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NUMERICAL STUDY OF FLAMMABLE GASES DISPERSION IN OIL
PLATFORMS

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Abstract. *Activities of oil exploration and production in Onshore and Offshore structures are associated with an imminent risk of gas or oil leakage, which, encountering any kind of ignition, can cause fires and explosions, that have the potential to cause substantial financial losses and deaths. In the present work, CFD analysis was performed to analyze the leakage of natural gas from a leakage point located in the gas compression module at an offshore platform. The flow turbulence was modeled with the RANS methodology employing the two-equation $\kappa - \epsilon$ model. The transport equations of mass, momentum, energy, and turbulent quantities were numerically solved with ANSYS CFX. To verify the interaction of the clouds formed with the structures of the unit, 8 cases of gas leaks were simulated in steady state regime, in which two wind intensities were considered: 0.5 m/s representing the calm condition, and 6.5 m/s representing the highest speed ever recorded. From the simulation results, critical spots were identified. The volume of the cloud was determined for each scenario and subsequently an equivalent TNT calculation was performed to identify potential risks of the offshore structure in the event of ignition of the dispersed gaseous material.*

Keywords: Gas dispersion; CFD, CFX; Equivalent TNT

1. INTRODUCTION

The prevention of fires and explosions caused by flammable gas leaks is a matter of great concern in oil and gas exploration and production plants. The onshore and offshore units are endowed with a complex structural organization, and areas of great congestion, which allow the accumulation and recirculation of gases, which, upon finding some source of ignition, can explode and cause serious damage to the platform.

In view of the accidents with the P36 platform in 2001, in the Campos Basin and with the Piper Alpha platform in 1988, in the North Sea, which caused great financial losses and the loss of several lives (HSE, 2002), robust gas detection systems must be considered in offshore systems projects. As an alternative to provide more accurate information for risk analysis, to anticipate possible occurrences, computational fluid dynamics (CFD) has been widely used, as it has the ability to simulate various situations that would be extremely difficult and expensive to reproduce experimentally.

Through statistical data, presented by HSE (2002), it was possible to verify that gas leaks correspond on average to 55% of the leaks that occurred in offshore units, so that the gas compression system, as well as the compressors, are at the top of the list of systems and equipment that fail the most.

Strøm and Bakke (1999) used the software FLACS (FLACS-CFD, 2021) to develop a methodology for improving the detection system of a jacket-type oil platform, with a limited area up to the wellheads. Fiates (2015) performed several gas dispersion simulations using a representative geometry of an offshore oil exploration plant. Its main objective was to create a methodology for calculating the volume of the flammable gas cloud, employing the OpenFOAM CFD software (OpenFOAM, 2021). To carry out their simulations, a stationary approach was used, considering that the concentration of the dispersed gas in the environment becomes stable after a certain time.

From the literature review (Strøm and Bakke, 1999 and Fiates, 2015) a limited amount of works in this subject is available, although it is particularly important to aid in strategic measures to minimize risk situations. Therefore, to contribute with the literature, here, a numerical analysis of the dispersion of flammable gases from an offshore platform is conducted, employing the commercial software CFX, and the equivalent TNT technique to quantify the potential damage to be caused to the unit in case of cloud ignition.

2. METHODOLOGY

To analyze the dispersion of gases from the compressor of a FPSO (Floating, Production, Storage and Offloading), an adapted 3D geometry was created (Figure 1a). The compression system, as well as the compressor used in this study, are shown in Figure 1b, and Figure 1c. The focus of the present work are the first 6 modules of the platform, which were considered as critical, since the gas might disperse toward the interior of the platform, increasing the risk of accidents.

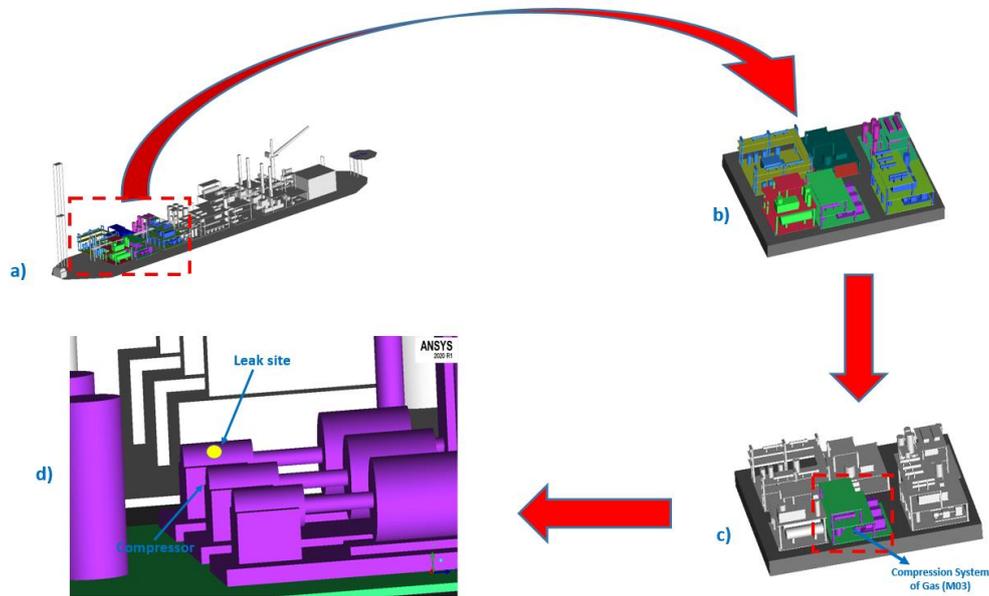


Figure 1. Simplified geometry of an FPSO-type platform, highlighting the gas compression system

A typical compressor of 150 kgf/cm^2 and $130 \text{ }^\circ\text{C}$ was defined. To simplify the problem, reducing the computing effort, a critical situation corresponding to steady state was considered. Two wind flow in the positive direction of X , represented as X^+ (Figure 2) were analyzed: 0.5 m/s and 6.5 m/s , corresponding to a calm and a strong wind condition. For each wind condition, four points of failure of the system (points of release of the gas) were studied, i.e. leakage in the north, south, east, and west side of the compressor (X positive and negative directions, X^+ , X^- , and Z positive and negative directions, Z^+ , Z^-), where the coordinate system is indicated in Figure 2.

To carry out the simulations, a typical composition of gases used in offshore systems was considered. A hole size of 10 mm was defined. Adopting the hypothesis of isentropic expansion through the orifice, the outflow velocity of the gas, as well as the flow of the leaking fluid, were determined as 340 m/s and 1.42 kg/s , respectively, according to the considerations of Birch et al. (1987) and HSE (2002). The hydrocarbon mass was determined, based on the gas volume and a gas density of 0.766 kg/m^3 .

To define the proper size of the domain (Figure 2), a test was performed employing different sizes for the environment, so that the domain size did not interfere in the results, and it was defined as twice as large as the platform geometry.

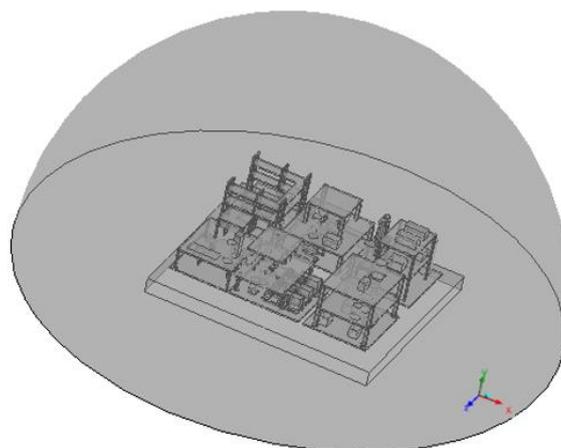


Figure 2. Domain size, with the platform inside.

2.1 Mathematical equations

To analyze the problem of natural gas dispersion over an offshore platform, it is necessary to determine the fields of velocity \bar{u} , pressure P , temperature T and molar concentration of species y_i . To model the turbulence, the RANS methodology was selected, with the $\kappa - \varepsilon$ turbulence model. The conservation equations presented below were defined considering the hypotheses of a Newtonian fluid with constant μ molecular viscosity, and constant thermophysical properties, such as thermal conductivity k , specific heat at constant pressure c_p and mass diffusion coefficient \mathcal{D} . In addition, the density was defined according to the ideal gas equation of state, $\rho = P \bar{W} / (\mathcal{R} T)$, where \bar{W} is the fluid average molar weight and \mathcal{R} is the universal gas constant.

The steady state time average conservation equations of mass and momentum are

$$\nabla \cdot (\rho \bar{u}) = 0 \quad (1)$$

$$\nabla \cdot (\rho \bar{u} \bar{u}) = \nabla \cdot [(\mu + \mu_t)(\nabla \bar{u} + \nabla^T \bar{u})] - \nabla \tilde{p} + \rho \vec{g} \quad (2)$$

where \vec{g} is the acceleration vector of gravity, μ is the molecular viscosity and μ_t is the turbulent viscosity, defined according to the κ - ε model as

$$\mu_t = C_\mu \rho \frac{\kappa^2}{\varepsilon} \quad (3)$$

where κ is the turbulent kinetic energy, ε its dissipation rate, and $C_\mu=0.09$ is an empirical constant. \tilde{p} is a modified pressure, defined as $\tilde{p} = P + 2 / 3 (\rho \kappa + \mu_t \nabla \cdot \bar{u})$. Transport equations for κ and ε , based on the standard $\kappa - \varepsilon$ model must also be solved.

The time average energy equation is

$$\nabla \cdot (\rho \bar{u} T) = \frac{\bar{u} \cdot \nabla P}{c_p} + \nabla \cdot \left[\left(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t} \right) \nabla T \right] \quad (4)$$

where the first term on the right side represents the compression work. $Pr = \mu c_p / k$ is the Prandtl number and $Pr_t = 1$ is the turbulent (empirical) Prandtl number.

The flow was considered as a mixture of two species: air and natural gas, therefore $y_{GN} + y_{air} = 1$, and only one species mass conservation equation needs to be solved. The time average natural gas mass conservation equation is

$$\nabla \cdot (\rho \bar{u} y_{GN}) = \nabla \cdot \left[\left(\frac{\mu}{Sc} + \frac{\mu_t}{Sc_t} \right) \nabla y_{GN} \right] \quad (5)$$

where $Sc = \mu / (\rho \mathcal{D})$ is the Schmidt number. $Sc_t = 1.0$ is the turbulent (empirical) Schmidt number. The subscript GN refers to natural gas.

The boundary conditions were defined as:

- **Farfield:** Region delimited by the hemisphere that surrounds the entire platform, with non perturbed conditions, where a temperature of 273 K and atmospheric pressure were prescribed, as well as the wind velocity, entering the domain at the upstream region and leaving downstream.
- **Solid surfaces:** Solid surfaces such as structures and equipment, as well as the platform floor were modeled as a non-slip wall, which means the velocity vector equals zero in all directions, with a scalable wall function (ANSYS, 2020). All solid surfaces were considered adiabatic and impermeable.
- **Gas leak source:** The source of gas leak has been set as a “source point”, with null mass flow at 253 K temperature. In his studies, Gomes (2012) states that the “source point” (source term) can be used as a boundary condition for gas entry in the computational domain, if an adequate refinement is carried out in the leakage region.

The conservation equations were discretized with an upwind scheme and solved coupled with the default algorithm of CFX.

Unstructured tetrahedral mesh type was defined in the computational domain and the number of elements and distribution were determined based on a grid test, employing four mesh distributions as indicated in Table 1.

To evaluate the mesh impact, two lines inside the gas cloud, with the origin at the compressor leak point were created, and the hydrocarbon concentration distribution along these lines for the different mesh distribution was compared (Figure 3). Analyzing the results in Figure 3, it was possible to verify that MESH 4 (with fewer elements, with a small concentration near the solid walls) generated similar results to meshes with more elements. Therefore, MESH 4 with approximately 4.000.000 elements was selected to be employed in this work.

Table 1. Mesh test setup

Case	MESH 1	MESH 2	MESH 3	MESH 4
Total number of elements	569 855	5 032 379	11 578 556	4 024 123

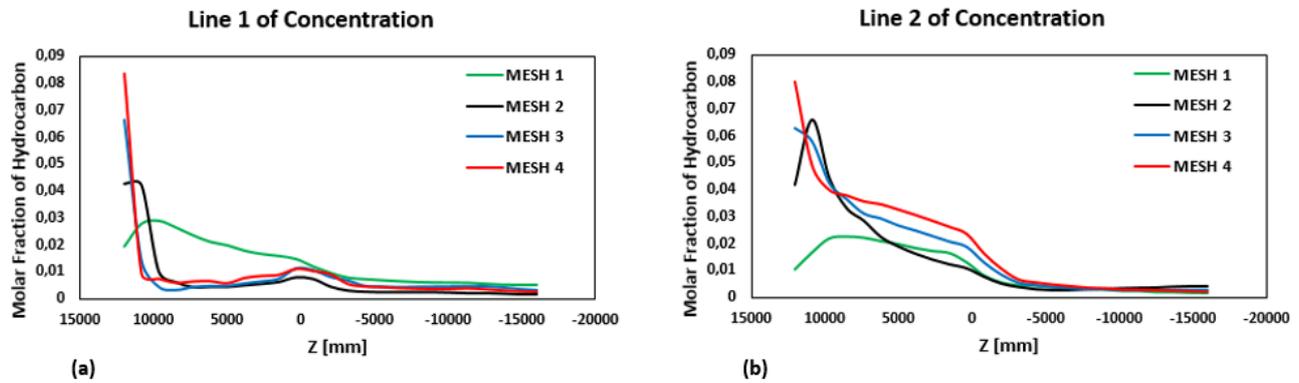


Figure 3. Hydrocarbon concentration lines at the Z coordinate. (a) Concentration line 1; (b) concentration line 2.

2.2 TNT Equivalent Model

The compound 2,4,6-Trinitrotoluene, commercially known as TNT, is a highly explosive compound that, over the years, has reached an important status in the world economy due to its extensive use. The equivalent TNT model consists of comparing the potential of the explosive mixture studied with the mass of TNT needed to produce the same effect. To perform its calculation, only the portion of the gas cloud that is between the flammability limits is considered, and it is essential to determine the efficiency of TNT related to the explosion, which is later transformed into overpressure, which was defined here as 2%. The equivalent TNT calculations were performed from the volumes of the generated clouds, calculated using the Ansys CFX calculator utility, considering the mass fraction values of the leaked gas, with a concentration of 100% for the Lower Flammability Limit (L.F.L), calculated from the proportions of each component contained in the gas mixture, according to Casal (2007).

The application of the method consists of calculating the equivalent mass of TNT (W_{TNT}), defining an efficiency in TNT (η) as a basis and applying the following equation:

$$W_{TNT} = \frac{\eta m \Delta H_c}{E_{TNT}} \quad (6)$$

where m is the mass in kg of the gas that effectively contributes to the explosion, rated between the lower and upper limits of flammability; ΔH_c is the combustion energy of the mixture of hydrocarbons contained in the cloud, given in kJ/mol, and the constant of energy released by 1 kg of TNT (E_{TNT}), which is equal to 4686 kJ/kg. With the equivalent mass in hand, it is possible to calculate the relative explosion distance (d_n), where r represents the distance to the explosive axis given in meters.

$$d_n = \frac{r}{W_{TNT}^{1/3}} \quad (7)$$

Through the calculation of the relative explosion distance, it is possible to estimate the value of the overpressure (ΔP) generated in case of ignition of the inflatable cloud (Casal (2007)).

$$\frac{\Delta P}{P_a} = \frac{1}{d_n} + \frac{4}{d_n^2} + \frac{12}{d_n^3} \quad (8)$$

where P_a represents the atmospheric pressure (101.325 kPa). In this work, values of r was set as 10 m.

Table 2 presents a relationship between the overpressure caused by the ignition of the explosive cloud and its destruction potential:

Table 2. Some damage effects produced by a shock wave (Lees, 1996).

	<i>Peak side-on overpressure</i>	
	(psi)	(kPa ^a)
Annoying noise (137 dB), if of low frequency (1–15 Hz)	0.02	
Occasional breaking of large glass windows already under strain	0.03	0.2
Loud noise (143 dB). Sonic boom glass failure	0.04	
Breakage of windows, small, under strain	0.1	0.7
Typical pressure for glass failure	0.15	1.0
'Safe distance' (probability 0.95 no serious damage beyond this value)	0.3	2.0
Missile limit		
Some damage to house ceilings; 10% window glass broken		
Limited minor structural damage	0.4	2.8
Large and small windows usually shattered; occasional damage to window frames	0.5–1.0	3.5–6.9
Minor damage to house structures	0.7	4.8
Partial demolition of houses, made uninhabitable	1.0	6.9
Corrugated asbestos shattered	1–2	6.9–13.8
Corrugated steel or aluminium panels, fastenings fail, followed by buckling		
Wood panels (standard housing), fastenings fail, panels blown in		
Steel frame of clad building slightly distorted	1.3	9.0
Partial collapse of walls and roofs of houses	2	13.8
Concrete or cinder block walls, not reinforced, shattered	2–3	13.8–20.7
Lower limit of serious structural damage	2.3	15.9
50% destruction of brickwork of house	2.5	17.3
Heavy machines (3000 lb) in industrial building suffer little damage	3	20.7
Steel frame building distorted and pulled away from foundations		
Frameless, self-framing steel panel building demolished	3–4	20.7–27.6
Rupture of oil storage tanks		
Cladding of light industrial buildings ruptured	4	27.6
Wooden utilities poles (telegraph, etc.) snapped	5	34.5
Tall hydraulic press (40 000 lb) in building slightly damaged		
Nearly complete destruction of houses	5–7	34.5–48.3
Loaded train wagons overturned	7	48.3
Brick panels, 8–12 in. thick, not reinforced, fail by shearing or flexure	7–8	48.3–55.2
Loaded train boxcars completely demolished	9	62.1
Probable total destruction of buildings	10	69.0
Heavy (7000 lb) machine tools moved and badly damaged		
Very heavy (12 000 lb) machine tools survived		
Limit of crater lip	300	2000

3. RESULTS AND DISCUSSIONS

Considering two wind speeds and four leakage direction (north, south, east, and west from the source point), Table 3 presents the volume of gas, and hydrocarbon mass, as well as the equivalent TNT mass (W_{TNT}), relative explosion distance d_n and overpressure. With these data, it is possible to classify the possible damages to be caused, in case of ignition of the gas cloud.

Table 3. Flammable gas cloud volumes and equivalent TNT calculation.

Case	Wind Speed (m/s) (\hat{X})	Leakage Direction	Gas Volume (m ³)	Hydrocarb Mass (kg)	W_{TNT}	d_n	Overpressure (kPa)
1	0.5	\hat{X}	8.68	6.65	1.50	8.73	18.74
2		\hat{Y}	10.47	8.02	1.81	8.20	20.57
3		\hat{Z}	6.93	5.31	1.20	9.41	16.79
4		\hat{Z}	6.76	5.18	1.17	9.49	16.59
5	6.5	\hat{X}	6.42	4.92	1.11	9.66	16.19
6		\hat{Y}	31.65	24.24	5.48	5.67	37.10
7		\hat{Z}	9.91	7.59	1.71	8.35	20.01
8		\hat{Z}	7.60	5.82	1.32	9.13	17.56

Figure 4 and Figure 5 show the top view of contours of natural gas concentration in Y height equal to 4 m, for the region containing 100% of the L.F.L, for the calm conditions, and for the maximum speed, 0.5 m/s and 6.5 m/s,

respectively. Analyzing the results, longer plumes are found in the +X direction for the calm wind and -X in the presence of strong wind. The plume size in the $\pm Z$ direction is clearly smaller.

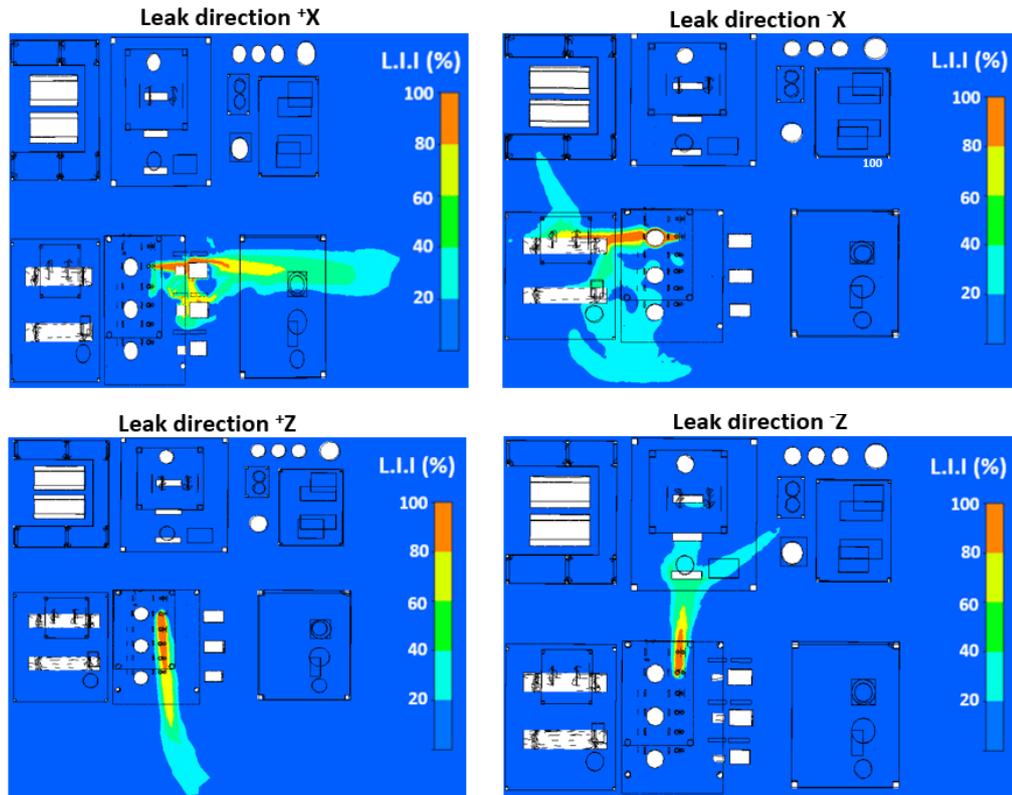


Figure 4. Cloud contour (Natural gas mass fraction iso-curves), 0.5 m/s winds – leakage in $\pm X$ and $\pm Z$ directions.

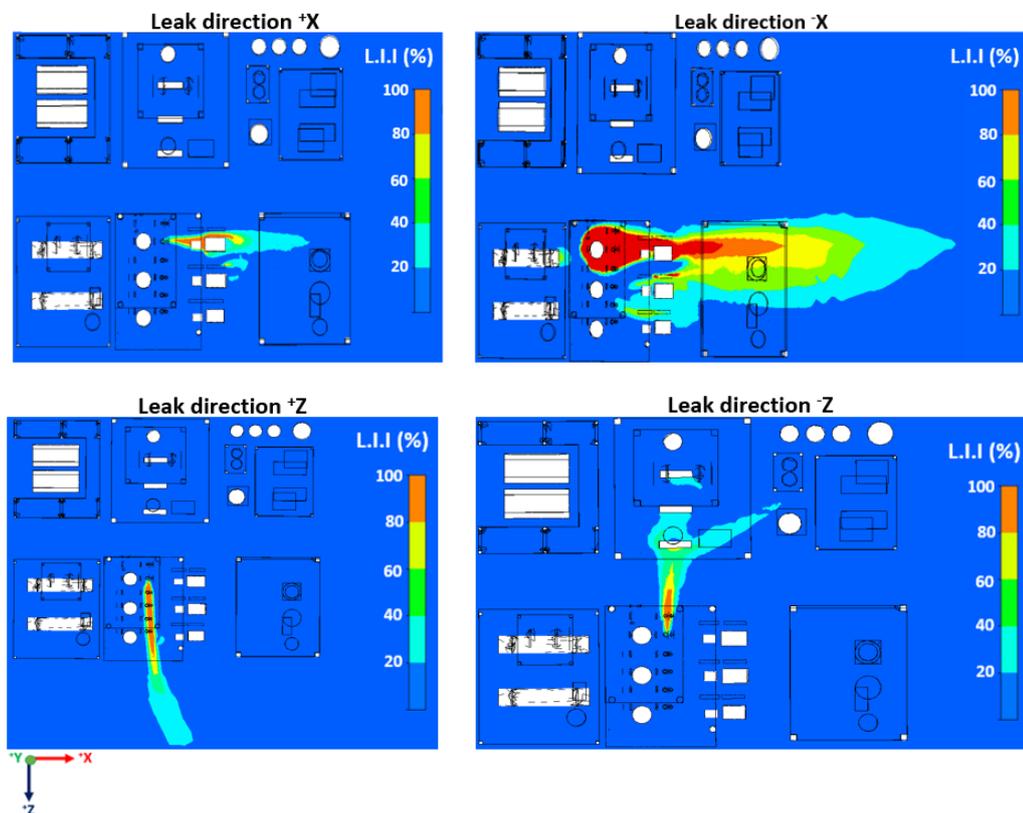


Figure 5. Cloud contour (Natural gas mass fraction iso-curves), 6.5 m/s winds – leakage in $\pm X$ and $\pm Z$ directions.

Through the data presented in Table 2, it is possible to observe that jets directed to some structure and/or equipment tend to form large accumulations of gases, increasing the possibility of fires and explosions. The flammable gas volume values and their respective calculated overrun values comprise the range from 6.42 to 31.65 m³ and 16.19 to 37.10 kPa, respectively.

The worst scenario corresponds to the strong wind with leakage in the -X direction, with high concentration of natural gas in a large region of the platform. This result agrees with the overpressure measure listed in Table 3.

4. CONCLUSIONS

The performance of the gas dispersion experiments, associated with the application of the equivalent TNT calculation technique in flammable gas clouds in offshore environments, proved to be efficient, considering that it was possible to verify the behavior of the gas clouds in various scenarios, and subsequently associate the volume of leaked gas with the potential for destruction of the unit.

Relating the overpressure results with the data in Table 2, which relates the shock waves with the possible damage caused, it is possible to observe that, in case of ignition of the gas clouds, serious damage to the offshore unit could be caused, such as broken windows and others simpler structures, considerable damage to heavy equipment, shocks to steel structures, among others.

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