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Understanding the Effect of Surface Terrain on Pollution Transport around Gebeng Industrial Area

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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 onthe scale-down rig. **Findings:**The CFD prediction showed good agreementwithin 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, In[1] studiedthe nitrogen oxide dispersion and its concentration level around the Rayalaseema Thermal Power plant.In[2] showed that the atmospheric fluctuation strongly depends on the wind speed, direction and temperature. In[3] investigated the concentration of air pollutants (i.e., particulate matter, sulfurdioxide 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 pollutionare 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 theeffect of surface topography on the air dispersion in Gebeng industrial area as a precautionary guide for evacuation during emergency and hencethis is the aim of this work.

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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 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 transportaroundGebeng industrial area.

2. Methodology

The present work focuses theGebeng industrial area, Pahangof 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 TanjungGelang (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 hillsis ranging from 109m up to 215m. 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.

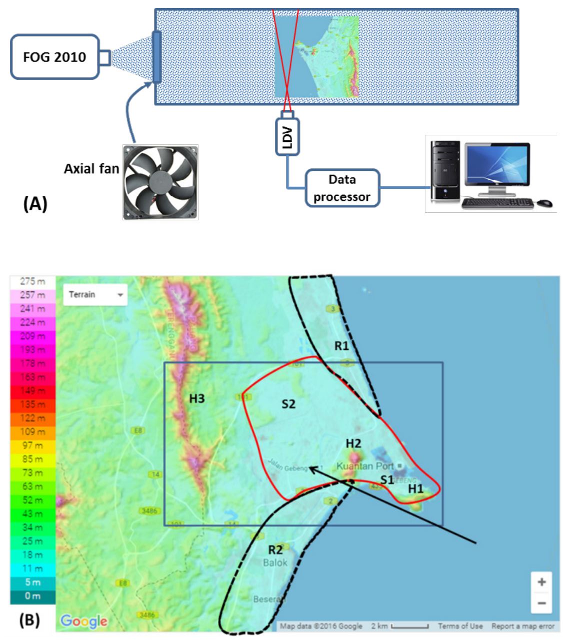

Figure 1. A) Experimental setup, B) Modelled wind direction and hills location around Gebeng industrial area. Square box indicates the study area, Gebeng industrial area and Kuantan port is located inside the red line area, dotted black line marked R1 and R2 is the residential area.

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 drivenby 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 areawas obtained from Google map using SketchUp and the TIN surfacesplitting was done using Rhinoceros software. The terrain surface was meshed using ANSYS Workbench Meshing 16.2 and the simulation was performed using ANSYSFluent R16.2. The area of study was taken from up to 42 topographical map which is about 14km (east-west) x 7km (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:

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

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

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 occursfrom April until the end of September. The highest wind speed (17.8m/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 12.4m/s.

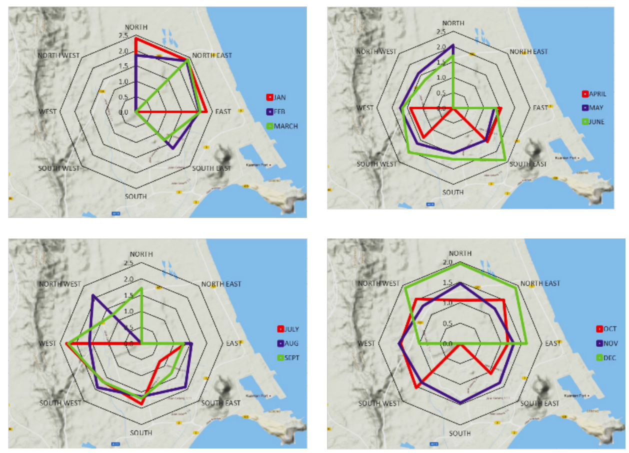

Figure 2. Whole year wind speedand direction in Gebeng industrial area.

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 Septemberevery year in this area in see Figure2. Some of the chemical plants such as DoveChem, Air Products and FPG Oleochemicalsare 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 andPetronas Chemicals PDH. In this case a hypothetical chlorine gas leakage is assumed.

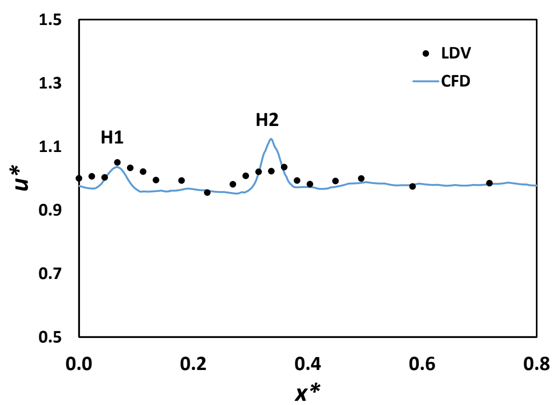

Figure 3. CFD and LDV measurement of flow around Gebeng industrial area.

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 BalokBaru Secondary School, BalokPerdana, KampungBerahi and KampungSelamat 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.

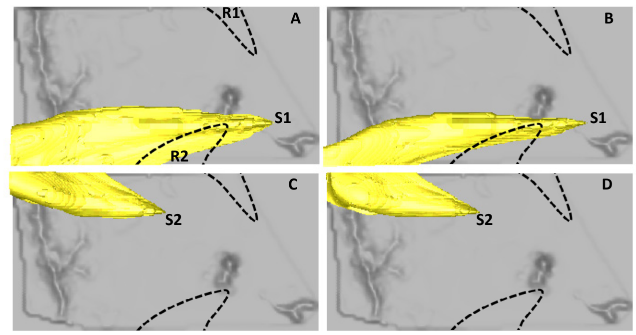

Figure 4. Air pollutant from points S1 and S2 dispersed by eastern wind.Residential area marked by R1 and R2. A) 6 m/s, B) 17.8 m/s, C) 6 m/s, D) 17.8 m/s.

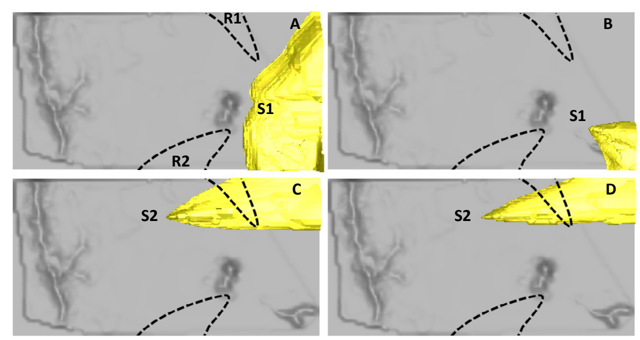

Figure 5. Air pollutant from points S1 and S2 dispersed by western wind. Residential area marked by R1 and R2. A) 6 m/s, B) 17.8 m/s, C) 6 m/s, D) 17.8 m/s.

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 KampungGebeng, 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 hillcreates a recirculation certain wind pattern in the wake of the hill that affect the dispersion of pollutant. For instance the vector plot inFigure 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].

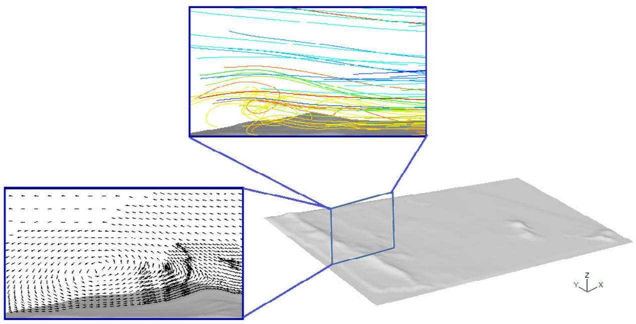

Figure 6. Vector and pathlines of flow over hill H3.

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 BalokBaru Secondary School, BalokPerdana, KampungBerahi and KampungSelamat. While gas release from Gebeng phase 2 (S2) during April to September may affect the residential area R1 around KampungGebeng, Rizk Beach Residence and Mermaid Inn.

5. Acknowledgement

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