini LDV (Measurement Science Enterprise) was used to measure the air velocity based on the Doppler effect. The mini LDV system consists of a transmitter/receiver, laser probe, signal processor, electronic traverse and processing software. The laser probe is equipped with an Ar-ion laser with a wavelength of 658 μm. The laser was triggered and the laser point position was controlled through Micronix traverse by the MSE 1-D software. Velocity from a single position was recorded by averaging over 10000 of data.

2.2 CFD Setup

The terrain of Gebeng industrial area was obtained from Google map using SketchUp and the TIN surface splitting was done using Rhinoceros software. The terrain surface was meshed using ANSYS Workbench Meshing 16.2 and the simulation was performed using ANSYS Fluent R16.2. The area of study was taken from up to 42 topographical map which is about 14 km (east-west) x 7 km (north-south). The height of the flat sky face is 2500 m above the groundto ensure the flow at the surface is independence to that of the sky[10]. A second-order discretization was enabled for the scalar equations of turbulence and momentum. Standard k-ε (SKE) model was used for turbulence flow. The transport equation for turbulent kinetic energy and dissipation rate of SKE is given by:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon \quad (1)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(P_k + C_{3\varepsilon}P_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (2)$$

where k is the turbulent kinetic energy, ε is turbulent dissipation rate, μ is turbulent viscosity, ρ is density, σ_k is Prandtl-Schmidt number for k at a constant value of 1.0, σ_ε is turbulent Prandtl number, P_k and P_b is the production of turbulence kinetic energy due to mean velocity gradient and buoyancy effect, respectively. Model constant used are:

$$C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_\mu = 0.09, \sigma_k = 1.0, \sigma_\varepsilon = 1.3$$

The ambient air flow was set at 1.3003 m/s in the Southeast direction. The simulation was performed using a steady-state solver and all residuals were set to fall below 1 x 10^{-5} to ensure a good convergence. Once a pseudo-steady solution was achieved, data was recorded for over 1000 time steps and averaged. The velocity prediction was compared with the LDV measurement. Once the validation is done, a case study to evaluate the dispersion of chlorine from two hypothetical sources is modelled via species transport model.

3. Results and Discussion

3.1 Wind Rose

The wind data such as the mean wind speed and direction was obtained from a local weather station (Kuantan meteorological department) for the whole year in 2014 is shown in Figure 2. Based on the data obtained, the southwest monsoon season usually occurs from April until the end of September. The highest wind speed (17.8 m/s) usually occurs in the middle of July. The northeast monsoon season commences in early December and ends in March. The maximum wind speed is in the early December is 12.4 m/s.

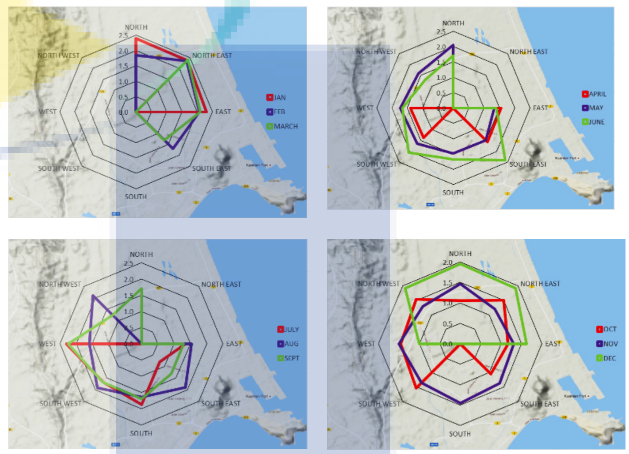

Figure 2. Whole year wind speedand direction in Gebeng industrial area.

3.2 CFD Validation

Comparison between the CFD prediction and LDV measurement is shown in Figure 3. The streamwise velocity is normalised with the inlet velocity ($u^* = u/u_{in}$) to ensure a fair comparison between the measurement using a scale-down model and actual terrain CFD simulation can be performed. The length in the flow direction is also normalised with the total length of the subject area ($x^* = x/L$) so that the result can be matched in a correct perspective of the actual terrain and the scaled-down model. The result shows that CFD and experimental data are in good agreement with <3% deviation on the measured mean flow. A correct flow features around the hills H1 and H2 was obtained. Hence, this model can be used to evaluate the effect of surface terrain on pollution dispersion.

3.3 Prediction of Noxious Gas Dispersion around Gebeng Industrial Area

A hypothetical noxious gas leak from a chemical plant at Gebeng industrial area was modelled for the case of wind from western and eastern direction with the velocity of 17.8 m/s and 6 m/s representing the high and low actual velocity in the area. The wind in the eastern direction usually occurs between October to March, while wind in western direction occurs from April to September every year in this area in (see Figure 2). Some of the chemical plants such as DoveChem, Air Products and FPG Oleo chemicals are situated near the Kuantan port, hence one source point S1 of 10 m × 10 m was created in between hill H1 and H2. The second source S2 was set at a position between hill H2 and H3 where many chemical plants are located, e.g., Lynas Advanced Material Plant, BASF Petronas Chemicals, Polyplastics and Petronas Chemicals PDH. In this case a hypothetical chlorine gas leakage is assumed.

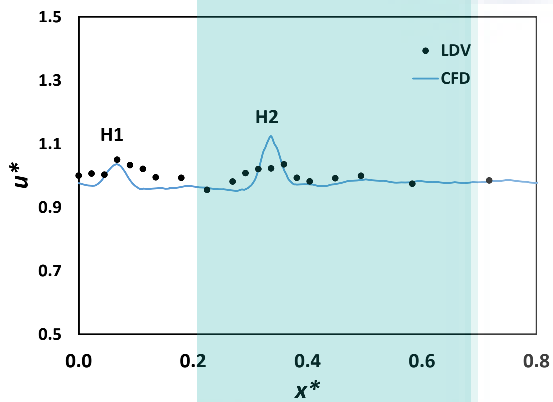

Figure 3. CFD and LDV measurement of flow around Gebeng industrial area.

Result from the CFD simulation is shown in Figures 4 and 5, whereby the chlorine with concentration of greater than 1×10^{-6} kg/m^3 is marked as iso-surface. Higher wind speed (17.8 m/s) creates a smaller plume than that of slower wind speed (6 m/s). The chlorine gas plume moves slightly southward due to the position of hill H2 (Bukit Pengorak) and H3. The plume moves southward towards the end of hill H3, where the terrain is flat. Thus, the surface terrain actually affects the dispersion of the chlorine gas in addition to the wind speed and direction. It was observed that gas released from S2 is not affecting the residential area in the north (R1) and south (R2) of Gebeng industrial area closed to the coastal area. Therefore, the risk of noxious gas leaks affecting the local population is limited during the period from October to March, if the leaks occur at position S2. However, if gas leakage happens at position S1, the residential area R2 around Balok Baru Secondary School, Balok Perdana, Kampung Berahi and Kampung Selamat will be severely affected regardless the wind speed during the particular incident. In fact 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 during the month from October to March. The safer place will be going southward towards Kuantan city.

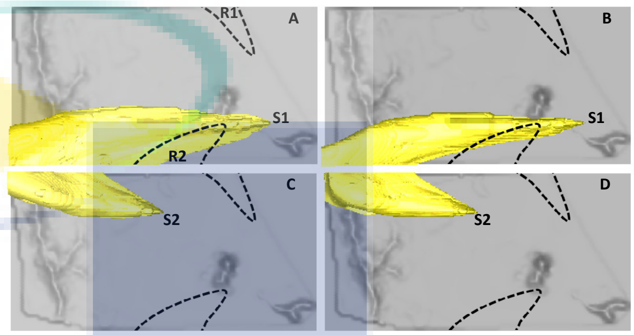

Figure 4. Air pollutant from points S1 and S2 dispersed by eastern wind. Residential area marked by R1 and R2. A) 6 m/s, B) 17.8 m/s, C) 6 m/s, D) 17.8 m/s.

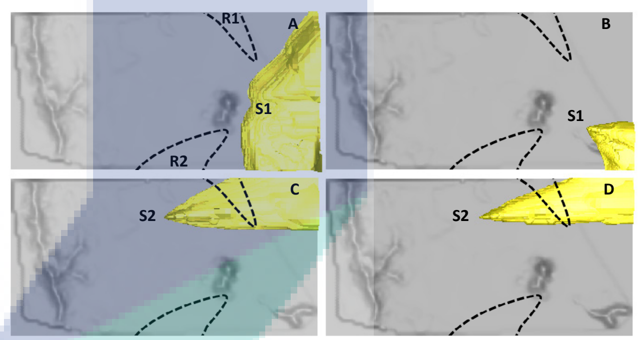

Figure 5. Air pollutant from points S1 and S2 dispersed by western wind. Residential area marked by R1 and R2. A) 6 m/s, B) 17.8 m/s, C) 6 m/s, D) 17.8 m/s.

Figure 5 shows the gas plume for the case of western direction which is usually occurs during April to September every year. It can be seen that noxious gas release at this time of the year can affect the residential area R1 around Kampung Gebeng, Rizk Beach Residence and Mermaid Inn if the source come from S2. Leakage of noxious gas from source S1 is not likely to affect the residential area. The larger area is affected if the wind speed is slower (6 m/s), because the pollutant density and the ambient temperature inversion yielded a larger plume size.

Wind past hill creates a recirculation certain wind pattern in the wake of the hill that affect the dispersion of pollutant. For instance the vector plot in Figure 6 shows clearly the recirculation behind the hill H3. The pathlines plot also shows the extent of the recirculation zone in the wake region. A smooth deflection of the mean flow over the hills can be observed, with the mean separation streamline emerging from the downstream surface of the hills. This recirculation is due to the difference in air velocity above and at the wake region of the hill. Velocity above the hill is much higher, meanwhile velocity in the hill wake region is moving in the opposite direction, and hence creating the recirculation effect[11].

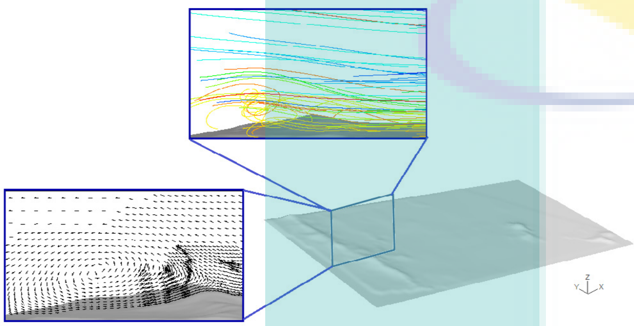

Figure 6. Vector and pathlines of flow over hill H3.

4. Conclusion

A CFD simulation of the atmospheric wind pollutant transport in Gebeng industrial area has been successfully assessed. The CFD simulation showed good agreement with the LDV measurement with deviation within 3% of the experimental data. The terrain surface affects the direction of the gas plume, whereby the plume evades the hills H2 and H3. Any potential noxious gas release from chemical plant in Gebeng industrial area can potentially affect the safety of the nearby coastal residential area depending on the source of the gas release and wind direction. During October to March any noxious gas release from the position near the Kuantan port is affecting the residential area R2 around Balok Baru Secondary School, Balok Perdana, Kampung Berahi and Kampung Selamat. While gas release from Gebeng phase 2 (S2) during April to September may affect the residential area R1 around Kampung Gebeng, Rizk Beach Residence and Mermaid Inn.

5. Acknowledgement

We acknowledge UMP support through grant RDU150314.

6. References

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Influence of Monsoon Seasons on Accidental Chlorine Leak and Dispersion around Gebeng Industrial Area

Woon Phui Law, Norliyana Erain, Noram Ramli, and Jolius Gimbun

***Abstract*—This paper presents the dispersion of a hypothetical chlorine leak around Gebeng industrial area using ALOHA. The effect of a different wind direction and wind speed in the meteorological microscale area was investigated. The wind speed ranging from 1.32 to 10.7 m/s obtained from a local weather station was considered. Heavy gas dispersion model was used to determine the concentration of chlorine plume within an area of concern. The leakage rate was set at 792 kg/h. The result showed that the residential areas R1 and R2 are affected by the plume dispersed by southwest and northern winds, respectively. Greater hazard ranges can be achieved under the wind speed below 2.3 m/s. Meanwhile, the hazard zone reduced to nearly half when the wind speed is above 5.4 m/s. The appropriate evacuation routes were developed to reduce risk of exposure to toxic gas. Finding from this work is useful to understand the risk of noxious gas dispersion around Gebeng industrial area.**

***Index Terms*—Chlorine leaks, monsoon seasons, Gebeng, heavy gas dispersion**

I. Introduction

GEBENG, Pahang is one of the leading industrial areas in Malaysia which supply petrochemical products such as polymers. Chlorine is commonly used in the polymer and petrochemical plants, e.g., Polyplastics Asia Pacific and Petronas-MTBE. Exposure to chlorine can cause acute or chronic effects depending on its concentration. For instance, tickling of the nose and throat can occur at a level of 0.014 ppm [1]. Above 1 ppm, chlorine can cause a mild irritation of eyes, respiratory system, and headache. Higher level at 30 ppm resulted to chest pain, nausea, dyspnea, and cough [2]. A chlorine leak incident can be dangerous when it occurs nearby the residential area. Furthermore, the wind speed and wind direction affect the dispersion of chlorine gas [3]. Therefore, it is important to evaluate the risk of chlorine leaks from industrial plant to the residential area which include the identification of a safety evacuation route.

The gas dispersion model such as Areal Location of Hazardous Atmosphere (ALOHA) has been widely employed for the risk assessment of accidental release of hazardous gases. For instance, Gharabagh et al. [4] employed a heavy gas dispersion model for the assessment of chlorine pipeline failure. Derudi et al. [5] focused on the liquefied natural gas releases from a regasification plant. ALOHA is easy to use and requires relatively low computational demand. To the best of our knowledge, the risk of chlorine leaks dispersion has yet to be assessed for Gebeng industrial area, Pahang. Hence, the current study aims to predict the effect of wind direction and wind speed on the chlorine leaks dispersion around Gebeng industrial area using ALOHA. In addition, a safe evacuation route for Gebeng industrial area in the event accidental leakage of chlorine is proposed based on the simulation result.

II. Methodology

ALOHA 5.4.7 was developed by the National Oceanic and Atmospheric Administration's (NOAA) and U.S. Environmental Protection Agency (EPA) [6]. It is often used to study the gas dispersion of noxious chemical in the event of an accidental release using either the Gaussian or Heavy gas dispersion models. In the present work, the heavy gas dispersion model was used instead of the Gaussian model since the chlorine is denser than air. ALOHA accounts for the gravitational forces in which the dispersion of heavy gas is affected by the wind and atmospheric turbulence. Approximately 700 pure chemicals are included in the chemical database of ALOHA [7]-[8]. All chemicals are treated as non-reactive chemicals.

In the present work, the incident scene is the pipeline leaks connected to a 1000 L horizontal cylindrical tank which is often used commercially. The liquefied chlorine (1.30 T) is stored at ambient temperature. The maximum chlorine leakage rate of 792 kg/h was calculated by [9]:

$$Q_T(t) = \frac{A_h L_c}{v_g - v_l}\sqrt{\frac{1}{N_F T_t c_{pl}}} \tag{1}$$

where $Q_T(t)$ is the mass flowrate, A_h is the area of leak source, L_c is the heat of vaporization, v_g and v_l are the specific volume of gas and liquid phases, respectively, T_t is the temperature of the fluid, c_{pl} is the heat capacity of fluid, and N_F is given as:

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$$N_F = \frac{v_l L_c^2}{2(P_{eff} - P_a) C_{dis}^2 (v_g - v_l)^2 T_t c_{pl}} + \frac{l_p}{l_c} \quad (2)$$

where P_{eff} is the effective pressure, P_a is ambient pressure, C_{dis} is the discharge coefficient at 0.61, l_p is the length of pipe, and l_c is 0.1 m. The concentration of chlorine plume is calculated using the heavy gas dispersion model which is almost similar to Colenbrander's model [10]:

$$C(x,y,z) = C_c(x)\exp\left[-\left(\frac{|y|-b(x)}{S_y(x)}\right)^2 - \left(\frac{z}{S_z}\right)^{1+n}\right] |y| > b(x) \quad (3)$$

$$C(x,y,z) = C_c(x)\exp\left[-\left(\frac{z}{S_z}\right)^{1+n}\right] |y| \le b(x) \quad (4)$$

where $C(x,y,z)$ is the concentration of the plume, $C_c(x)$ is the centerline ground-level concentration, $S_y(x)$ is the horizontal dispersion coefficient, $S_z(x)$ is a vertical dispersion coefficient, and $b(x)$ is the half-width of homogeneous core section. $S_y(x)$ and $S_z(x)$ were obtained from the algebraic expressions for a specific atmospheric stability class, which is developed by Briggs [11]. The concentration of chlorine in the threat zone analysis was set at 0.014 ppm (tickling effect), 1 ppm (mild irritation), and 30 ppm (life-threatening effect). The dispersion of chlorine plume was set at a meteorological microscale, which is about 10 km. ALOHA is deemed valid for use in this work because Gebeng industrial area has a mainly flat terrain with 8 to 10 m elevation from sea level.

The wind direction in Gebeng industrial area is affected by the southwest monsoon usually occurs during the dry season (June to September) and the northeast monsoon occurs during the wet season (November to April). Northern wind dominates the wet season, whereas the dry season is dominated by the southwest wind [12]. The two inter-monsoon seasons are during May and October, respectively (Fig. 1). A partly cloudy model was chosen in the ALOHA setup since Kuantan has over 55% cloudy days annually. The humidity was set at 80% and air temperature was set at 26.9 °C, respectively. Hourly meteorological data were obtained from Kuantan Meteorological Department [13]. Simulation was performed for the mean and maximum wind speed.

III. Results and discussion

Fig. 2 shows the Gebeng industrial area which measures about 15 km (west-east) × 14 km (north-south). The potential chlorine leak is marked where the chemical plants that utilize chlorine are situated. The two residential areas marked as R1 and R2 are located in the north and south of the industrial area, respectively. Residential area R1 covering Kampung Baging, Sanctuary Resort, Kampung Darat Sungai Ular, Kampung Sungai Ular, mosques, resorts, homestays, and Kampung Gebeng. Whereas, R2 includes mosques, Kampung Berahi, Balok Perdana, Kampung Seberang Balok, Kampung Balok, Kampung Balok Baru, Nelayan Balok market, homestays, and schools.

A hypothetical chlorine leakage that occurred in a chemical plant at Gebeng industrial area was predicted for the case of two monsoon winds with varying wind speed. The mean wind speed is between 1.32 to 2.3 m/s and the maximum wind speed is in the range of 5.4 to 10.7 m/s. Figs. 2(a) and (b) show the chlorine plume dispersed by the northern wind at mean and maximum wind speed, respectively from November to April. Whereas, Figs. 2(c) and (d) show the chlorine plume for the cases of southwest wind (June to September) with the mean and maximum wind speed, respectively. The result shows that the plume dispersed by a lower wind speed formed a wider and larger hazard zone. A lower wind speed is not strong enough to push the dense chlorine plume and hence causing the plume to accumulate closer to the leak source. Therefore, the nearby residential area is exposed to a higher hazard risk.

At approximately 0.55 km from the leak source, the concentration exceeds 30 ppm for all wind speeds below 2.3 m/s. RP Chemicals (M) Sdn Bhd and the area along Jalan Gebeng 1/10 are affected by the plume dispersed by southwest and northern winds, respectively. In contrast, the plume at a level of 30 ppm only dispersed up to the distance of 0.395 km with the higher wind speed (>5.4 m/s) and there is no residential area affected. During the month of November to April with the lower wind speed (see Fig. 2(a)), the area from south of the Balok Makmur mosque until the kindergarten Tadika Seri Zamrud are exposed to the plume at a mild concentration of 1 ppm. Meanwhile, the area from the Seri Makmur petrol station to Villaku Residence is affected by the plume at a concentration of 0.014 ppm. During June to September (see Fig. 2(c)), the area within 5 km distance from Eastman Chemical (M) Sdn Bhd to Tenshin Ore Trading Sdn Bhd are affected by the concentration of 1 ppm, while the area from Grandee Biotechnologies Sdn Bhd to Kemaman Seaview Hotel are affected by the level of 0.014 ppm. With the higher wind speed, the residential areas R1 (from Grandee Biotechnologies Sdn Bhd northeastern towards Kemaman Seaview Hotel) and R2 (from Bernas ECMS warehouse southern towards Tanahair Ventures Sdn Bhd) are mostly affected by the plume at the level of 0.014 ppm, as shown in Figs. 2(b) and (d). During the inter-monsoon month in May and October every year, wind mainly comes from the North and Southwest direction. Therefore, both residential areas of R1 and R2 are affected should the accident happens during the inter-monsoon season in a manner to that of combined the effect of both the north and southwest wind.

The result shows that an accidental chlorine leak from Gebeng industrial area is not causing a life-threatening chlorine concentration in the nearby residential area of all cases evaluated, i.e., high and low wind speed at two different monsoon seasons. However, even at a lower concentration of 0.014 ppm, a safety evacuation is necessary in the event of an accidental chlorine release. A proper emergency preplanning is necessary in the event of accidental chlorine leaks from the chemical plant. School and public hall are often used as an assembly evacuation point in the event of an accident. The proposed assembly evacuation point is towards north or west of the residential area R2 during November to April, as shown in Figs. 2(a) and (b). The suitable evacuation locations such as schools, i.e. Sekolah Kebangsaan Cherating and Sekolah Menengah

Kebangsaan Sungai Baging, which are located at north of residential area R2 are in 19 to 24 km and 16 to 21 km, respectively, from the affected area. While, the school, Sekolah Kebangsaan Lembah Jabor at the west of residential area R2 is within 12 to 16 km from the affected area.

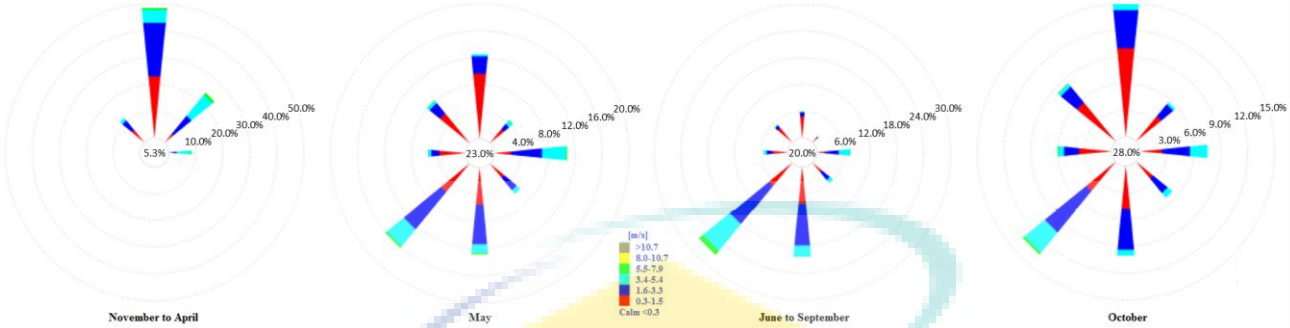

Fig. 1. Windrose for Gebeng industrial area. Data averaged from 1998-2007 [13].

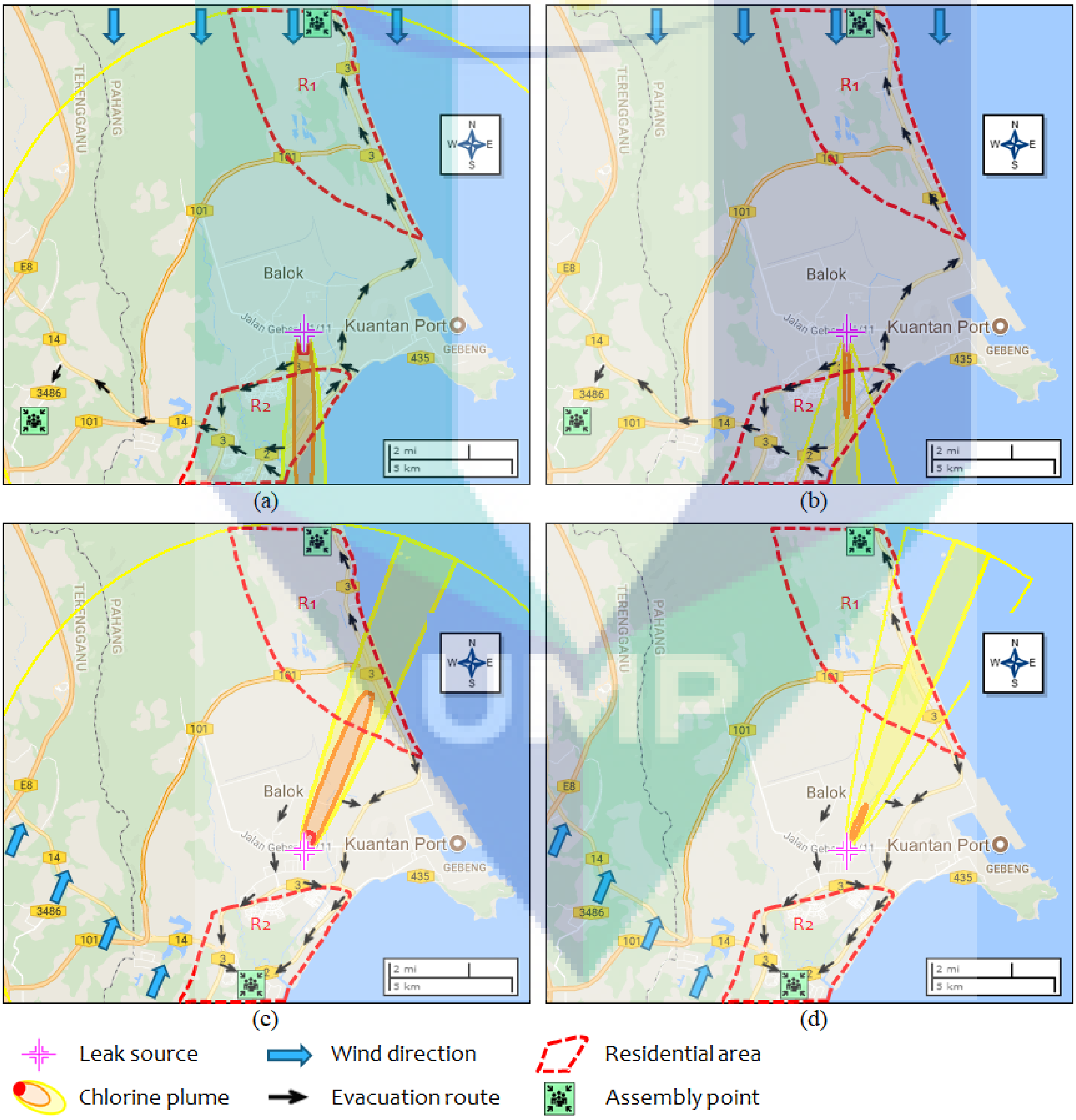

Fig. 2. Prediction of chlorine plume dispersion and evacuation route around the Gebeng industrial area for the northern wind (November to April) at (a) mean wind speed, (b) maximum wind speed, and southwest wind (June to September) at (c) mean wind speed, (d) maximum wind speed

The evacuation route for the accidental leaks of chlorine during June to September is shown in Figs. 2(c) and (d), whereby the residents should move towards the north or southwest of the residential area R1 for safety purpose. The residents nearby the Kemaman Seaview Hotel should move north towards the schools, i.e., Sekolah Kebangsaan Cherating and Sekolah Menengah Kebangsaan Sungai Baging, which are about 9 to 11 km and approximately 8 km, respectively from the affected area. While, the residents staying around the leak source should move southwest towards the safer locations such as the school Sekolah Kebangsaan Balok and the public hall Dewan Orang Ramai Balok, which are located around 9 and 14 km, respectively from the affected area.

In the event of an accident during the inter-monsoon month in May and October, a combined risk of both the north and southwest wind should be considered due to higher frequency of wind from both directions during this period. Utilization of the school Sekolah Kebangsaan Lembah Jabor at the west of residential area R2 is the best option during the inter-monsoon season.

I. Conclusion

A risk assessment of chlorine leaks dispersion around Gebeng industrial area has been successfully performed using ALOHA heavy gas dispersion model. It was found that the dispersion of chlorine plume is significantly affected by the wind condition. The plume released during June to September affecting the residential area R1. While the residential area R2 is affected by the plume released during November to April. A lower wind speed produced a wider plume and affects a larger area of the residential area in comparison to the higher wind speed. It can be concluded that the risk of exposure to hazardous chlorine concentration is two-fold higher at a wind speed below 2.3 m/s compared the one above 5.4 m/s. The result shows that an accidental chlorine leak from Gebeng industrial area is not causing a life-threatening chlorine concentration in the nearby residential area of all cases evaluated. The result obtained from this work is useful to predict the hazardous zones and potential impact area due to accidental chlorine leakage. The results also provide a guidance to determine a safe emergency evacuation route in the event of accidental chlorine leaks.

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16 Appendix F

Financial report

RESEARCH PAYMENT HISTORY

Research Project Details

Project ID	RDU150314
Project Title	ASSESSMENT OF POLLUTION DISPERSION FROM GEBENG INDUSTRIAL AREA
Project Leader	0300 - JOLIUS BIN GIMBUN
Project Category	SAINS TULEN (PURE SCIENCE)
Project Status	Tamat
Start Date - End Date	01/04/2015 - 31/03/2017

Vote Code : 24000 - Rental ▼ Select

Research Payment History Info

Vot	Approved (RM)	Expenditure (RM)	Balance (RM)
11000 - SALARY & WAGES	5,000.00	4,999.50	0.50
21000 - TRAVEL & TRANSPORTATION	3,000.00	366.60	2,633.40
22000 - TRANSPORTATION OF GOODS	0.00	0.00	0.00
23000 - COMMUNICATION & UTILITIES	0.00	0.00	0.00
24000 - RENTAL	3,000.00	0.00	3,000.00
26000 - SUPPLY OF RAWS MATERIALS	0.00	0.00	0.00
27000 - RESEARCH MATERIALS & SUPPLIES	9,000.00	8,661.35	338.65
28000 - MAINTENANCE & MINOR REPAIR SERVICES	0.00	0.00	0.00
29000 - SPECIAL SERVICES (CONFERENCE FEES <= 2500)	6,000.00	8,412.50	-2,412.50
35000 - SPECIAL EQUIPMENT (NOT MORE THAN <= 40%)	2,000.00	2,000.00	0.00
Total (RM)	**28,000.00**	**24,439.95**	**3,560.05**

Research Payment History Details

Vote Code : 24000 - RENTAL

Vote Code : 35000 - SPECIAL EQUIPMENT (NOT MORE THAN <= 40%)

Voucher No	Payment Date	Asset Code	Asset Details	Description	Amount (RM)
PB104(R)-1509-0012	22/09/2015	FTA1000-PB104(R)-1509-0012-00001	Anemometer	Pembelian Anemometer SNS5205 (HongKong), Air Velocity: 0.10 - 30.00 m/s Bagi Kerja-Kerja Penyelidikan RDU150314	2,000.00

Vote Code : 11000 - SALARY & WAGES

Voucher No	Payment Date	Description	Amount (RM)
BR205-1510-0441	08/10/2015	BAYARAN ELAUN SKIM PELAJAR BEKERJA (SEPT 2015) (RDU150314) (LIEW SHI YAN-KC10056)	1,001.00
BR205-1511-1112	26/11/2015	BYN ELAUN SPB LIEW SHI YAN KC10056 RDU150314 BULAN 10/2015	1,001.00
BR205-1512-0406	09/12/2015	BYN ELAUN SPB LIEW SHI YAN KC10056 RDU150314 BULAN 11/2015	1,001.00
BR205-1512-2160	31/12/2015	BYN ELAUN SPB LIEW SHI YAN KC10056 RDU150314 BULAN 12/2015	1,001.00
BR205-1603-0544	14/03/2016	BYN ELAUN SPB LIEW SHI YAN MKC15031 RDU150314 BULAN 2/2016	995.50
BR205-1603-0970	17/03/2016	BYN ELAUN SPB LIEW SHI YAN MKC15031 RDU150314 BULAN 2/2016	995.50

Vote Code : 21000 - TRAVEL & TRANSPORTATION

Voucher No	Payment Date	Description	Amount (RM)
BR104-1510-0131	20/10/2015	BAYARAN TNT BAGI KERJA-KERJA PENYELIDIKAN RDU150314 (LAW WOON PHUI) - MENGHADIRI DANTEC DYNAMICS PARTICLE IMAGE VELOCIMETRY (PIV) MEASUREMENT AND ANALYSIS WORKSHOP PADA 08-10 SEPT 2015 DI UM, KUALA LUMPUR (RDU150314)	366.60

Vote Code : 27000 - RESEARCH MATERIALS & SUPPLIES

Voucher No	Payment Date	Description	Amount (RM)
PB104(R)-1508-0012	10/08/2015	Pembelian Bahan Mentah Bagi Kerja-Kerja Penyelidikan RDU150314	1,368.00

PB104(R)-1512-0008	15/12/2015	Pembelian Salvianolic Acid A, 10mg Bagi Kerja-Kerja Penyelidikan RDU150314	1,800.00
BR104-1512-0366	31/12/2015	BAYARAN TUNTUTAN BAGI MENJALANKAN BAGI KERJA-KERJA PENYELIDIKAN RDU150314 (JOLIUS BIN GIMBUN) - PEMBELIAN BAHAN MENTAH	400.00
BR104-1603-0064	14/03/2016	BAYARAN PEMBELIAN BAHAN MENTAH BAGI KERJA-KERJA PENYELIDIKAN RDU150314	280.00
PB104(R)-1604-0015	25/04/2016	Pembelian Bahan Mentah Bagi Kerja-Kerja Penyelidikan RDU150314	2,518.00
PB104(R)-1605-0004	05/05/2016	Pembelian Poly(Ethylene Oxide), MV CA. 600,000, 182028-500g Bagi Kerja-Kerja Penyelidikan RDU150314	1,000.00
BR104-1608-0050	15/08/2016	BAYARAN TUNTUTAN BAGI KERJA-KERJA PENYELIDIKAN RDU150314 (JOLIUS BIN GIMBUN) - PEMBELIAN BAHAN MENTAH	270.00
BR104-1610-0091	15/10/2016	BAYARAN TUNTUTAN BAGI KERJA-KERJA PENYELIDIKAN RDU150314 (JOLIUS GIMBUN) - PEMBELIAN BAHAN MENTAH	742.00
BR104-1704-0138	26/04/2017	BAYARAN TUNTUTAN BAGI KERJA-KERJA PENYELIDIKAN RDU150314 (JOLIUS GIMBUN) - PEMBELIAN BAHAN MENTAH	283.35

Vote Code : 29000 - SPECIAL SERVICES (CONFERENCE FEES <= 2500)

Voucher No	Payment Date	Description	Amount (RM)
L1506-006921	19/06/2015	Pindahan peruntukan dari 529100 geran penyelidikan ke akaun amanah FLUIDSCHE bagi bayaran yuran FLUIDSCHE 2015	1,200.00
L1507-000673	13/07/2015	Pindahan peruntukan bagi bayaran khidmat pengujian di Makmal CARIFF (01/2015)	1,000.00
L1507-000673	13/07/2015	Pindahan peruntukan bagi bayaran khidmat pengujian di Makmal CARIFF (01/2015)	225.00
L1603-009358	31/03/2016	PINDAHAN PERUNTUKAN BAGI BAYARAN KHIDMAT TEKNIKAL AKAUN AMANAH SEMINAR CARIFF (FTA3005) BIL 3/2016	150.00
L1607-001157	18/07/2016	PINDAHAN PERUNTUKAN BAGI BAYARAN KHIDMAT TEKNIKAL KE AKAUN TABUNG AMANAH MAKMAL BERPUSAT (UCL3000) BIL 15/2016	282.00
L1607-001179	18/07/2016	PINDAHAN PERUNTUKAN BAGI BAYARAN KHIDMAT TEKNIKAL KE AKAUN TABUNG AMANAH SEMINAR CARIFF (FTA3005) BIL 11/2016	80.00
L1607-000841	29/07/2016	PINDAHAN PERUNTUKAN BAGI BAYARAN KHIDMAT TEKNIKAL KE AKAUN TABUNG AMANAH MAKMAL BERPUSAT (UCL3000) BIL SERAHAN 18/2016	720.00
BR104-1608-0107	18/08/2016	BAYARAN PERKHIDMATAN PENGUJIAN BAGI KERJA-KERJA PENYELIDIKAN RDU150314	240.00
L1610-002881	13/10/2016	PINDAHAN PERUNTUKAN BAGI BAYARAN KHIDMAT TEKNIKAL KE AKAUN TABUNG AMANAH MAKMAL BERPUSAT (UCL3000) BIL SERAHAN 36/2016(PARK GRANT)	200.00
L1612-003634	15/12/2016	PINDAHAN PERUNTUKAN BAGI BAYARAN YURAN SEMINAR FLUIDSCHE 2017 KE AKAUN AMANAH SEMINAR CARIFF(FTA3005) SERAHAN 22/11/2016	2,014.00
L1703-009424	20/03/2017	PINDAHAN PERUNTUKAN BAGI BAYARAN KHIDMAT TEKNIKAL KE AKAUN TABUNG AMANAH SEMINAR CARIFF(FTA3005) SERAHAN 5/2017	2,000.00
L1707-000088	07/07/2017	Pindah peruntukan bgi khidmat teknikal CARIFF BIL. 7/2017	301.50