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A Parametric Study to Investigate Human Injury and Fatality due to Vapor Cloud Explosion

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Abstract. The processing area of an offshore platform consists of various equipment for handling, separation and transferring of crude oil and natural gas. Consequently, the chances of an accidental release are quite high as compared to other areas. Among the major hazard posed on an offshore platform, Vapor Cloud Explosion (VCE) is the fatal one. Among the various factors that impact the resulting overpressure developed due to VCE: leak rates, wind speeds, and wind directions are the important ones. The current paper investigates the effect of these factors (leak rates, wind speeds and wind directions) on explosion strength on an offshore platform. The release, dispersion and resulting VCE are modelled by utilizing Computational Fluid Dynamics (CFD) software Flame Acceleration Simulator (FLACS). Furthermore, risk estimation for human injury/fatality (risk of eardrum rupture, head impact, and whole-body displacement) has been done considering these factors using probit models. The results showed that these factors (leak rates, wind speeds, and wind directions) have a major impact on resulting explosion strength and consequently, on the risk of human injury/fatality. Risk of head impact is quite high while risk of eardrum rupture and whole-body displacement is low. The current study can be useful in designing effective safety measures to reduce the impact of such accidents.

1 Introduction

An offshore platform, or (casually) an oil rig is a vast structure which is used to extract oil and natural gas. The purpose of the majority of an offshore platform is to extract the hydrocarbons from the ocean floor, processing and transferring or storing the hydrocarbons [1]. These hydrocarbons are highly combustible. Offshore platforms have packed congested geometry and limitation of escape routes. Towards that end, a minor mistake in the operation under such conditions is a pathway to a great disaster to occur on the platform. Any accidental hydrocarbon release can result into fire and Vapor Cloud Explosion (VCE) that could result into total collapse of an offshore platform, loss of life and environmental pollution [2].

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Numerous studies have utilized commercial CFD software FLACS for modeling the consequences involved in hydrocarbon releases i.e. dispersion and resulting VCE [3-7]. Gavelli et al. [6] modeled the LNG release, dispersion and resulting VCE using FLACS during offloading process. The study concluded that congestion has a significant effect on the resulting over-pressure. Dadaszadeh et al. [3] proposed an integrated approach for modeling of fire and VCE using FLACS. An integrated risk approach was developed considering the risk of human injury/fatality due to VCE and pool fire. Recently, Azzi et al. [7] studied the effect of selecting dispersion scenario choices on the resulting explosion risk using FLACS. The study showed how the choices by individual analysists for selection of factors i.e. leak direction, leak location and wind direction influence the results. In order to model VCE, dispersion of vapor cloud is modelled first. All these studies did not study the effect of factors like leak rates, wind speeds and directions on the resulting dispersion and VCE modelling i.e. over-pressure developed and also, the effect of these factors on risk of human injury/fatality.

The present study investigated the effect of factors i.e. leak rates, wind speeds and directions on the VCE strength using CFD software FLACS. Furthermore, risk estimation of human injury/fatality considering these factors is also done.

2 Research methodology

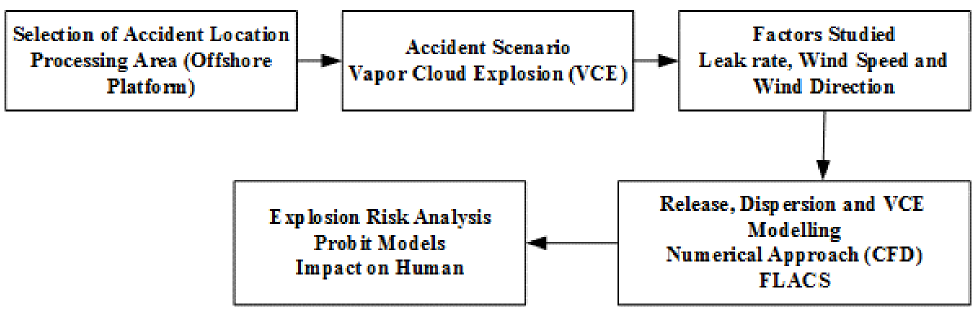

Fig. 1. Research Methodology

For the present study, leakage of propane gas is considered leading to VCE that is modelled by CFD software Flame Acceleration Simulator (FLACS) that has the capability to model discharge, dispersion and VCE of various flammable fuels with good accuracy. For the current study, FLACS was used and the resulting over-pressure due to VCE was estimated based on different factors considered as explained in next section.

Three factors have been studied, namely leak rate, wind speed, and wind direction. The wind speeds that were chosen in the simulations are 3 m/s, 4 m/s and 5 m/s that normally occurred on an offshore platform in Peninsular Malaysia. Two wind directions have been taken and the leak rates were chosen from the NORSOK standards [8]. Based on the three factors, 18 scenarios of VCE were modeled based on the combination of the levels. Table 1 enlist the number of factors and levels for each factor.

Table 1. Factors and Levels

Factor	No of Levels	Values
Wind Speed	3	3,4 and 5 m/s
Wind Direction	2	East to West, West to East
Leak Rate	3	8, 12 and 16 kg/s

The risk of explosion considering human injury/fatality is calculated using a risk-based approach. It is evident that effects of VCE on people will be a function of over-pressure produced by VCE. The risk has been calculated using the following Equation 1,

$$Risk = Severity\ of\ Injury/fatality\ (S) \times Probability\ of\ Injury/fatality\ (P) \quad (1)$$

The effects of VCE on a human can be eardrum rupture, head impact and whole-body displacement [9]. A certain hypothetical score was given to each injury/fatality based on the severity of damage in Table 2.

Table 2. Score for severity of different effects of VCE [6]

Hazard (VCE)	Score (S)
Eardrum rupture (injury)	5
Head impact (fatality)	10
Whole body displacement (fatality)	10

For calculation of probability P of injury/fatality due to VCE for various effect (eardrum rupture, head impact and whole-body displacement) following Equation 2 is used [15],

$$P = \frac{1}{2}\left[1 + erf\left(\frac{P_r - 5}{\sqrt{2}}\right)\right] \quad (2)$$

3 Result and discussion

3.1 Release, dispersion and VCE on offshore platform

Fig. 2 shows the geometry of the offshore platform. The leakage duration of propane gas was considered to be 40 s from a hole of 0.05 m^2 while total duration of dispersion simulation was 100 s. Firstly, leakage of propane must be simulated for the explosion to occur. Later, when the dispersed clouds were in the flammability range of propane i.e. 2.1 % - 9.5 %, explosion simulations were run. The core domain for simulations is 48 m × 28 m × 10 m with a grid size of 1 m for dispersion simulation and 0.5 m for explosion simulation. Around the leak location, the grid was refined to 0.063 m while at the location away from the leak source, the grid was stretched to a factor of 1.2. The grid refinement at the leak location is needed to ensure that the release flow is accurate. Sensitivity analysis was done to make the solution independent of grid size.

3.1.1 Effect of wind speeds and directions on dispersed cloud area

From the dispersion simulation, the fuel concentrations and area covered of dispersed cloud within flammable limits for different cases were observed and plotted. Fig. 3 shows dispersion profile due to 8 kg/s leak considering different wind direction (West to East & East to West) and different wind speeds of 3 m/s and 5 m/s. The results clearly show that wind speed has a major effect on the dispersed cloud area. At higher wind speeds, the area covered by the dispersed cloud is less as compared to the area covered by the cloud at lower wind speed and same trend was seen from East to West direction.

3.1.2 Effect of wind speeds and directions on VCE over-pressure

Based on dispersion results, the explosion simulations were run and the value of the maximum overpressure for each case was determined. Fig. 4 represents the overpressure

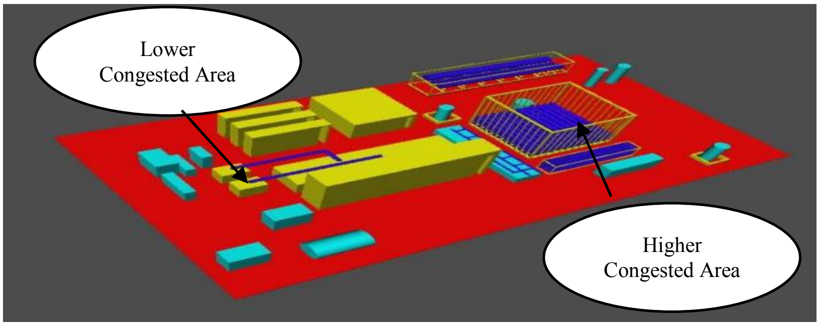

Fig. 2. Offshore platform geometry

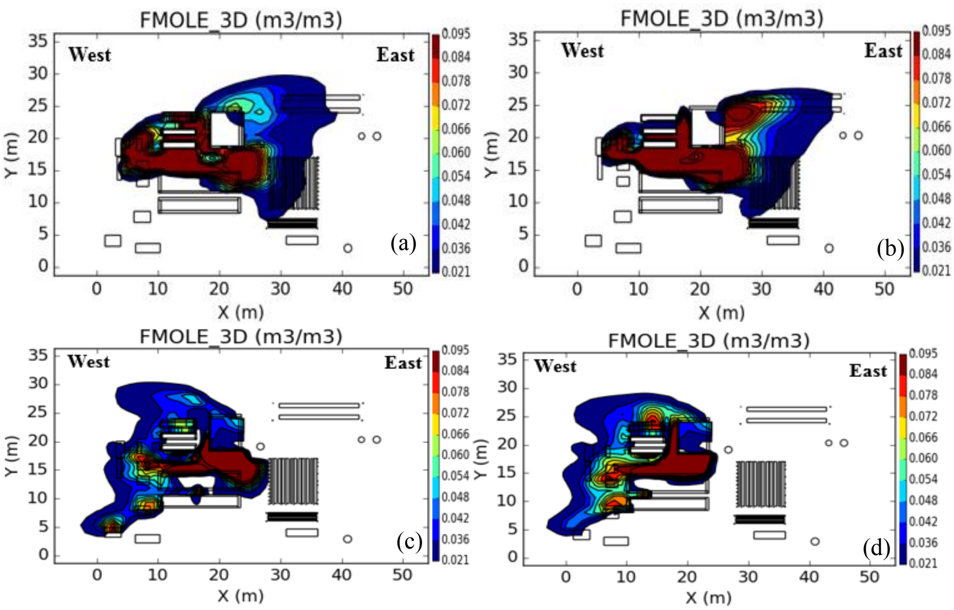

Fig 3. Dispersed cloud profile. (a) Wind speed of 3 m/s with West to East direction. (b) Wind speed of 5 m/s with from West to East direction. (c) Wind speed of 3 m/s with East to West direction. (d) Wind speed of 5 m/s with from East to West direction.

trend with increasing wind speed with different leak rates considering different wind directions. From Fig. 4 (a), the overpressure for each leak rate are decreasing as the wind speed increase. The highest leak rate also leads to the highest overpressure in the explosion simulation. The leak rate of 16 kg/s resulted into more area covered by the dispersed cloud and explosion over-pressure developed is more as compared to other low leak rates.

At lower wind speed, the dispersed cloud area was larger as compared to higher wind speed that resulted in high over-pressure at low wind speed. However, the over-pressure developed also depends upon on the location where the cloud has dispersed. The congestion and confinement vary in different places of an offshore platform. Higher congestion and confinement lead to higher over-pressure. Hence, wind direction has also a significant impact on developed over-pressure because that will push the dispersed cloud in lower or higher congested area.

For the effect of wind direction, the cases with direction from West to East developed higher overpressure compared to East to West. This is due to the dispersion of gas that covers the area of the offshore platform as shown in Fig. 5. The West to East direction pushed the dispersed cloud into more congested area as compared to East to West direction, where the dispersed cloud is pushed into relatively less congested area. As the over-pressure due to VCE also depends upon the congestion provided, low over-pressure has been observed in less congested area as shown in Fig. 4 (b).

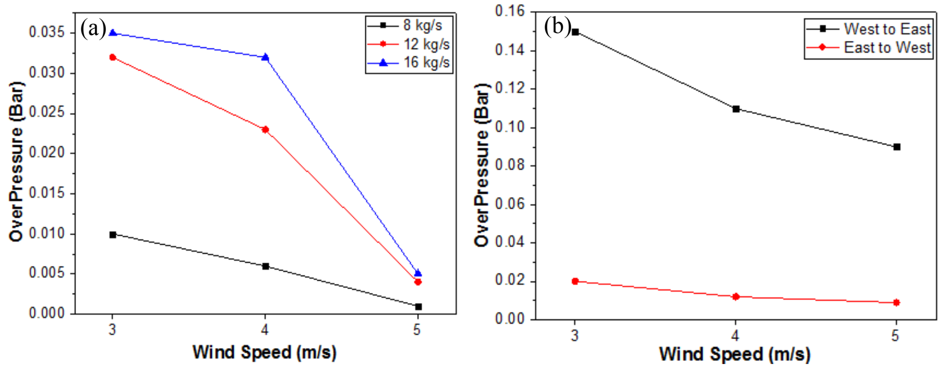

Fig 4. Variation of over-pressure. (a) At different wind speeds. (b) At different wind directions.

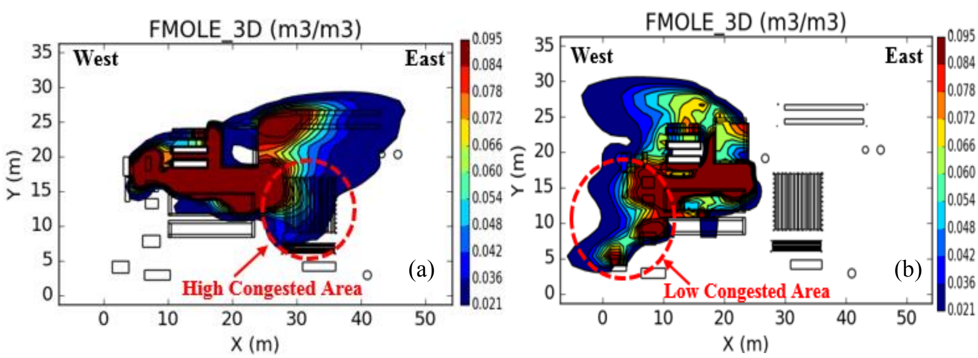

Fig. 5. Wind direction effect on dispersed cloud position considering leak rate of 12 kg/s. (a) Wind direction from West to East. (b) Wind direction from East to West.

3.2 Risk Estimation

Table 3 represents the probability and risk of different effects (eardrum rupture, head impact, and whole-body displacement) for different cases modelled. Eardrum rupture will result in to injury that has less severity and assigned a score of 5 while head impact and whole-body displacement will result in to fatality i.e. high severity and score of 10 is assigned. So, based on these values, risk value of less than 5 is considered to be low risk (slight injury), between 5-10 is moderate risk (serious injury) and 10 and above is considered to be high risk (fatality) [6]. Highest over-pressures have the highest probability of injury/fatality to occur where these cases represent the explosion scenario of wind direction from West to East with different wind speeds.

The probability and risk of head impact was the highest compared to the risk of eardrum rupture and whole-body displacement. This is due to head impact are categorized as an indirect effect of the explosion [9]. The whole-body displacement is also an indirect effect; however, whole-body displacement is having low probability as well as risk as it is more difficult to displace the whole-body compared to the head only. The probability of the eardrum rupture is for number of cases because eardrum rupture is a direct effect of the explosion and it will result into injury while other two effects will result in fatality.

Table 3. Risk of Injury/Fatality due to VCE over-pressure

Cases	Probability of Eardrum Rupture (%)	Risk	Risk Level
Case 1	69.93	3.5	Low Risk
Case 4	53.62	2.68	Low Risk
Case 7	47.80	2.39	Low Risk
Case 8	26.04	1.30	Low Risk
Case 5	23.13	1.16	Low Risk
Case 2	10.79	0.54	Low Risk
Case 15	4.90	0.24	Low Risk
Case 12	4.06	0.20	Low Risk
Case 14	3.67	0.18	Low Risk
Cases	**Probability of Head Impact (%)**	**Risk**	**Risk Level**
Case 1	100	10	High Risk
Case 4	99.94	9.99	Moderate Risk
Case 7	94.95	9.50	Moderate Risk
Cases	**Probability of Whole Body Displacement (%)**	**Risk**	**Risk Level**
Case 1	27.97	2.80	Low Risk
Case 4	2.61	2.61×10^{-1}	Low Risk
Case 7	0.82	8.20×10^{-2}	Low Risk

4 Conclusion

The study demonstrated the effect of leak rates, wind speeds and directions towards the dispersion of vapor cloud and resulting over-pressure developed due to VCE on the offshore petroleum facility and the resulting human injury/fatality. The highest overpressure was developed by the wind speed of 3 m/s and wind direction from West to East. Increasing the wind speeds to 5 m/s will reduce the explosion overpressure. Changing the wind direction from East to West will also cause lower overpressure because the dispersed cloud is pushed into the low congested area of the platform. The risk of head impact is very high for scenarios 1, 4 and 7 while risk of whole body displacement and eardrum rupture have low risk for same scenarios. Hence, safety measures need to be considered by taking the effect of these factors and to minimize the risk of human injury/fatality.

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