Modeling the effect of hypothetical chlorine leakage from Malay-Sino Chemical Industries using ALOHA software and development of an emergency evacuation route around Teluk Kalong industrial area

W P Law¹, J Gimbun¹,2,*
¹Centre of Excellence for Advanced Research in Fluid Flow, Universiti Malaysia Pahang, 26300 Gambang, Pahang, Malaysia
²Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang, 26300 Gambang, Pahang, Malaysia
*jolius@ump.edu.my

Abstract. Malay-Sino Chemical Industries in Teluk Kalong is the largest chlor-alkali manufacturer in Malaysia, which may potentially affect the safety of plant workers and nearby residential area in the event accidental chlorine leakage. The dispersion of a hypothetical chlorine leakage from Malay-Sino Chemical Industries in Teluk Kalong industrial area was modelled using ALOHA. The effect of different wind direction, wind speed and time in the meteorological mesoscale area was evaluated. The wind speed ranging from 1.55 to 11.1 m/s obtained from a local weather station was considered. Heavy gas dispersion model was used to determine the concentration of chlorine plume within the area of concern. The leakage rate was set at 702 kg/h. The result showed that the residential area R5 (Kampung Bukit Kuang, and Kampung Sungai Terjun) is affected by the plume dispersed by northern wind at night. A greater hazard zone can be formed under the wind speed below 1.55 m/s. A suitable safety evacuation routes were proposed to reduce the risk of exposure to hazardous gas. Finding from this work is useful to understand the risk of hazardous gas dispersion around Teluk Kalong industrial area.

1. Introduction
Chlorine is commonly produced as chlor-alkali product for application in the polymer and water treatment plant. Exposure to chlorine can cause acute or chronic effects depending on its concentration ranging from tickling of nose and throat at a level of 0.014 ppm [1] to chest pain, nausea, dyspnea and cough at a higher level above 30 ppm [2]. Chlorine gas leaks from chlor-alkali plant has happened in the past, such as the incident on 18 September 2016 in Bukit Merah industrial park, Lahat, Perak [3]. The incident is due to the failure of a ferric acid tank causing the leaked acid to react with sodium hypochlorite in the pipes and produced chlorine gas. The chlorine gas dispersed into the atmosphere immediately and a toxicity level of chlorine at 3 ppm was detected around the plant. A total of eight personnel was hospitalized during the incident. Two workers were hospitalized and one of the workers was diagnosed with pneumonia, which was placed in the intensive care unit. Six firemen were hospitalized due to extreme exhaustion after carrying five tons of sodium tanks during the neutralization process. The nearby residential area located within 1.5 km from the plant is also affected. Most of the affected residents suffered from irritation to eyes, nose and throat. It can be seen
that chlorine leakage is affecting the safety of plant workers, including the firemen and nearby residential area. Malay-Sino Chemical Industries Sdn. Bhd at Teluk Kalong is the largest manufacturer of chlor-alkali product in Malaysia. There are two manufacturing facilities, one located in Bukit Merah industrial park, Perak and another in Teluk Kalong industrial area, Terengganu. The plant in Teluk Kalong industrial area is approximately three times larger production than the one in Perak, thus the risk it poses should the accident happen is grievous. Teluk Kalong industrial area is surrounded by a number of residential areas and University College which may be affected by the accidental chlorine release. No previous study on the chlorine dispersion at Teluk Kalong, and hence this is the aims of this study. Therefore, it is important to evaluate the potential risk of chlorine leakage from Malay-Sino plant in Teluk Kalong industrial area to the nearby residential area. In addition, the meteorological condition is significantly affecting the dispersion of air pollutant. Abdullah et al. [4] reported that the atmospheric stability is different at day and night time, which affects the wind speed as well as the dispersion of pollutant. Meanwhile, the other studies such as Erain et al. [5], Law et al. [6] and Sudarsan et al. [7] concluded that the wind speed and wind direction changes at each monsoon season are affecting the dispersion of pollutant plume and the potential risk zone. Therefore, this study incorporates the effect on atmospheric stability, wind speed and wind direction to the chlorine gas dispersion modelling.

The air hazard modelling software like the Areal Location of Hazardous Atmosphere (ALOHA) is often applied to estimate and respond to the accidental release of hazardous chemicals owing to economic, fast prediction and it is easy to assess. ALOHA has been widely used to predict the hazardous chemical release in the past, such as the chlorine pipeline failure [8], liquefied natural gas from the gasification plant [9] and sulfuric acid dispersion from the petrochemical plants [10]. To the best of our knowledge, no study on the chlorine leakage dispersion is available for Teluk Kalong industrial area. Hence, the present study aims to predict the effect of wind direction, wind speed and time of day on the chlorine leakage dispersion around Teluk Kalong industrial area using ALOHA modelling. Wind direction and speed changed during the monsoon season as well as it may differ at night and daytime, thus affecting chlorine dispersion. Based on the model prediction, the emergency evacuation route for Teluk Kalong industrial area in the event of accidental chlorine leakage is proposed.

2. Methodology

The modelling of hazardous chlorine leakage was performed using ALOHA 5.4.7 [11]. It is developed to estimate the chemical dispersion in the event of accidental release using the information on specified site, period, atmospheric stability, wind data, chemical properties, leakage source and chemical release rate. Approximately 700 pure chemicals were included in the chemical database of ALOHA [12-13]. All chemicals are treated as non-reactive chemicals. The chemical dispersion was modelled using spreading algorithm such as the Gaussian and heavy gas dispersion models. The spreading algorithm was selected using the critical Richardson number. The critical Richardson number is estimated based on the density of chemical, release rate and wind speed. In the present work, the heavy gas dispersion model was chosen for downwind dispersion since the chlorine is denser than air. ALOHA heavy gas model accounts for the gravitational forces in which the dispersion of heavy gas is affected by the wind and atmospheric turbulence.

In the present work, the hypothetical leakage was assumed to occur at a short pipeline connected to a 1 m³ commercial horizontal cylindrical tank, where the liquefied chlorine (1.32 T) is stored at ambient temperature. The maximum average sustained release rate of chlorine was estimated at 0.195 kg/s through a short pipeline [14]:

\[
Q_p(t) = \frac{A_p L_c}{v_g - v_l} \sqrt{\frac{1}{N_p T c p d}}
\]  

(1)
where $Q_H(t)$ is the mass flowrate (kg/s), $A_b$ is the area of the leak source (m$^2$), $L_e$ is the specific latent heat of vaporization (J/kg), $V_g$ and $V_l$ are the specific volume of gas and liquid phases (m$^3$/kg), respectively, $T_i$ is the temperature of the fluid (K), $c_{pl}$ is the heat capacity of fluid (J/kg K), and $N_F$ is given by:

$$N_F = \frac{V_g L_e^2}{2(P_{eff} - P_a) C_{disp}(V_g - V_l) T_i c_{pl}} + \frac{l_p}{l_e}$$

(2)

where $P_{eff}$ is the effective pressure (Pa), $P_a$ is ambient pressure (Pa), $C_{disp}$ is the discharge coefficient at 0.61, $l_p$ is the length of pipe (m), and $l_e$ is 0.1 m. The concentration of the plume is calculated using the heavy gas dispersion model which is given by [15]:

$$C(x, y, z) = C_s(x) e^{-\left(\frac{|y - b(x)|^2}{S_h(x)}\right)^{1+n} - \left(\frac{z}{S_d(x)}\right)^{1+n}}$$

(3)

$$C(x, y, z) = C_s(x) e^{-\left(\frac{z}{S_d(x)}\right)^{1+n}}$$

(4)

where $C(x,y,z)$ is the concentration of the plume (ppm), $C_s(x)$ is the centerline ground-level concentration (ppm), $S_h(x)$ is the horizontal dispersion coefficient (m), $S_d(x)$ is a vertical dispersion coefficient (m), and $b(x)$ is the half-width of homogeneous core section (m). $S_h(x)$ and $S_d(x)$ were obtained from the algebraic expressions for a specific atmospheric stability class [16]. Three different concentrations of chlorine plume such as 0.014 ppm (tickling effect), 1 ppm (mild irritation), and 30 ppm (life-threatening effect) were set for the threat zone analysis. The dispersion of chlorine plume was modelled within about 10 km radius (meteorological mesoscale). ALOHA is deemed valid for use in this work because Teluk Kalong industrial area has a mainly flat terrain with about 9 m average elevation from sea level.

The wind data were obtained from Continuous Air Quality Monitoring Station located approximately 2 km from Teluk Kalong industrial area [4]. The wind direction in Teluk Kalong industrial area varies with the time, i.e. day (7 am to 6 pm) and night time (7 pm to 6 am). Abdullah et al. [4] reported that the wind flows mostly from the northwest and southeast direction for the whole year in 2015. The wind flows mostly from the north, northeast and northwest during the northeast monsoon season (November to March). During the southwest monsoon (mid of May to September), the wind flows mostly from southeast at day time, meanwhile northwest and southeast direction at night. The two inter-monsoon seasons occur during April to mid-May and in October. During the inter-monsoon, the eastern and southeastern wind dominates at daytime and the northwestern wind at night (see figure 1). In the atmospheric setup, cloud cover at 50% was chosen since the Teluk Kalong industrial area is partly cloudy most time during the southwest monsoon. Meanwhile, cloud cover at 80% (mostly rainy day) was chosen for the other monsoon seasons. The humidity was set at ranged from 86% to 90% and the air temperature was set at ranged from 25.6 °C to 27.3 °C based on the monsoon seasons. ALOHA considers the period (either day time or night time), wind data and cloud condition to determine the atmospheric stability. The atmospheric stability class of B and E was chosen for the cases of weaker wind condition during day and night time, respectively, meanwhile stability class of D was used for the cases of stronger wind condition either in day or night time. Modelling was performed for a different wind direction, wind speed (minimum and maximum wind speed) and time (day time and night time).

3. Results and discussion

The study area is located around Teluk Kalong industrial area, Terengganu of about 11.1 km (west-east) × 14.7 km (north-south), as shown in figure 2. The present study focusses on the hypothetical
chlorine leakage from Malay-Sino Chemical Industries chlor-alkali plant. The concentration of chlorine plume at 0.014 ppm, 1 ppm and 30 ppm are represented by yellow, orange and red contour.

![Windrose for Teluk Kalong industrial area at day time and night time, respectively, during (a-b) northeast monsoon (early of year), (c-d) northeast monsoon (end of year), (e-f) southwest monsoon, (g-h) intermonsoon 1, (i-j) intermonsoon 2. Data averaged from year 2015 [4].](image)

**Figure 1.** Windrose for Teluk Kalong industrial area at day time and night time, respectively, during (a-b) northeast monsoon (early of year), (c-d) northeast monsoon (end of year), (e-f) southwest monsoon, (g-h) intermonsoon 1, (i-j) intermonsoon 2. Data averaged from year 2015 [4].
Figure 2. Prediction of chlorine plume dispersion and evacuation route around Teluk Kalong industrial area at day time (a) maximum wind speed, (b) minimum wind speed, and at night time (c) maximum wind speed, (d) minimum wind speed.
Two major cities, i.e., Kijal and Chukai are located within 14 km from the industrial area. Residential areas R1 to R4 are the division of Kijal city, while the residential area R5 and R6 are Chukai city. The results show that the width of chlorine plume is larger when the wind speed is lower in this work, which is in agreement with the previous study by Paul et al. [17], who reported that the hazard zone is smaller when the chlorine plume is dispersed by a stronger wind. A comparison of ALOHA and computational fluid dynamics (CFD) prediction on gas dispersion was made by Zavila et al. [18]. They show that predictions of CFD and ALOHA is essentially similar with most of the predicted risk area overlaps for both models. Like chlorine, NH₃ is also considered as a dense gas. CFD of course is more accurate, but it takes a long time to complete up to a month. Meanwhile, ALOHA can perform the modelling within minutes, which may benefit the emergency evacuation plan. Hanna et al. [19] also shows that the prediction of chlorine dispersion by ALOHA is comparable to other commonly available model such as TRACE, PHAST, HGSYSTEM, SLAB and SCIPUFF. The ALOHA prediction in this work is considered valid by taking into account all the aforementioned validations and comparison.

A hypothetical chlorine leakage that occurred in a Malay-Sino Chemical Industries at Teluk Kalong industrial area was predicted for the case of different wind direction, wind speed and time. The minimum wind speed was set at 1.55 m/s and the highest wind speed is in the range of 7.25 to 11.1 m/s. Figures 2(a) and 2(b) show the chlorine plume dispersed by eastern and northwestern wind at maximum and minimum wind speed, respectively at day time. Whereas, figures 2(c) and 2(d) show the chlorine plume for the cases of northern and northwestern wind at maximum and minimum wind speed, respectively at night time. At daytime, the crosswise dispersion of chlorine plume is larger (up to 2.33 km) when the wind speed is low [6]. The lower wind speed is not sufficiently strong to push and dilute the dense chlorine plume and hence causing the plume to accumulate closer to the leak source. Therefore, the industrial area is exposed to higher hazard risk, although the residential area is not affected (figure 2(b)). In contrast, the chlorine plume is likely to spread in the streamwise direction instead of crosswise direction at night time. The plume is approximately 2.8 km longer with a lower wind speed. The lower wind speeds (stability class: E) at night is much stable compared to the higher wind speed (stability class: D). According to Abdullah et al. [4], the calm wind causes a higher probability of high concentration air pollutant to move downwind. The wind flow with higher stability (figure 2(d)) causes the plume to disperse further in the streamwise direction than that of lower stability wind (figure 2(c)). Therefore, at lower wind it is easier for the plume to disperse downwind without much atmospheric disturbance. Besides, it was found that the wind stability varies at daytime and at night. At a lower wind speed, the wind is more stable (stability class: E) at night (figure 2(d)) compares to day time (stability class: B) (figure 2(b)). Hence, a narrow and long plume with low wind speed was formed at night. However, there is no difference in wind stability at day or night time when the wind speed is above 7.25 m/s, as shown in figures 2(a) and 2(c). The result shows that the wind stability also plays important role in the dispersion of chlorine plume.

Figures 2(a) and 2(b) show a dangerous chlorine plume at 30 ppm (high concentration) was dispersed up to a distance of 186 m and 305 m at lower and higher wind speed, respectively. Unichamp Mineral Sdn Bhd located west of the leak source is affected when the wind speed is higher, whereas no area is affected by the 30-ppm plume at the lower wind speed. The plume at a level of 1 ppm dispersed up to 1.1 km with a higher wind speed and no residential or industrial area affected. However, Tosoh Advanced Material Sdn Bhd, Handal Offshore Svc Sdn Bhd and Pra Services Sdn Bhd are exposed to the chlorine plume at a level of 0.014 ppm. At a lower wind speed, the plants such as See Sen Chemical Bhd, Tioxide (M) Sdn Bhd, Huntsman Tioxide plant, Essfa Sdn Bhd and Unichamp Resources Sdn Bhd, which is located within 2 km from the leak source are affected by the mild level of chlorine plume at 1 ppm. Meanwhile, Darul Iman Training Centre is exposed to the plume at a level of 0.014 ppm.

At night time, the plume at a level of 30 ppm and 1 ppm are dispersed up to 231 m and 1.4 km, respectively, with a higher wind speed (> 7.25 m/s), as shown in figure 2(c). No residential or industrial area exposed to these two higher concentrations of chlorine plume. However, major part of
the industrial area such as Kemaman Bitumen Company Sdn Bhd (Refinery), Carigali Hess Operating Company Sdn Bhd, Petrofac (M) Sdn Bhd, Petroleum Industry of Malaysia Mutual Aid Group, ZM Engineering Construction Sdn Bhd, Caricion Tube Sdn Bhd, Halliburton Energy Services, Destini Oil Services Sdn Bhd and Geologging Sdn Bhd, and a minor part of residential area R5 (i.e. Kampung Sungai Terjun) are exposed to the plume at the level of 0.014 ppm. At a lower wind speed (1.55 m/s), the leaked plume at dangerous level of 30 ppm is dispersed up to a distance of 422 m (figure 2(d)). See Sen Chemical Bhd located at 450 m from the leak source is at high risk of exposure to dangerous levels of chlorine plume. Whereas, the plants such as Huntsman Tioxide plant, Essfa Sdn Bhd, Unichamp Resources Sdn Bhd and Tioxide (M) Sdn Bhd are affected by the plume at a level of 1 ppm.

The result shows that an accidental chlorine leakage from chlor-alkali plant in Teluk Kalong industrial area can potentially cause exposure of a life-threatening chlorine concentration to the person working in around the industrial area for the cases of higher wind speed at day time and lower wind speed at night. Therefore, a proper emergency evacuation route is necessary in the event of accidental chlorine leakage from the chlor-alkali plant. School and public hall can be utilized as an evacuation point in the event of an accident. The proposed assembly evacuation point is towards north, east or southwest of the leak source in the event of a high wind speed at day time, as shown in figure 2(a). The suitable evacuation locations such as school, i.e. Sekolah Kebangsaan Bukit Anak Dara and mosque, i.e. Masjid Kampung Bukit Anak Dara located at north of leak source is within 6.9 km from the affected area. The TATI University College, school (Sekolah Kebangsaan Teluk Kalong) and mosque (Masjid Kampung Telok Kalong) at the east of the leak source are within 2.9 to 6.6 km from the affected area. Another evacuation point is mosques, i.e. Masjid Bukit Kuang and Masjid Lama Bukit Kuang and schools, i.e. Sekolah Rendah Kebangsaan Bukit Kuang and Sekolah Menengah Kebangsaan Bukit Kuang, which is located southwest of the leak source within 6.5 km from the affected area. The evacuation route for the accidental chlorine leakage with lower wind speed at day time and night time are shown in figures 2(b) and (d), respectively, whereby the victims should move towards northeast or southwest of the leak source for safety purpose. The proposed assembly points such as TATI University College, school (Sekolah Kebangsaan Teluk Kalong) and mosque (Masjid Kampung Telok Kalong) located at the northeast of leak source are in 1.7 to 4.4 km from the affected area. Other alternative such as mosques, i.e. Masjid Bukit Kuang and Masjid Lama Bukit Kuang and schools, i.e. Sekolah Rendah Kebangsaan Bukit Kuang and Sekolah Menengah Kebangsaan Bukit Kuang located southwest of the leak source within 8.4 km from the leak source. In the event of a higher wind speed at night (figure 2(c)), the residents from Kampung Sungai Terjun should move east towards the safer locations such as mosques, i.e. Masjid Bukit Kuang and schools, i.e. Sekolah Rendah Kebangsaan Bukit Kuang and Sekolah Menengah Kebangsaan Bukit Kuang, which are located within 4.8 km from the affected area. The victims from affected industrial area should move southwest towards the school (Sekolah Kebangsaan Teluk Kalong) and mosque (Masjid Kampung Telok Kalong), which are about 4.5 to 8.5 km from the affected area. As shown in figure 2, utilization of assembly points around residential area R2, R4 and R5, which is located in the north, east and southwest of the leak source are the ideal option in the event of accidental chlorine leakage from the Malay-Sino Chemical Industries in Teluk Kalong industrial area.

4. Conclusion
An accidental chlorine leakage around Teluk Kalong industrial area has been successfully modelled using ALOHA software. It was found that the dispersion of chlorine leakage is significantly affected by the wind direction, wind speed and time. A lower wind speed produced a wider plume at day time but a longer plume at night in comparison to the higher wind speed due to the different wind stability. It can be concluded that the risk of exposure to hazardous chlorine concentration is tenfold higher at a wind speed below 2 m/s compared to the one above 7.25 m/s. The plume released affects the industrial area for all cases evaluated. Only residential area R5 is affected by the plume released at night with a northern wind. The result shows that an accidental chlorine leakage from Malay-Sino Chemical Industries may cause a life-threatening chlorine concentration in Teluk Kalong industrial area. The
result obtained from this work is useful to predict the hazardous zone and potential impact area due to accidental chlorine leakage from Malay-Sino Chemical Industries chlor-alkali plant. The results also provide a guidance to determine a safe emergency evacuation route in the event of accidental chlorine leakage.

Acknowledgments
We acknowledge funding from Ministry of Education Malaysia through grant FRGS/1/2018/TK02/UMP/02/17 managed by the Department of Research and Innovation Universiti Malaysia Pahang (RDU190145).

References
[1] Calabrese E J and Kenyon E M 1991 Air Toxics and Risk Assessment (Chelsea: Lewis Publishers)
[2] US Department of Health and Human Services (HHS) 1993 Hazardous Substances Data Bank (National Library of Medicine, Bethesda, US)
[3] Yeap A 2016 Chlorine gas causes scare around plant. Retrieved from https://www.thestar.com.my/ (accessed on 4 October 2017)
[4] Abdullah M H, Ali M I, Ngien S K 2016 Analysis for wind characteristics in Teluk Kalung, Kemaman, Terengganu Int. J. Sci. Environ. 5(6) 3827-3833
[5] Erain N, Law W P, Ramli N I, Chin S C and Gim bun J 2017 Understanding the effect of surface terrain on pollution transport around Gebeng industrial area Ind. J. Sci. Technol. 10 1-5
[6] Law W P, Erain N, Ramli N I, Gim bun J 2019 Assessment of chlorine leak dispersion around Gebeng industrial area and potential evacuation route Atmos. Res. 216 117-129
[7] Sudarsan J S, Thattai D, Shah U K, Mitra A 2016 Micrometeorological tower observations and their importance in atmospheric modelling and space technology Ind. J. Sci. Technol. 9(42) 1-6
[8] Gharaba gh M J, Asilian H, Mortasavi S B, Mogaddam A Z, Hajizadeh E and Khavanin A 2009 Comprehensive risk assessment and management of petrochemical feed and product transportation pipelines J. Loss Prev. Process Ind. 22 533-539
[9] Derudi M, Bovolenta D, Busini V and Rota R 2014 Heavy gas dispersion in presence of large obstacles: selection of the modeling tools Ind. Eng. Chem. Res. 53 9303-10
[10] Ramli A, Ghani N A, Hamid N A, Desa M S 2018 Consequence modelling for estimating the toxic material dispersion using ALOHA: Case studies at two different chemical plants Multidisciplinary Digital Publishing Institute Proceedings 2(20) 1268
[11] National Oceanic and Atmospheric Administration (NOAA) 1999 Areal Location of Hazardous Atmosphere Program (ALOHA) revision 5.4.1 (Environmental Protection Agency, Washington, US)
[12] Daubert T E and Danner R P 1989 Physical and Thermodynamic Properties of Pure Chemicals Design Institute for Physical Property Data vol 4 (New York: American Institute of Chemical Engineers, Hemisphere Publ. Co.)
[13] National Oceanic and Atmospheric Administration (NOAA) 1990 Hazardous materials response group and US environmental protection agency, Chemical emergency preparedness and prevention office CAMEOTM 3.0 for the Apple Macintosh Computer (National Safety Council, Washington, DC) p 235
[14] Fauske H and Epstein M 1988 Source term considerations in connection with chemical accidents and vapour cloud modelling J. Loss Prev. Process Ind. 1(2) 75-83
[15] Colenbrander G W 1980 Proc. 3rd Int. Symp. on Loss Prevention and Safety Promotion in the Process Industry vol 1 15-19 September 1980 Basel (Switzerland: Swiss Society of Chemical Industries) p 29
[16] Briggs G A 1973 Diffusion estimates for small emissions vol 23 Air Resources Atmospheric Turbulence and Diffusion Laboratory Report ATDL-79 USDOC-NOAA p 83
[17] Paul R, Mondal A, Choudhury S 2014 Dispersion modeling of accidental release of chlorine gas
Proc. Int. Conf. on Chem. Eng. 29-30 December 2014 Dhaka, Bangladesh

[18] Zavila O, Dobes P, Dlabka J, Bitta J 2015 The analysis of the use of mathematical modeling for
emergency planning purposes The Sci. For Popul. Prot. 2 1-9

[19] Hanna S, Dharmavaram S, Zhang J, Sykes I, Witlox H 2008 Comparison of six widely-used
dense gas dispersion models for three recent chlorine railcar accidents Process Saf. Progr.
27(3) 248-259