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Original Article

Flammable gas dispersion modelling on an offshore platform

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Abstract

Flammable gas dispersed from the vent on an offshore platform can react in an explosive manner by the existence of air or pure oxygen at a certain concentration within its flammability limits. Due to unwanted accidents that might occur, resulting in loss of life and asset damage thus, flammable gas dispersion modelling was conducted to identify any recommendation or mitigation if required. Due to no risk assessment on the offshore platform to perceive the dispersion model based on various perspectives, multiple software was used in assessing recommendations and mitigation. Therefore, the flammable gas dispersion study carried out was to obtain dispersion modelling on the identified offshore platform's vent as an early solution to avoid the occurrence of risk scenario. The model of flammable gas dispersion has been developed by using two notable fire and explosion modelling software: Areal Locations of Hazardous Analysis (ALOHA) and Process Hazard Analysis Software Tool (PHAST). The meteorological conditions consist of wind speed, and atmospheric stability has been used as manipulated variables. Meanwhile, the vent designs (height, diameter, angle, pressure, temperature and flowrate of flammable gas release) and vent composition remain unchanged for all the selected weather conditions. The impairment assessment conducted showed the dispersion contour obtained through ALOHA and PHAST, no risk reduction and recommendations required as the plume dispersed at the highest cloud height, thus both the manned area or escape routes and muster area were not affected by the flammable gas released from the vent.

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1 Introduction

Onshore process platforms are neither free from accidents nor completely safe, as well as offshore platforms. The limited spaces process area for an offshore platform and environmental condition can increase the fatality when an accident occurs. An incident such as Piper Alpha Explosion (1988), the deadliest historical accident on an offshore oil and gas platform contributes towards high fatalities, environmental damage and economic losses [1]. Flammable material release from the platform in form either liquid or gas can contribute to unwanted accidents such as pool fire, fireball and flash fire [2].

Flammable gas can be released directly from the vent to the environment. Gasses such as ethane, methane and propane are highly flammable which typically found as the components from the vent's release. Dispersion modelling is one of the approaches conducted by countless chemical engineers and researchers to analyse the severity due to flammable gas. This review aims to assess flammable gas dispersion on the identified offshore platform vent and provide any recommendations and mitigation if required based on the attained results.

The dispersion model of flammable gas is one of the branches of consequence modelling. The research on consequence modelling consists of source models and dispersion models, which can be overview as in Fig. 1.

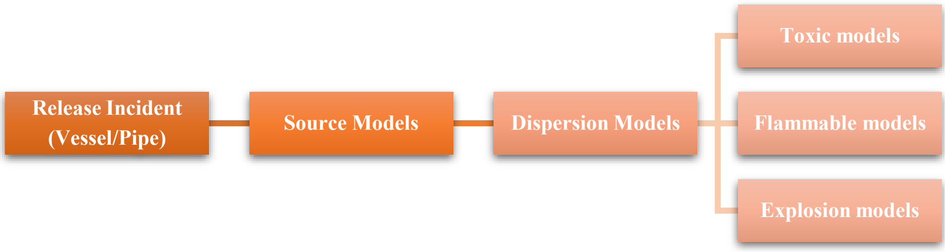

Fig. 1 Dispersion model's overview.

1.1 Source models

The quantity of material flow from an outlet hole of containment devices or vessel pipe was determined using source models as stated in Fig. 1. The results from the source model's analysis are crucial due to it was used in describing on how the material dispersed and transported. A mechanical energy balance, as shown in Eq. (1) was used to describe various energy associated with the flowing gases [3].

$$\int \frac{dP}{\rho} + \Delta\left(\frac{\bar{u}^2}{2\alpha g_c}\right) + \frac{g}{g_c}\Delta z + F = -\frac{W_s}{\dot{m}} \tag{1}$$

where : P is pressure (force/area), ρ is density, (mass/volume), $\bar{u}$ is average instantaneous velocity for fluid (length/time), g is acceleration due to gravity (length/time^2), g_c is gravitational constant (length/time^2), α is unitless velocity profile correction factor, z is height above datum (length), F is net frictional loss term (length force/mass), W_s is shaft work (force length), and $\dot{m}$ is mass flow rate (mass/time).

After few assumptions has been made from the mechanical energy, the discharge of gas through a hole on a vessel can be described in form of Eq. (2) [3].

$$Q_m = C_0 A P_0 \sqrt{\frac{2 g_c M}{R_g T_0} \frac{\gamma}{\gamma - 1}\left[\left(\frac{P}{P_0}\right)^{2/\gamma} - \left(\frac{P}{P_0}\right)^{(\gamma+1)/\gamma}\right]} \tag{2}$$

where : C_0 is discharge coefficient (dimensionless), A is area of the hole (length^2), P_0 is pressure upstream of the hole (force/area), M is molecular weight of the gas (mass/mole), γ is heat capacity ratio, C_p/C_y (unitless), R_g is ideal gas constant (pressure-volume/mol-deg), T_0 is initial upstream temperature of the gas (deg), and P is downstream pressure (force/area).

1.2 Gas dispersion modelling

Gas dispersion modelling emission in Fig. 1 can be classified into two models, as shown in Fig. 2, including plume (continuous) and puff (instantaneous) [4]. The release of materials with a steady steady-state concentration can be described as a plume. Meanwhile, the puff is material from a single release with a temporary concentration and a fixed amount [5].

The dispersion phases distinguished into neutral or light gas clouds and heavy (or dense) gas clouds [6]. Both phases differ, including wind shear at interfaces, inertia of the released material, and turbulence dumping [6]. The gas dispersion modelled through several tools and strategies, including Gaussian, Lagrangian, Eulerian and Computational Fluid Dynamics (CFD) models [7].

The model used for continuous steady-state ground releases of heavy gas well-known as Gaussian plume models. The pollutant concentrations follow a normal distribution in both vertical and horizontal aspects by using the Gaussian models. Gaussian models only calculate a single formula resulting in an extremely fast response time. However, it produces poor results in situations such as low wind speeds, where the three-dimensional diffusion is significant [7]. Lagrangian models were used to simulate the trajectories of "puffs" of pollutants emitted from the source at regular intervals. The most common model was a "Gaussian puff" model when each puff assumed to follow a Gaussian distribution as it moves downwind and expands [8]. Each puff will be treated independently due to the varying rates and move in various directions. The idea of Eulerian models focusing on solving the atmospheric transport equation defined as Eq. (3) numerically in fixed coordinate frame [7].

$$\frac{dc}{dt} = -\nabla \cdot (c\vec{v}) + S_c + \nabla \cdot (D_c \nabla c) \tag{3}$$

which can be defined as, $\vec{v}$ is wind vector, S_c is source term, and D_c is diffusion coefficient. The Computational Fluid Dynamics (CFD) has been introduced in environmental modelling to overcome urban air pollution problems, as the source and receptor points are typically located within a few hundred meters of each other. This scenario contributes towards a very complex geometry [8]. Mocho et al. [9] had applied the Computational Fluid model in investigating the movement of formaldehyde in an indoor setting. The results from the investigation shown an improvement in the accuracy of the results compared to using box model.

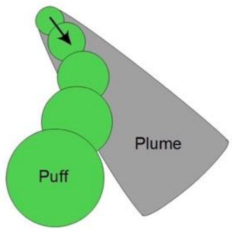

Fig. 2 Puff and plume model.

1.3 Wind velocity and atmospheric stability

Wind, natural phenomenon of the earth defined as the movement occur when the air is heated and rises to the atmosphere where the cool air comes and takes its place. Two factors affect the dispersion of flammable gas caused by the wind: wind velocity and atmospheric stability. Wind velocity significantly affects the pollution concentration in the localize area as the pollution concentration will become lower as the wind speed is higher [10] Meanwhile, the atmospheric stability of the area where gas is released will determine the severity and the size of area affected due to the hazards significantly. The stability of the atmosphere can be described through the Pasquill's stability clarification system based on Table 1 and Table 2 [11].

Table 1 Pasquill stability conditions based on meteorological conditions.

Surface wind speed	Daytime incoming solar radiation			Nigh time cloud cover	
	Strong	Moderate	Slight	>4/8 low cloud	<3/8 cloud
<2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Table 2 Classification of designated stability class.

Stability class	Classification
A	Very unstable
B	Unstable
C	Slight unstable
D	Neutral
E	Stable
F	Very stable

1.4 Parameters affecting the dispersion

Several other parameters were considered in conducting the dispersion modelling. In a study by Johnson [8] possible data inputs can be characterized into four types such as emission, source, location and meteorological. Surface roughness is one of the important location characteristics due to it determines the shape of wind profile affecting the turbulence generation [12]. Urban areas will be considered extremely rough compared to rural area such as countryside with a wind gradient closer to laminar flow [12]. Varieties of solar heating of street walls and ground resulting in thermal effects are one of the meteorological characteristics. The sun warms the air near the wall or on the surface of the ground during the day, causing strong upward motion of air [13]. The temperature difference led to a strong buoyancy force, thus affecting the pollution transport to the layer upwards from the street canyon [13].

1.5 Mitigation approaches

Considering accidents could occur both on process plants and offshore platforms, a counter measure has been taken into account to reduce the risk. Mitigation is a safety measure taken to eliminate or reduce risk of hazards and their effects towards personnel, environment and asset [14]. Catastrophic accidents was reduced to an insignificant severity by conducting the five steps on preventing and controlling accidents, as shown in Fig. 3.

Based on the research by Fthenakis [15], several technologies in preventing accidents and the mitigation options has been reviewed and discussed. In the early development of a project, the most competent strategy in reducing the hazards through the application of suitable technologies, materials or process capable in reducing the amount of release (flammable gas, toxic gas, hazardous materials) [15]. The implementation of latest technologies in the early stage of a project are important as this approach can reduce financial resources and efforts later. This early effort can be conducted such as by using environmentally friendly raw materials. Undesired consequences result from the events that initiate the scenario [16]. Strategies for preventing undesired initiating events causing accidents to occur should be evaluated and implemented [15]. Maintenance, worker training, inspections and operating procedures are some of the engineering and administrative courses of actions can be conducted [15]. Fail to suppress the initiating events, the next step to be considered is preventing or minimize the releases. This can be done by implementation of safety devices or options such as early detection, isolation valves and double containment to reduce the release of liquid or gas due to occurrence of unwanted leak [15]. The next step to be taken is to control or minimize the release to the environment. Equipment such as chemical scrubbers designated to remove pollutants or more in gas depending on client's needs can be applied to the process plants to control environmental releases [15]. Final steps in preventing or minimizing the hazards as the final defensive barrier by preventing or minimizing the materials released exposure to the populations [15]. Several early measurements can be taken in the early project plans such as isolated or remote location of gas storage, hazards signage and exclusion zones near to the plant boundaries.

However, any form of risk-reducing assessment or mitigation application should be considered As Low as Reasonably Possible (ALARP) approach. Reducing risks beyond their risk-reduction point is applicable and possible however a typical question such as, "Is it reasonably practicable?" has been raised in real-world industries due to it can be a non-cost-effective measure to be taken [17]. Through the ALARP approach, the high risks of potential accidents can be reduced by applying the mitigation to a point where the cost is beneficial, and the level of risk is tolerable [18]. Although cost benefiting application of risk mitigation effort should be applied, what is the maximum tolerable risk level to ensure its morally tolerable [17]. The limits are based on the category; it has been proposed the acceptable value for individual fatal risks to be 10^{-5} to 10^{-3} per year in Switzerland [19]. For category 1, no application of being intolerable due to the personnel's freedom of choice to expose themselves to the risks. Category 2 tolerability limit: one death in 1000 per year and Category 4 tolerability limit: one death in 100 000 per year [17].

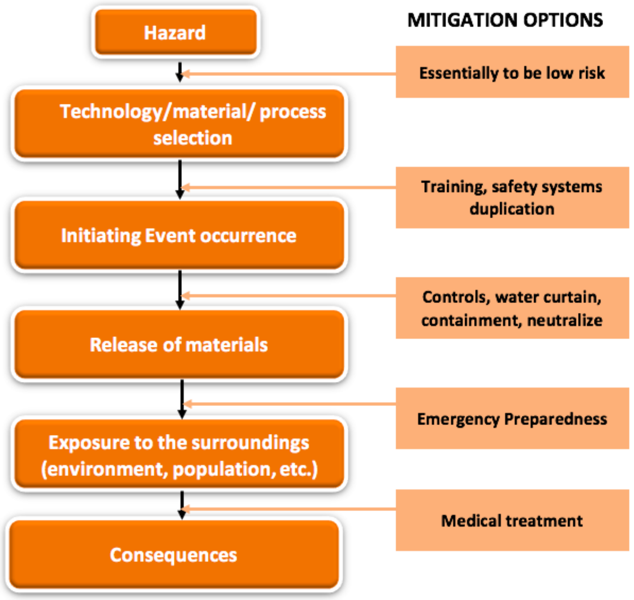

Fig. 3 Accident releases and mitigation options.

2 Methodology

2.1 Methodology overview

Fig. 4 shows the overall flowchart of proposed methodology of this current work. The detailed procedure is described below.

The first step in conducting the dispersion modelling was the case selection when the flammable gas was released from the vent. All the information required gathered for the selected vent scenario, including vent composition, weather case (wind speed and atmospheric stability) and vent design (vent height, vent diameter, vent angle, pressure, temperature and flowrate). The critical receptors on the offshore platform then was identified. After identifying the critical receptors, flammable gas dispersion modelling conducted using ALOHA and PHAST v8.4. The dispersion levels from the results was tabulated for a given range of distances of interest based on flammability level. Any potential impact on the critical receptors was assessed if the flammability limits is not within the acceptance criteria.

The design of the vent played an important role in the personnel's life and asset damage. Several criteria and the design of vent, affect the flammable gas dispersion. Table 3 shows the design specification of an offshore platform's vent to be used in assessing the dispersion modelling.

Based on the Pasquill-Gifford Stability Classes, two weather scenarios were selected for the dispersion modelling: category 1.5/F (stable night with moderate clouds and light or moderate wind) and category 5.0/D (neutral-little sun and high wind or overcast or windy night). Wind velocity and atmospheric stability play a major role in determining the flammable gas dispersion behavior.

The occurrence of unwanted risk scenarios such as flash fire or pool fire were determined by the composition inside the vent. The highly flammable gas composition can affect the personnel exceeding the acceptable region based on the ALARP caused by acute fire or explosion. The flammable gas composition is shown in Table 4.

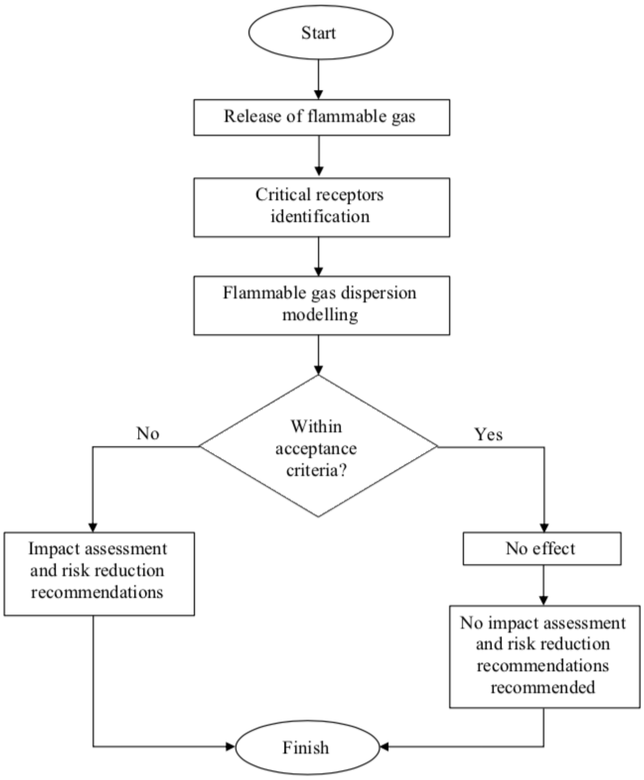

Fig. 4 Overall methodology flowchart.

Table 3 Selected offshore platform's design.

Parameters	Value
Height	3.892 m
Diameter	100 mm
Angle	Horizontal
Pressure and Temperature	30°C and 1 bar
Flowrate	2083.8 kg/hr

Table 4 Composition inside the offshore platform's vent.

Components	Composition (percent weight)
Methane	78.7
Carbon Dioxide	58.2
Ethane	5.01
Propane	5.32
n-Butane	2.88
n-Pentane	0.79
n-Hexane	1.34
Nitrogen	0.14

2.2 Gaussian Plume Model

The model used to describe the dispersion of flammable gas for ALOHA and PHAST with continuous steady-state ground releases of heavy gas is known as Gaussian plume models and can be described as Eq. (4).

$$\bar{c}\left(x,y,z\right)=\frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}\exp\left(-\frac{y^2}{2\sigma_y{}^2}\right)\left[\exp\left(\frac{-\left(z-h\right)^2}{2\sigma_z{}^2}\right)+\exp\left(\frac{-\left(z-h\right)^2}{2\sigma_z{}^2}\right)\right] \tag{4}$$

where, $\bar{c}\left(x,y,z\right)$ is average concentration (g/m^3), Q is source emitting rate, σ_y, σ_z is dispersion coefficients in the y and z directions, $\bar{u}$ is average wind speed (m/s), y is cross-wind direction (m), z is distance above ground (m), h is height of the source above ground level plus plume rise if any (m).

2.3 Critical receptors on the offshore platform

In an offshore platform as shown in Fig. 5, several equipment or areas require personnel to indulge with, with the possibility of being affected by the flammable gas dispersion. Furthermore, these receptors can be the source of ignition to occur. In the early stage of conducting the dispersion modelling, it is required to identify the critical receptors on the offshore platform [20]. Critical receptors in Table 5 were assessed for the flammable gas dispersion including manned area or escape routes and muster area.

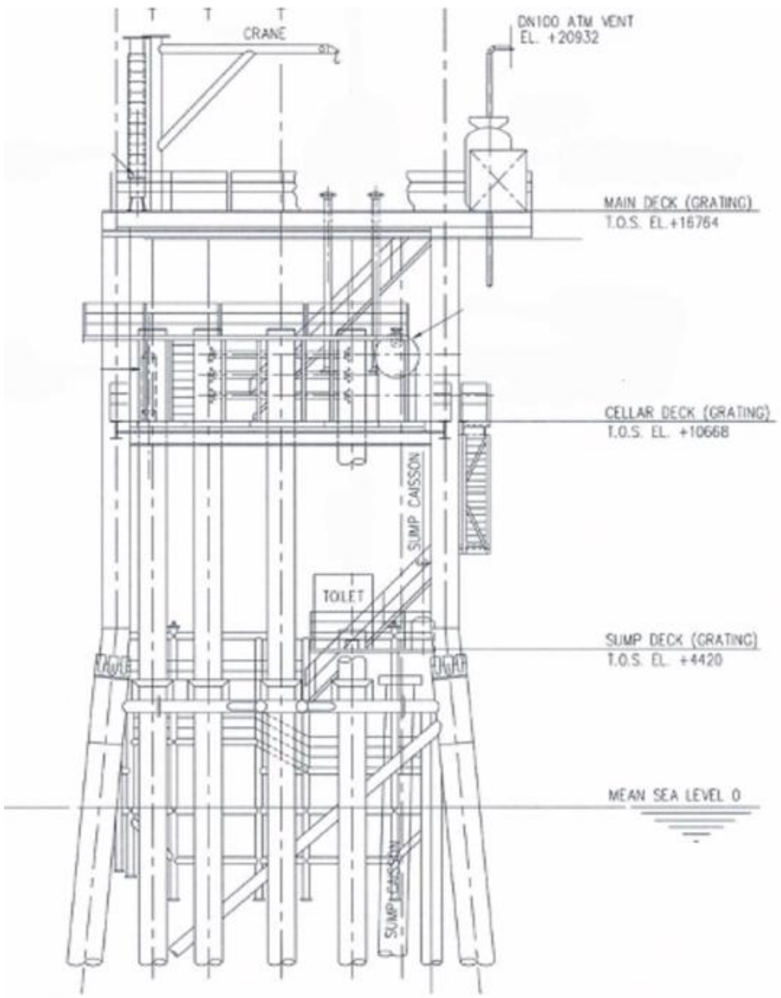

Fig. 5 Offshore platform used to assess in the flammable gas dispersion modelling.

Table 5 Critical receptors assessment for personnel safety.

Critical receptors	Descriptions
Manned area / escape routes at main deck	100% LFL gas concentration was determined and assessed either it reaches the manned area at 31.848 m height from the mean sea level or simultaneously impaired both escape routes.
Muster area at sump deck	100% LFL gas concentration was determined and assessed either it reach muster area platform located at 4.42 m from the mean sea level.

2.4 Flammability Limits

Generally, flammable materials in gas or liquid form can be characterized based on flammability limits. There are two flammability limits: lower flammability limit (LFL) and upper flammability limit (UFL). LFL is the lowest concentration of flammable materials to be ignited meanwhile, UFL is the highest concentration of flammable gas or liquid to be ignited. Anything below the LFL is too lean to be ignited, and anything higher than UFL is too rich to be ignited. The lower flammability limit (LFL) will be the acceptance criteria for the flammable gas dispersion, as stated in Table 6.

Table 6 Lower flammability limits (LFL) acceptance criteria.

Hazard	Criterion		Impact Criteria
	LFL	ppm	
Flammable Gas Dispersion	100%	47180	Immediate fatality
	50%	23590	Maximum distance of potential ignition of flammable gas

2.5 Modelling Program

Areal Locations of Hazardous Analysis (ALOHA) software is developed by the United States Environmental Protection Agency (UESPA), a free program to assist in the possibilities of unwanted scenario able to occur during the release of flammable or toxic materials in form of liquid or gas from the source of release [21]. This software will be used in estimating the potential risk due to flammable gas dispersion.

Process Hazard Analysis Software Tool (PHAST) software is developed by a company known as Det Norske Veritas (DNV), a paid-based program designed to analyze the hazards and consequence management in the real-world chemical industries [21]. PHAST v8.4 will be used in assessing the dispersion model based on the wind speed and atmospheric stability.

3 Results and discussion

3.1 Flammable Gas Dispersion Modelling (PHAST)

The side view of the dispersion contours obtained by modelling through PHAST were shown in Fig. 6 and Fig. 7, meanwhile the top view of the flammable gas dispersion were shown in Fig. 8 and Fig. 9. The top view will be used in comparing the resemblance of the contour form with the result obtained by using ALOHA.

The impairment assessment has been conducted as shown in Table 8 to identify either the dispersion of flammable gas to reach the critical receptor or not. Based on the dispersion contour as shown in Fig. 6 till Fig. 9, the manned area or escape route at the main deck and the muster area at the sump deck are not affected by the dispersion of flammable gas. This is due to the downwind distance of the dispersion at 100% LFL (47180 ppm) which is the worst case is occur at highest cloud height as flammable gas dispersed from the vent located at 52.78 m height from mean sea level. The plume didn't reached the manned area at 31.848 meter height and the muster area at sump deck which is at height of 4.42 m from the mean sea level.

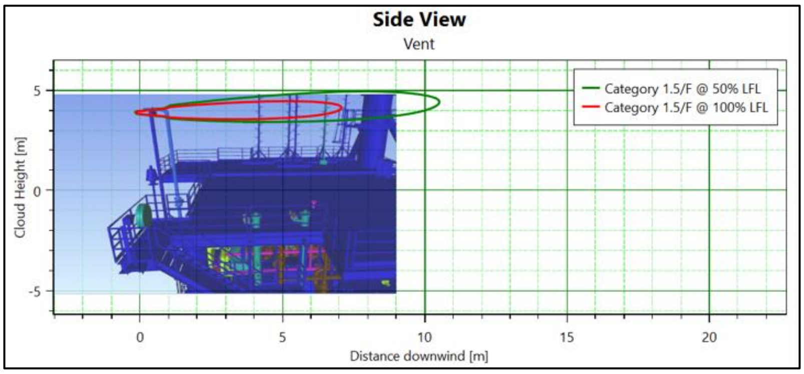

Fig. 1 Dispersion contour (side view) of weather 1.5/F.

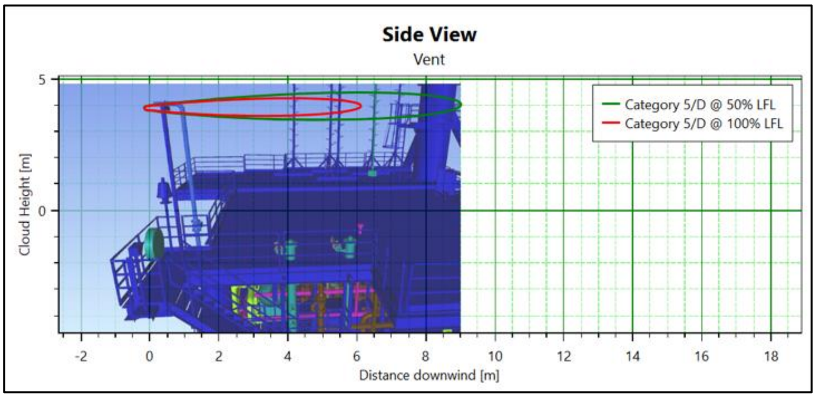

Fig. 2 Dispersion contour (side view) of weather 5.0/D.

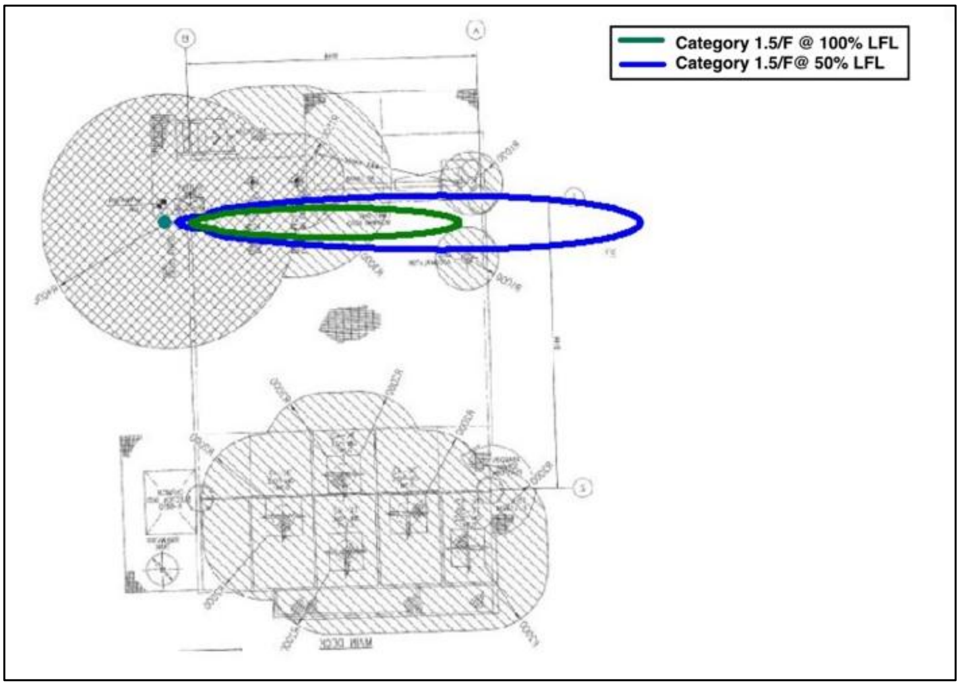

Fig. 3 Dispersion contour (top view) of weather 1.5/F.

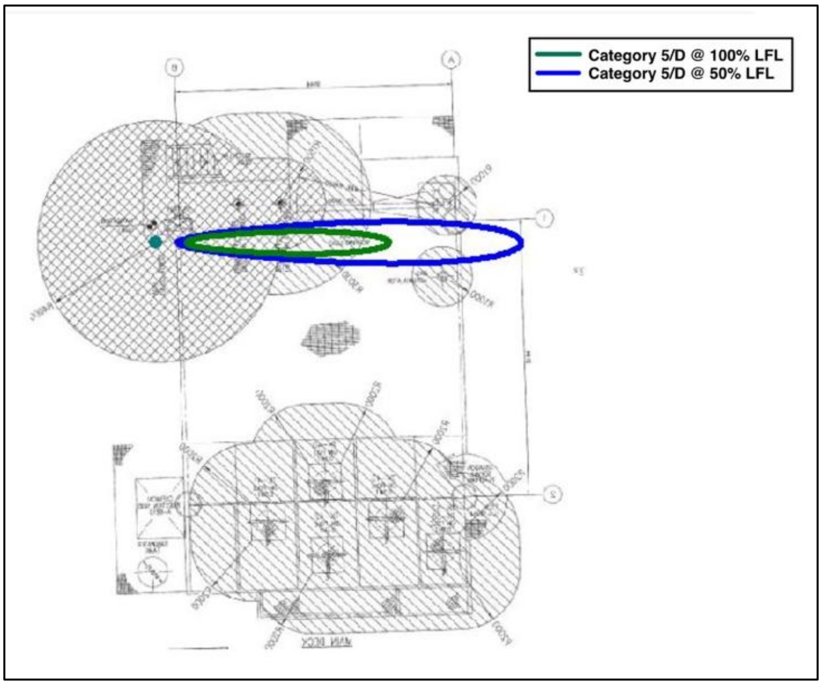

Fig. 4 Dispersion contour (top view) of weather 5.0/D.

Table 1 Downwind distance of flammable gas dispersion.

Weather	Downwind distance (m)	
	100% LFL	50% LFL
1.5/F	3.20	9.22
5.0/D	3.04	7.94

Table 2 Critical receptor affected by the dispersion of flammable gas.

Critical receptor	Impairment Assessment (Yes / No)	
	100% LFL	50% LFL
Manned area / escape routes	No	No
Muster area	No	No

Due to the flammable gas dispersion of 100% LFL (47180 ppm) and 50% LFL (23590 ppm) does not reach any critical receptors for the identified vents, thus no further recommendation required as relief and didn't affect the personnel safety.

3.2 Flammable gas dispersion modelling (ALOHA)

The top view of the dispersion contours obtained by modelling through ALOHA were shown in Fig. 10 until Fig. 16. The dispersion contours obtained as components of the mixture in flammable gas dispersed from the vent on the offshore platform.

Based on the dispersion contour obtained of each component in the flammable gas, the downwind distance was summarised as in Table 9.

The dispersion contour of carbon dioxide in Fig. 10 was not modelled in the ALOHA due to the concentration of the carbon dioxide never exceed the LFL meanwhile the dispersion contour of n-Butane in ALOHA was not modelled due to the effects of near-field patchiness resulting in dispersion predictions less dependable due to the short distances [22]. The near-field patchiness is a situation describing the gas concentrations not be able to be described as a bell-shaped curve. The impairment assessment has been conducted as shown in Table 10 to identify either the dispersion of flammable gas able to reach the critical receptor. Based on the dispersion contour, the manned area or escape route at the main deck and the muster area at the sump deck are not affected by the dispersion of flammable gas. This is due to the downwind distance of the dispersion at 100% LFL (47180 ppm) as shown in Table 9 which is the worst case is occur at highest cloud height as flammable gas dispersed from the vent located at 52.78 m height from mean sea level. The plume didn't reached the manned area at 31.848 meter height and the muster area sump deck which is at height of 4.42 m from the mean sea level.

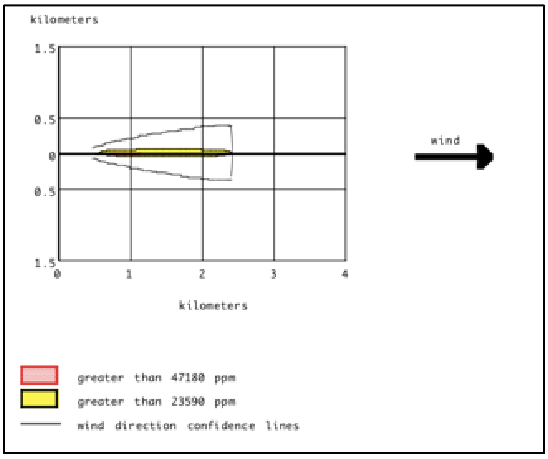

Fig. 5 Dispersion contour of methane.

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Model Run: Gaussian
Red    : LOC is not exceeded --- (47180 ppm)
Note: Threat zone was not drawn because
    the ground level concentrations never exceed the LOC.
Yellow: LOC is not exceeded --- (23590 ppm)
Note: Threat zone was not drawn because
    the ground level concentrations never exceed the LOC.
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Fig. 6 Dispersion result of carbon dioxide.

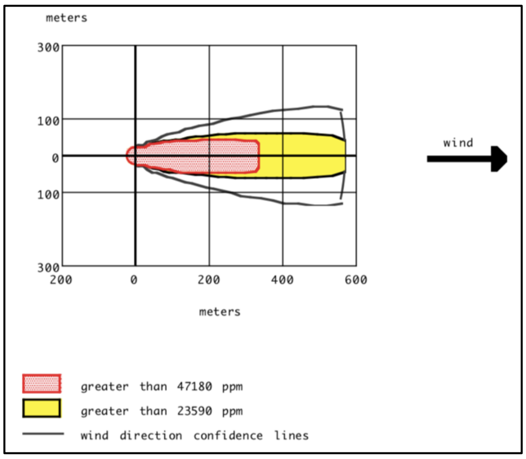

Fig. 7 Dispersion contour of ethane.

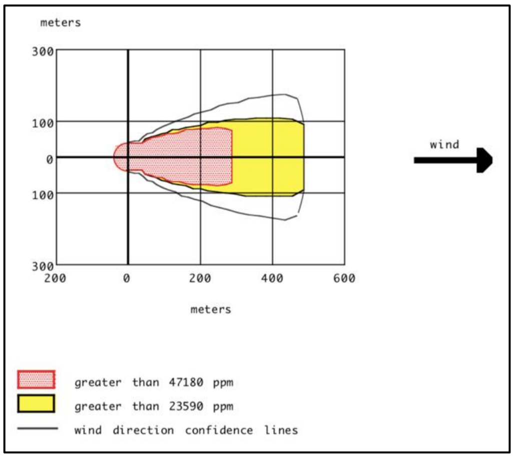

Fig. 8 Dispersion contour of propane.

Threat Modeled: Flammable Area of Vapor Cloud
Model Run: Heavy Gas
Red : less than 10 meters(10.9 yards) --- (47180 ppm)
Note: Threat zone was not drawn because effects of near-field patchiness make dispersion predictions less reliable for short distances.
Yellow: 11 meters --- (23590 ppm)
Note: Threat zone was not drawn because effects of near-field patchiness make dispersion predictions less reliable for short distances.

Fig. 9 Dispersion contour of n-Butane.

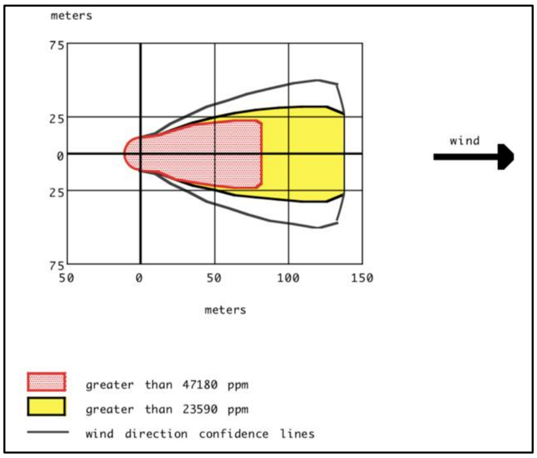

Fig. 10 Dispersion contour of n-Pentane.

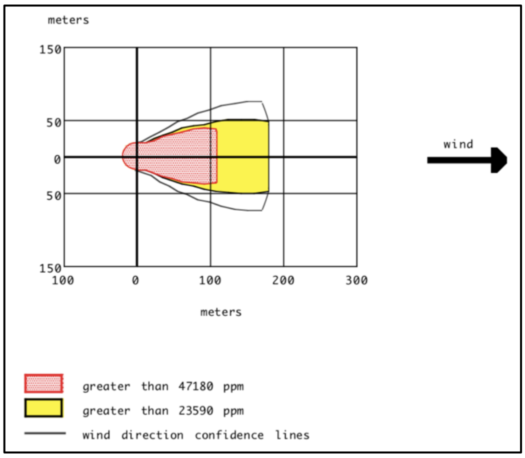

Fig. 11 Dispersion contour of n-Hexane.

Table 9 Threat zone distance with the respective components in flammable gas mixture.

Components	Downwind distance (m)	
	47180 ppm	23590 ppm
Methane	1100	2400
Carbon Dioxide	-	-
Ethane	335	573
Propane	299	508
n-Butane	Less than 10 m	11
n-Pentane	83	143
n-Hexane	110	182

Due to the flammable gas dispersion of 100% LFL (47180 ppm) 50% LFL (23590 ppm) does not reach any critical receptors for the identified vents, thus no further recommendation required as relief and didn't affect the personnel safety.

Table 10 Critical receptor affected by the dispersion of flammable gas.

Critical receptor	Impairment Assessment (Yes / No)	
	47180 ppm	23590 ppm
Manned area / escape routes	No	No
Muster area	No	No

3.3 Comparison of flammable gas dispersion modelling between PHAST and ALOHA

The results attained for the flammable gas dispersion modelling by using ALOHA are based on the 5.0/D weather condition with 5 m/s wind speed with windy day and neutral conditions. The result based on the 1.5/F weather condition cannot be attained due to the ALOHA's limitations such as very low wind speeds, very stable atmospheric conditions, wind shifts and terrain steering effects, and concentration patchiness, particularly near the source. At very low wind speeds particularly less than 1.34 m/s, the flammable gas dispersed from the vent does not mix quickly with the surrounding air resulting in the concentration of the flammable gas in the chemical cloud remain higher than the prediction of ALOHA, especially near the vent. Furthermore, very stable atmospheric conditions such as stability classes E and F where under these atmospheric conditions, the flammable gas concentration can remain high far even though from the vent. Naturally, the wind typically shifts speed and direction according to the terrain, as an example in urban areas, the wind flows around skyscrapers forming eddies. However, ALOHA ignored these effects and assumed the wind speed and direction are constant throughout the area downwind of the release of flammable gas. ALOHA also limited to the release and dispersion of pure chemicals and several solutions only resulting in any chemical reactions, particulates and chemical mixtures didn't account [22]. The wind speed was set at 1.5 m/s was considered as low wind speed, ALOHA will auto set the minimum wind speed based on the stability class, ground roughness and reference height. The dispersion contour modelled as a mixture in PHAST, however in ALOHA the dispersion contour modelled as individual component due to the limitations of ALOHA to model the flammable gas as a mixture.

Although the downwind distance value as summarised in Table 7 and Table 9 of the flammable gas obtained from PHAST and ALOHA were distinct due to the limitations of modelling using the ALOHA, however the contour of the dispersion for 100% LFL (47180 ppm) and 50% (23590 ppm) had similar form to one another based on the modelling as shown in Fig. 10 till Fig. 16.

The difference in interface for both ALOHA and PHAST resulting in several other meteorological conditions has been considered based on the required inputs by both software. Table 11 showed the additional meteorological conditions required for the flammable gas dispersion modelling using ALOHA in the perspectives of wind direction, wind roughness and cloud cover.

Table 11 Critical receptor affected by the dispersion of flammable gas.

Meteorological conditions	Descriptions
Wind direction	From Southwest Monsoon (SW)
Wind roughness	Open Water
Cloud cover	None

4 Conclusion

The release of flammable gas from the vent of an offshore platform without any assessment could leads towards unwanted risks or impact to the critical receptors which can affect any personnel within the area. The availability of various risk assessment software including PHAST and ALOHA able to become the first step in eliminating the consequences able to occur due to the flammable gas.

The impairment assessment performed based on the dispersion contour obtained through ALOHA and PHAST, no risk reduction and recommendations required as the plume disperse at the highest cloud height, thus both the manned area or escape routes and muster area weren't affected by the flammable gas released from the vent.

Although both software modelled the dispersion contour of flammable gas, however the difference in interface resulting in additional conditions mainly on the meteorological condition need to be considered when using the ALOHA. Moreover, the limitations of ALOHA in modelling a very low wind speed conditions resulting in the weather condition of 1.5/F cannot be modelled.

Declaration of Conflict of Interest

The authors declared that there is no conflict of interest with any other party on the publication of the current work.

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