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COMPARATIVE ANALYSIS OF DANGER ZONE RANGES DETERMINED FOR LNG IN THE COASTAL AREA

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Abstract: The analysis of danger zone ranges for LNG in the coastal area is an important task on account of, inter alia, the safety of human life. It is not an easy process, which is why we consider an danger situation for various weather conditions in the function of constant wind speeds and for various wind speeds in constant weather stability. Pasquill weather stability scale and Beaufort scale with regard to terrain roughness were adopted for the analysis. Both scenarios were considered in the example of Q-flex type vessels in the Świnoujście terminal for two methods of LNG release, i.e. related to a sudden explosion and slow release caused by a leak. The analysis was conducted and considered for the values in the top and bottom flammability limit. Modelling of the danger zone range was analysed with DNV PHAST software, version 7.11. In the process of comparison of the situation related to the risk of explosion in the function of various weather stabilities according to Pasquill scale and constant wind speeds, the values of 1.5 m/s and 5 m/s were adopted, corresponding to 1 and 3 wind force on the Beaufort scale. Those speeds correspond to the water conditions featuring tiny ripples and small waves, the crests of which start to break. The adopted weather stabilities analysed for wind speed equal to 1.5 m/s are A, B, D. A-type stability signifies the least stable atmospheric conditions, and D-type means neutral conditions. In turn, for the wind speed of 5 m/s B, D and F parameters in Pasquill scale were selected. Furthermore, ranges for variable wind speed values were analysed for the selected Pasquill stability.

Keywords: danger zone ranges, LNG, wind speed, Pasquill stability

INTRODUCTION

Modelling of danger zones is important both from the perspective of human safety and from the standpoint of determining the procedures of possible evacuation (Singh and Lou, 2017). The decision-making process related to evacuating population from danger areas is not easy owing to the fact that it involves the work efforts of suitable services, financial outlays and the stress of evacuated individuals; therefore it is crucial to precisely define danger zones for humans and the environment (Alava and Calle, 2017; Raj and Lemoff, 2009). What is more, the modelling process itself is not a simple one, since conducting large-scale depressurization tests is not feasible for obvious reasons. Carrying out a small-scale test in real conditions often does not translate into a real situation. This arises from differences in the concentrations of the released substances and the situation carried out on a small scale and a real one. Furthermore, there is a series of external factor to be considered, such as the diameter of depressurization, substance outflow speed, height at which the depressurization occurred, mechanical obstacles, climatic conditions, atmospheric stability, terrain roughness or the human factor (Qi et al., 2010). All those elements affect one another and one cannot assume a priori that one of the above-listed factors will always be the most important. The percentage share of each of the enumerated factors determining the range of a danger zone varies depending on the value of the remaining factors. Furthermore, if one attempts to determine the range of a danger zone arising as a result of an explosive substance release – the situation gets complicated even further (Zhao et al., 2017). The availability of fresh air and the degree of room ventilation in which depressurization is taking place need to be taken into account along with the presence of other substances that may have an impact on the flammability of the analysed substance (Pitblado et al., 2006; Zalosh, 2016).

DESCRIPTION OF INITIAL CONDITIONS

The article presents a problem of determining a danger zones for LNG in the function of wind speed and in the function of weather stability (Bernatik et al., 2011). The examined area in which depressurization occurs is a water-covered terrain. A simulation for four wind speeds was conducted. Both low wind speeds (1.5 m/s, 5 m/s), and high wind speeds corresponding to a strong storm (22.5 m/s) were taken into consideration. Those selected speeds were assigned with wind force 1 to 9 in Beaufort scale. Higher wind speeds were not taken into account, since for the conducted simulation located in Świnoujście terminal (Poland) higher speeds do not typically occur – and the adopted maximum speed practically does not occur in that region. The analysis was carried out for varied conditions, starting with a situation in which we deal with a calm water surface and low wind speed, and finishing with a wind speed characteristic for storm conditions, thereby for large waves. The analysis was concluded with wind speed of 22.5 m/s, since greater wind speeds are extremely rare in the analysed region and they have no reference in reality (Wang, et al., 2017). Wave height was selected for the wind speeds in accordance with the Beaufort scale. Mutual relations between wind speed and wave height were compiled in table 1. The weather conditions set as initial conditions in the analysis were defined in table 2. High relative air humidity is determined by the location of the source of emission posing danger. The adopted location is the LNG terminal in Świnoujście of the following geographical coordinates 53°54′34.0″N 14°17′42.3″E. A single tank of LNG-carrying vessel was assumed to be the source of the analysed substance emission. In order to ensure possibly the most accurate depiction of real conditions, Q-flex type vessel was taken into consideration, since currently it is the largest vessel type that the LNG terminal services. Vessels of that type have a maximum total capacity of 217 000 m^3. They are fitted with four to five tanks. Therefore, the capacity of a single tank from which hazardous substance is being released was adopted, equal to 44 000 m^3 for both types of the analysed instances of depressurization. It was assumed that the tank is up to 98.5% full, taking into account the possibility of thermal expansion of the gas created from LNG.

Table 1
Mutual relations between wind speed and wave height

Wind speed [m/s]	Description	Wave height [m]	Description of water conditions	Terrain roughness [m]	Beaufort scale
1.5	Light air	0.1	Ripples on water	0.0033	1
5.0	Light breeze	0.6	Large wavelets	0.0200	3
15.6	Very strong wind	4.0	Sea heaps up and white foam streaks appear	0.1333	7
22.5	Strong gale	7.0	Very high waves with dense streaks of foam	0.2333	9

Table 2
Weather conditions set in the simulation

Physical quantity	Numerical value
Relative air humidity	0.9
Air temperature at the height of 10 m	9.85ºC
Water temperature	9.85ºC
Solar radiation flux	500 W/m^2

The LNG terminal receives LNG of strictly defined parameters. Therefore, the simulation was carried out for a mixture of the following composition: 95.4% mole methane, 3.2% mole ethane and 1.4% mole nitrogen.

The composition corresponds to light LNG (Sedlaczek, 2008). The composition and percentage share of individual LNG components is defined by EN 589: 2008 standard. For such a type of mixture first the upper flammability limit (UFL), lower flammability limit (LFL) and lower flammability limit – fraction (LFL-fraction) level were determined. LFL-fraction level was determined at 50% of the value of a lower flammability limit. This is a vital step in the process of conducting the simulation, since the size of explosion risk zone is defined for a situation in which we disregard the heterogeneity of substance propagation. Computed values of lower and upper flammability limits were compiled in table 3.

Table 3
Upper and lower flammability limit level for light LNG

Explosion limit	Value [ppm]
Upper flammability limit (UFL)	165893
Lower flammability limit (LFL)	43888
LFL-fraction	21944

Two wind speed values and terrain roughness were permanently tied with one another in the simulation. Such tie is necessary in the event when the terrain is not mainland on which wind inflicts no greater changes in terrain roughness (with the exception of specific situations, such as a tornado). In the case of a water area on which we analyse propagating substance, it is necessary to tie wind speed with water conditions. It is common knowledge that each wind speed change causes an instant water reaction in the form of foam emerging and wave height changing, which translates into a change in the terrain roughness (Luketa-Hanlin, 2006). Two depressurization scenarios were considered: rapid depressurization of ‘Catastrophic rupture’ type and an LNG leak through an opening of an 80 mm diameter.

RESULTS AND DISCUSSION

In the situations considered for the scenario of ‘Catastrophic rupture’, types A, B and D of Pasquall stabilities were taken into account. The choice of these stabilities is determined by wind speeds. For wind speed lower than 2 m/s, A, A/B, B type stability is chosen in accordance with Pasquall scale for daytime and D type stability for night-time conditions. In line with Table XX, wind speed of 1.5 m/s corresponds to wind force 1 in Beaufort scale, which is equivalent to the presence of ripples on water surface at the height of 10 cm, thus the water surface can be deemed to be relatively calm. The obtained values were presented in table 4.

Table 4
Ranges of danger zones for wind speed of 1.5 m/s and 'Catastrophic rupture' scenario for selected Pasquill stabilities and LPG concentrations

Concentration	Range for the set Pasquill stability [m]		
	A	**B**	**D**
UFL	1617	1657	1671
LFL	2263	2392	2391
LFL- fraction	2529	2687	2916

It can be easily seen from the values in the table that although ranges are increasing for high concentrations corresponding to the upper flammability level, yet the difference is so small, that it can be treated as negligible and assumed to be constant. It is only in the case of lower concentrations corresponding to the lower flammability level (LFL) and LFL-fraction when it becomes evident that Pasquill stability increase entails an expansion of danger zone range. This is determined by a decrease of all possible turbulences that effectively minimalize the danger zone range. The greater the possibility of energy exchange between the propagating substance and the environment, the smaller the range of the examined substance. In the 'Leak' scenario, for small concentrations or LFL-fraction level, the situation is similar (table 5), i.e. the ranges are expanding together with a rise of stability. For high concentrations the ranges are similar for each Pasquill stability. Anomalies are observed for the LFL level, where the ranges are increasing for A and B stabilities, whereas the range shrinks in the case of D-type stability. This is due to the fact that the speed of LNG leaking is relatively low, which affects a relatively low kinetic energy of the released substance. Following that, LNG quickly loses its energy and it is then carried only by wind, taking over its energy, and because the described stability refers to night-time, one needs to further account for the fact that there is no additional energy coming from solar radiation. This parameter appears to play a significant role in the event of depressurization in which liquid flow speed is relatively low. Wind speed of 5 m/s corresponds to sea conditions defined as mild wavelets of 0.6 m height accompanied by a gentle breeze. Such conditions are described as 3 in the Beaufort scale. For a wind speed so chosen, Pasquill stability scale equal to B, D and F was adapted. B stability scale corresponds to high solar radiation greater than 700 W/m^2, D-type stability means that solar radiation during daytime does not exceed 350 W/m^2, F-type stability is typically dedicated to lower wind speeds, but in this case it was selected on account of it offering the possibility of comparing night-time with daytime conditions. For the wind speed of 5 m/s the situation is similar to the previously discussed lower speed. The above-mentioned tendencies are much more distinct, i.e. for the 'Catastrophic rupture' scenario along with an increase of stability the size of explosion risk areas grow as well, and the lower the concentration of the analysed substance, the higher the range of such a zone. The difference in the ranges obtained for LFL-fraction level for extreme stabilities adopted for that wind speed is very significant – it reaches six times the value of the initial radius (table 6).

Table 5
Danger zone ranges for the speed of 1.5 m/s and a 'Leak' scenario for selected Pasquill stabilities and LPG concentrations

Concentration	Range for a set Pasquill stability [m]		
	A	**B**	**D**
UFL	177	175	168
LFL	396	440	300
LFL- fraction	487	567	567

Table 6
Danger zone ranges for wind speed of 5 m/s in the 'Catastrophic rupture' scenario for selected Pasquill stabilities

Concentration	Range for a set Pasquill stability [m]		
	B	D	F
UFL	1585	1733	1757
LFL	2549	2710	8957
LFL- fraction	4330	7287	27430

The situation for the same speed value is the same in the event of 'Leak' scenario. The obtained data were compiled in table 7. For the scenario in which a violent, sudden depressurization does not occur, one can distinctly observe a trend involving the expansion of danger zone size along with an increase of stability. The phenomenon is once again very clearly evident for low concentrations (LFL-fraction) and nearly imperceptible for high concentrations (UFL). In that scenario, for LFL-fraction level the increase of the range is not as spectacular as for 'Catastrophic rupture' type of a scenario, yet it is still highly noticeable, since the increase in range is over threefold for the set extreme stabilities. The above analysis brings a question to mind as to how the danger zone range changes owing to LNG release if we maintain constant Pasquill stability and if we change wind speed. Pasquill stability of D type was chosen for the analysis. For this type of stability the lowest wind speed that ought to be considered is 3 m/s for night-time conditions, whereas the upper limit is not set. After completing the calculations for wind speeds of 5 m/s, 15.6 m/s and 22.5 m/s, the calculations for wind speed of 1.5 m/s were added. The calculated data for both scenarios were compiled in table 8 and table 9.

Table 7
Danger zone ranges for wind speed of 5 m/s in the 'Leak' scenario for selected Pasquill stabilities

Concentration	Range for a set Pasquill stability [m]		
	B	D	F
UFL	99	108	100
LFL	183	267	443
LFL- fraction	254	428	939

Table 8
Danger zone ranges for D-type stability in 'Catastrophic rupture' scenario

Concentration	Range for given wind speed [m]			
	1.5 m/s	5.0 m/s	15.6 m/s	22.5 m/s
UFL	1671	1733	1076	1272
LFL	2391	2710	3892	3994
LFL-fraction	2916	7287	8299	5584

Table 9
Danger zone ranges for D-type stability in 'Leak' scenario

Concentration	Range for given wind speed [m]			
	1.5 m/s	5.0 m/s	15.6 m/s	22.5 m/s
UFL	168	108	67	56
LFL	299	267	151	137
LFL-fraction	566	428	229	198

In the event of a violent explosion, the danger zone ranges are initially growing along with wind speed, however as wind speed grows they start to decrease dramatically. The phenomenon may be attributed to the influence of terrain roughness, since for each of the analysed wind speeds the terrain roughness coefficient changes. The fact that deserved a notice is that such a high share of terrain roughness is not constant. With very high wind speeds it once again does not play a substantial part, similarly as in the case of low speeds. The phenomenon is very district in the event of high concentrations of UFL levels. For ‘Leak’ scenario the changes of those ranges are very significant, i.e. along with wind speed increase the danger zone range is shrinking. Wind speed growth is accompanied by the roughness terrain increase assigned to it in the simulation. In light of the obtained results it means that when constant stability value is maintained, terrain roughness coefficient gains significance.

CONCLUSIONS

In all of the examined situations the ranges change radically for 'Catastrophic rupture' scenario, whereas in the event of ‘Leak’ scenario similar correlations occur, yet they are not as marked. Hence, a conclusion arises that the manner of the substance release is one of the major parameters affecting the range. In the event when substance is not released rapidly, the change in the terrain roughness coefficient entails highly foreseeable changes, i.e. along with the rise in the terrain roughness coefficient, danger zone ranges decrease despite the fact that wind speed goes up. The terrain, which in this case is water, can effectively take over the kinetic energy of the released substance, diminishing the danger zone irrespectively of the substance concentration, since energy is being released gradually over time. The analysis of ranges with the assumed constant wind speeds in the function of Pasquill stability demonstrates that along with the increase of stability, the danger zone range expands. This is determined by the fact that in the case of low Pasquill stability, turbulences occur, thanks to which the range zone diminishes. This is owed to a quicker exchange of energy between a propagating wave and the environment, which translates into the shrinkage of the danger zone. The phenomenon becomes more evident the greater the speed of the accompanying wind. For low wind speeds, solar radiation affects the ranges of danger zones, but along with increase of the released substance speed and wind speed, the share of that factor greatly loses its significance.

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