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Impact of LNG Vapor Dispersion on Evacuation Routes inside LNG Terminals

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The liquid natural gas (LNG) industry has been growing rapidly in recent decades. A lot of LNG terminals have been built, or are in the planning stage. While determining or shaping safety analyses related to LNG terminals, consequence modeling is typically used to estimate the distances or the potential range of an LNG vapor dispersion. Through such analyses, areas potentially affected by flammable vapors are calculated. The evaporated natural gas dispersion from the pool formed by spilled LNG can be calculated by using computational fluid dynamics (CFD) modeling, in which an extensive number of simulations and analyses are estimated and presented. Evacuation of people from the LNG terminal to safe areas using safe routes is of great importance. The aim of this paper is to present the significance of conducting simulations with the objective of determining the length of the dispersed natural gas cloud from spilled LNG on a water surface, as well as the subsequent spatial endangerment of the existing evacuation routes for a specific LNG terminal.

Keywords: liquid natural gas, computational fluid dynamics, fire dynamics simulator, dispersion, evacuation

Highlights

- *The paper presents the impact of liquid natural gas (LNG) vapor dispersion on evacuation routes in a situation when there is spillage of large quantities of LNG from a moored LNG tanker.*
- *Fire dynamic simulator (FDS) is capable of modeling LNG vapor dispersion over unobstructed and obstructed flow fields, including sloped terrain.*
- *Important factors that influence or impact the evacuation simulation of individuals are their location, distance from the source of the accident, as well as their traveling speed during the evacuation.*
- *According to emergency action plans of LNG terminals, at least two exit routes must be available in a workplace to permit prompt evacuation of employees and other occupants during an emergency.*
- *The benefits derived from creating and conducting such simulations, databases and analyses for LNG leakage accidents is utilized for new evacuation models as well as LNG terminals (extant or planned), that need to decrease individual and societal risk.*

0 INTRODUCTION

Over 1100 energy related accidents have been recorded up to 2017. These accidents have caused the loss of 210,000 human lives [1]. This includes accidents that occurred in the sector of liquid natural gas (LNG) and have caused the loss of more than 220 human lives. An accident within an LNG terminal is a highly dangerous occurrence that requires an assessment of risk as well as on-time evacuation of the risk to the public. In compliance with the NFPA 59A standard [2], there is a requirement of at least two entrances that must be available in a single protective unit and such entrances must be positioned strategically to reduce the evacuation time and/or distance when an accident happens. Cote [3], as a factor that contributes to injury, lists escape quandaries, such as choosing the best exit route. The evacuation routes should be designed and publicized in such a way as to help the personnel reach safer areas within the accident zone and should also incorporate the possibility of panic among individuals during the accident and evacuation period. When placed in a high risk emergency situation, a person who does not have at his disposal all the relevant data that depicts the actual emergency situation and the accident itself will have difficulties making the right choice during evacuation. Without the required information, the evacuation becomes even more complex, increasing the chances of selecting a more dangerous evacuation route, exposing the person to an even greater risk and potential fatality.

Moilleau and Champassith [4] have shown that FDS based on CFD modelling of the dispersion of natural gas into the surrounding environment can estimate the potential behavior of the evaporated natural gas from the LNG pool. The CFD codes have the capability to define flow physics, taking into consideration complex geometry and its effects on vapour dispersion [5]. In situations where the safety analyses indicate that the well-being of the general public is endangered, by applying CFD models we can improve the analysis of site-specific hazards [6]. The paper [7] elaborates case studies which indicate the wind effect on LNG vapour dispersion - i.e., the cloud form, height, and maximum downwind distance. A team of researchers [8] conducted CFD simulations

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for LNG flammable vapour dispersion and LNG pool fire radiation, in order to determine the space that is beyond reach - i.e., not endangered - while taking into consideration the time related expansion as well as the spatial expansion of the accident. The spread of fire between tall obstructions like buildings or LNG storage tanks, can also be analysed and simulated by using FDS regarding the safe separation distance [9].

Vanem et al. [10] have thoroughly analyzed and studied the occurrence of LNG tanker accidents and successfully shaped the risk models to incorporate grades of evacuation, ranging from safe to dangerous. From a nautical operation view, it is important to analyze and identify the potential risk to the LNG carriers as a result of increased LNG activities [11]. Tanabe and Miyake [12] have studied the factors of the risk reduction concept, analyzing the design concept of emergency systems for LNG plants.

In this paper we aim to present the impact of LNG vapor dispersion in a situation of instantaneous spillage of extremely large quantities of LNG from a docked LNG tanker. The analysis focused on the length of the dispersion with a concentration of methane between 5 % and 15 % (low flammable limit), as well as on the impact on the existing evacuation routes of the dispersed gas.

1 METHODS

This paper illustrates experimental and numerical methods with the objective of analysing the impact of the LNG vapour dispersion on the evacuation routes located in the inner part of an LNG terminal. The potential consequences from an LNG tanker spillage accident are defined in compliance with various studies [6]. The obtained results were used to define and set up the simulations.

The parameters which describe the evacuation routes and the time during evacuation are taken from several international legislations; e.g., [13] and [14]. The numerical calculation for the dispersion of the natural gas from leaked LNG on a water surface was carried out using computational fluid dynamics software FDS, a widely-used CFD code. The results from the carried-out simulations in FDS were used to determine the area of the dispersed gas with flammable concentration in the air as well as the impact on the evacuation routes depending on the time elapsed after the occurrence of the accident. Fig. 1 shows the concept for development of an evacuation model that will produce the shortest and safest evacuation route.

The methodology flowchart (Fig. 2.) briefly describes the process of the evacuation model concept. The process begins with the analysis of the evacuation routes and determination of the position of the occupant in the 3D model of the LNG terminal. The data base created thru CFD-FDS shows the length of dispersed gas per *x*-axis, influenced by wind speed and direction and is linked with the time elapsed after the occurrence of the accident.

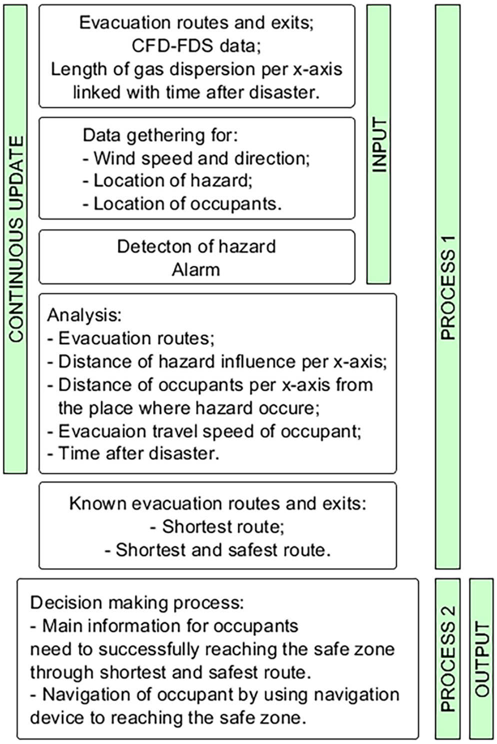

Fig. 1. *Concept for development of an evacuation model for LNG terminal*

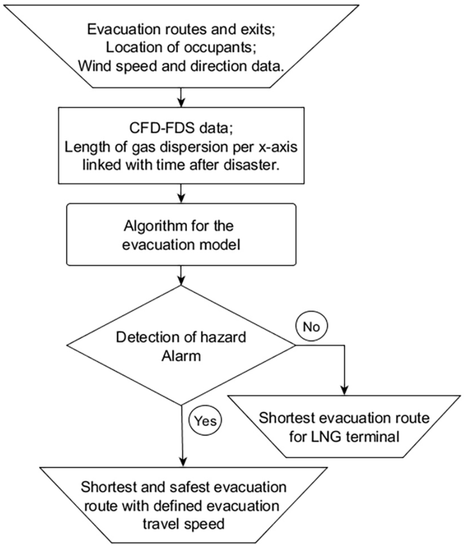

Fig. 2. *Flowchart of the methodology of the evacuation model concept*

The next step is the use of an algorithm that will solve the problem for determining the shortest and safest evacuation route.

Usually, Dijkstra's algorithm solves the shortest path route problem from a single source S to all other nodes in a graph with non-negative edge weights **[15]**. But in this case, we will also have to solve the shortest and safest path evacuation rout problem, and that means that Dijkstra's algorithm must be modified and adapted for the needs of the evacuation model. In the final step, the system selects an algorithm that will yield the final output of the solution dependent on whether the alarm was set off. In our example, the modification of Dijkstra's algorithm must follow the definitions described in Section 2.

2 MODELLING PROCESS

An extensive number of analyses are estimated and graphically presented by using the CFD-FDS program. In addition, the impact of the LNG leak accident can be analysed and linked, depending on the time passed after the accident. The outcome of such studies is a time-related and spatial presentation of the dispersion of the LNG evaporated in the air, including the concentration of the evaporated LNG. The thermal radiation is also calculated with the objective of obtaining a clearer picture of the potential hazards at hand. Zones considered to be a potential source of an LNG leakage accident are identified beforehand. Such identification calculates the highest quantity of LNG that could leak during an accident. Within each zone or zone cell, the potential hazard from the accident is specifically and separately analysed (dimensions of the crack from where the leakage occurs and level of danger from the accident, volume of LNG spilled, the affected zone where the LNG is spilled and other important factors). On the basis of the previous information and parameters, the Quantitative Risk Assessment (QRA) can be carried out with a more precise output. There is always a potential of complete LNG spillage from all exposed LNG tanks. For the purpose of making rational and conservative calculations of the dimensions of the LNG accident, one should assume that the LNG tanks have been emptied instantaneously. In this example, the analysis will be based on an accident occurring during a mooring of an LNG tanker in a period of off-loading, and relate to the uncontrollable emergency that may happen within the terminal. It should be added that in case of such an emergency, the terminal operations personnel are not in a position to prevent harm to the staff or the equipment by undertaking swift actions such as shutting valves, dismantling of equipment or starting the emergency shutdown system.

The uncontrollable emergency includes events and occurrences which might have the potential to expose staff, equipment or entire installations to natural gas in a liquid, cold vapor, or gaseous state which has a high probability of leading to fire, explosion or even the spreading to the areas outside the expected danger zone. One should not exclude terrorist attacks under any scenario, considering the fact that such events are estimated to cause an extremely negative effect. The calculations indicate that under a terrorist attack, the maximal crack in the tanker could reach 1500 mm **[16]**, thus creating a pool with a diameter reaching up to 400 m **[6]** and **[17]** to **[19]**. Crucial factors are the speed and direction of the wind.

In addition, the atmospheric class plays a significant role when calculating the length, speed, direction and the time frame of the dispersion of the evaporated natural gas. The calculations should never leave out the flammable concentration and the potential of the mixture of natural gas and air. If fire occurs, the quantity of thermal radiation into the surrounding environment can also be calculated, enabling presentation of this effect in a spatial and temporal frame **[20]** and **[21]**. The indicated example or simulation is carried out by applying a 3D LNG model. In addition, the simulation of the evaporation of natural gas from the LNG pool is carried out on a water surface of 40,000 m^2 (200 m × 200 m). The model being presented has dimensions of 3000 m per x axis, 2000 m per y axis and 200 m per z axis, see Fig. 3.

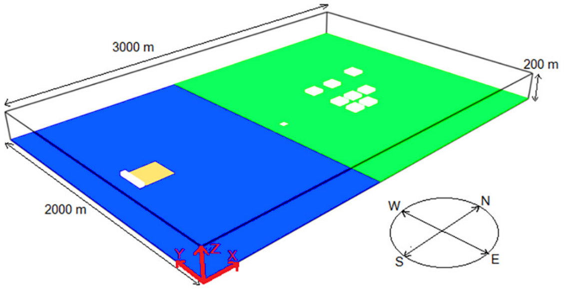

Fig. 3. *CFD-FDS model of sampled LNG terminal*

The scenarios differ from each other according to the speed of the atmospheric wind and the wind direction.

The simulation of the dispersion of methane from the LNG pool is calculated with the use of the FDS program. The following wind directions have been analysed: N, E, W, NE and NW. The remaining directions have been left out in this case because they do not endanger the terminal under the given example. Having the calculated data from the analyses at one's disposal enables the process of estimating the magnitude of the danger for the people at the different parts of the terminal, with special emphasis on the parts of the terminal where the road infrastructure cuts through, defining the FDS slices files on them.

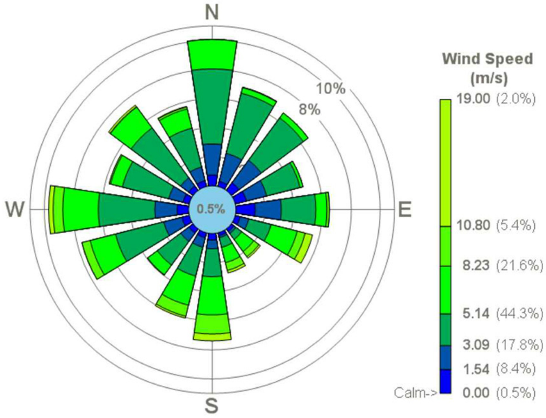

Fig. 4. *Wind rose for the sampled LNG terminal*

2.1 Initial Conditions

For the wind speeds (*W*) of the stated wind directions, the simulations apply 1.5 m/s, 3.1 m/s, 5.1 m/s and 8.2 m/s. The wind speeds are taken from the wind rose shown in Fig. 4. The initial temperature of the solid material is set to the ambient temperature of 20 °C. Additional hindrances which might have a potential effect on the gas dispersion are also taken into consideration [22]. The wind speed assumes a potential velocity distribution in the vertical direction (Fig. 6.) that satisfies the following equation:

$$v = v_0 \left(\frac{z}{10} \right)^{0.15}; \quad z = 0, \ldots, 200 \text{ m}. \qquad (1)$$

As presented in McGrattan [23] the state relations in the combustion model are calculated for a reaction of C_2H_4 (methane) and oxygen, where additional release of smoke particulates is added into reaction products to consider impurities in a LNG.

The atmospheric temperature profile is defined. The temperature gradient is 0.0025 °C/m and decreases with height.

The initial thermal radiation intensities depend on initial temperatures in the domain, radiation specter of black walls and on absorption coefficients.

2.2 Boundary Conditions

Domain borders are defined as open, only initial wind velocity profile is defined. Open boundary conditions represent energy and mass sink. A thermal radiation model assumes the boundary of the domain as black objects. Using such an assumption the environment will not radiate energy into the domain.

Obstacles located inside the domain have some effect on the simulation results, particularly on soot concentrations observed near this object. However, the objects have no thermal, particularly radiative contribution because they are chosen as inert.

2.3 Evacuation

The process of evacuation is an event which increases the safety distance between the population and an accident, but it is also a reaction to releases of toxic chemicals. The improvements to the process of warning, on-time response, planned actions for evacuation as well as accident management are becoming more and more frequent, better structured and focused towards the general safety. The last 10 to 15 years clearly indicate that safety has become a higher priority than in the past [24]. Today, the focus is on the quality of information and its availability, the delivery of such information to a target group and the comprehensiveness of accident warnings. Modern technology is supporting today's warning systems through mobile phones, the internet, GPS devices, etc. In case of an accident, a person located in an LNG terminal is alerted of the accident by alarm systems, yet is assumed not to be resourceful enough to choose the best evacuation route to a safe location. The probability of risk and consequently various dangerous circumstances under a selected evacuation route could lead to a fatality. If the scale or the magnitude of the accident is extensive, there is great possibility that any person can make a mistake while choosing which route to take to reach safer grounds. Therefore, evacuations should be well designed and executed on time, but more importantly should be based on actual information and pre-designed safety routes. This is the only method for decreasing risk and potential human harm in case of an accident.

2.4 Evacuation Route

The potential accidents in an LNG terminal may result in extensive endangerment within the inner space of the terminal as well as its near surrounding environment. Evacuation is an integral part in almost all safety plans. According to emergency action plans of LNG terminals, there must be at least two exit routes available within a workplace to enable adequate conditions for evacuation of employees and other occupants in case of an emergency. The exit routes are predetermined, located as far away as possible from each other to avoid situations where the exits routes may be closed by the accident. With the objective of describing the impact of the dispersed gas on the evacuation routes, within our example of an LNG terminal, we have defined four evacuation routes which lead to three exits (Fig. 5.) from the LNG terminal towards the outside:

- Evacuation route 1 leads to exit 1 and has a length of 2900 meters;
- Evacuation route 2 leads to exit 1 and has a length of 2900 meters;
- Evacuation route 3 leads to exit 2 and has a length of 2500 meters;
- Evacuation route 4 leads to exit 3 and has a length of 2100 meters.

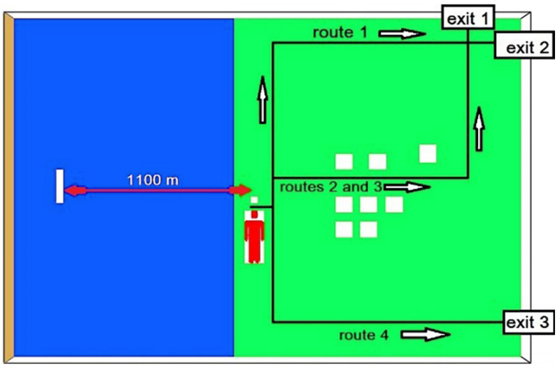

Fig. 5. *Evacuation routes and exits*

For each evacuation route a slide file has been defined in FDS, with the objective to more accurately analyse the parameters which describe the impact of the accident, depending on the elapsed time after the occurrence of the accident (Fig. 6.).

2.5 Evacuation Time and Individual Distance from the Risk Source

The evacuation time T_{evac} needed to reach a safe distance from the accident has been divided into four main times, Eq. (2). This categorization has been included in several international legislations; e.g., [13] and [14]:

$$T_{evac} = T_{det} + T_{warn} + T_{pre} + T_{trav}\,, \qquad (2)$$

where T_{det}, is detection time, T_{warn} alarm time, T_{pre} pre-evacuation or pre-movement time, and T_{trav} travel time.

Important factors that influence or impact the evacuation simulation of an individual are location, distance from the source of the accident as well as traveling speed during the evacuation. During the simulations, the example that is analyzed refers to an individual located at a distance of 1100 meters from the place of the accident, while the traveling speeds during the evacuation are 1 m/s, 2 m/s and 3 m/s.

The time parameter when the evacuations starts is the time elapsed which includes two behavioral elements for each individual - recognition time and response time. Recognition consists of the period after an alarm is evident, but before occupants begin to respond. Response time consists of the period after occupants recognize the alarm cues and begin to respond to them, but before starting the travel phase. This period includes the time needed for the individual to undertake all necessary activities listed in the ERP (emergency respond plan) for the adequate working position, in order to exclude additional expansion of the scope of impact of the accident.

In the process of evacuation, the distance of the individual from the source of the accident is presented by a distance on the x-axis. This means that in case of movement through the evacuation routes on the y-axis, the distance of the individual from the source of the accident will not change.

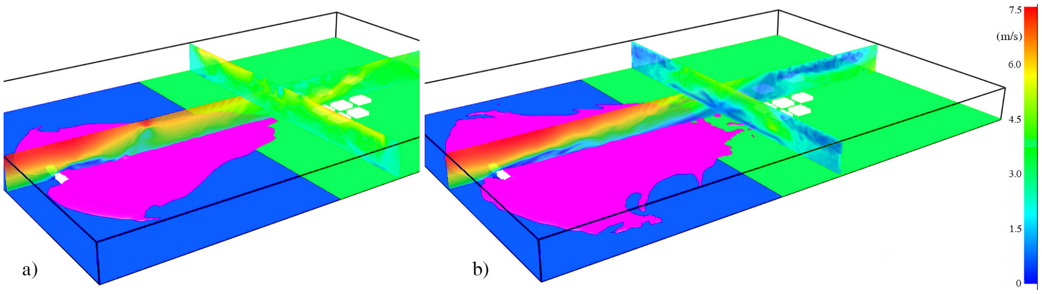

Fig. 6. *Velocity distribution in the vertical direction a) after 600 seconds, b) after 1200 seconds*

3 RESULTS AND DISCUSSION

After conducting the simulations, a database was produced that contributed to an analysis of the dimensions of the impact of the accident as well as for the individual from the source of the accident during the evacuation process. The following figures show the length of the dispersion on the x-axis with a concentration of methane in the air between 5 % and 15 % representing a flammability limit, for all those scenarios, depending on the time of the leaked LNG from the moored tanker (influenced area) (Fig. 7).

The graphs (Fig. 8) show the distance of the individual from the sources of the accident on the *x*-axis, depending on the elapsed time from the occurrence of the accident, according to which route the individual takes under the road network of the LNG terminal, as well as the distance of the dispersed natural gas from an LNG pool in a situation when the wind speed of 3.1 m/s (taken as an example for presenting the influence of the accident on the evacuation routes). The evacuation travel is projected by reaching one of the possible exits of the LNG terminal (exit 1, exit 2 and exit 3).

The graphs indicate when the individual who is in the process of evacuating will be caught by or not caught by the dispersed gas, in a situation when the individual is traveling according to the previously defined evacuation routes, heading towards the three possible exits, at different speeds. Under the previously defined example, the conclusion indicates that in a situation when the individual travels with an evacuation speed of 1 m/s, the individual would be caught by the impact of the accident regardless of which evacuation route he is traveling, heading towards one of the possible terminal exits. If the individual travels with an evacuation speed of 2 m/s under evacuation route 2 through exit 1 and under evacuation route 3 through exit 2, the individual is extremely close to the impact of the accident, with a strong possibility of being caught up in the accident.

The remaining evacuation routes are not safe considering that the impact of the accident jeopardizes the individual if either one of them is chosen. If the evacuation speed of the individual is 3 m/s, the evacuation of the individual is safe only taking evacuation route 2 through exit 1 and evacuation route 3 through exit 2, considering that the individual is always at a safe distance from the impact of the accident. Evacuation via route 3 through exit 2 is the safest option, because the individual will be evacuated in the shortest amount of time, reaching a safe distance from the accident and traveling under the safest

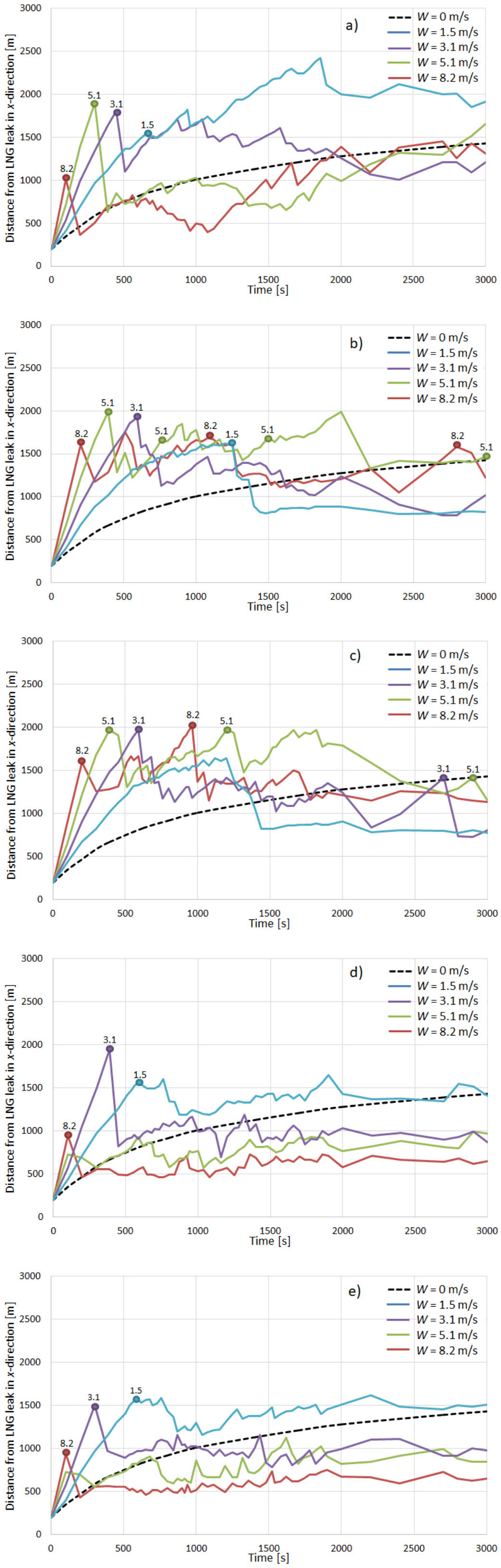

Fig. 7. *Influenced area from LNG vapor dispersion at different wind speeds and directions: a) N, b) E, c) W, d) NE, e) NW*

possible route. The results (Table 1) obtained from the performed simulations determined the number of safe evacuation routes as well as the probability of choosing an unsafe evacuation route (P_{unr}). In our example, the probability of choosing an unsafe route has a value of 0.57, in a situation where the LNG terminal has not implemented a technologically advanced evacuation model (Table 2). In a situation where a technologically advanced evacuation model is implemented in the LNG terminal, through its use it was found that the maximum value for probability of choosing an unsafe route is 0.25. These data affect the frequency of fatality (F_oF_i) shown in Eq. 3., which is crucial in calculation of Individual risk and Societal risk, as well as the number of fatalities in the event of a disaster.

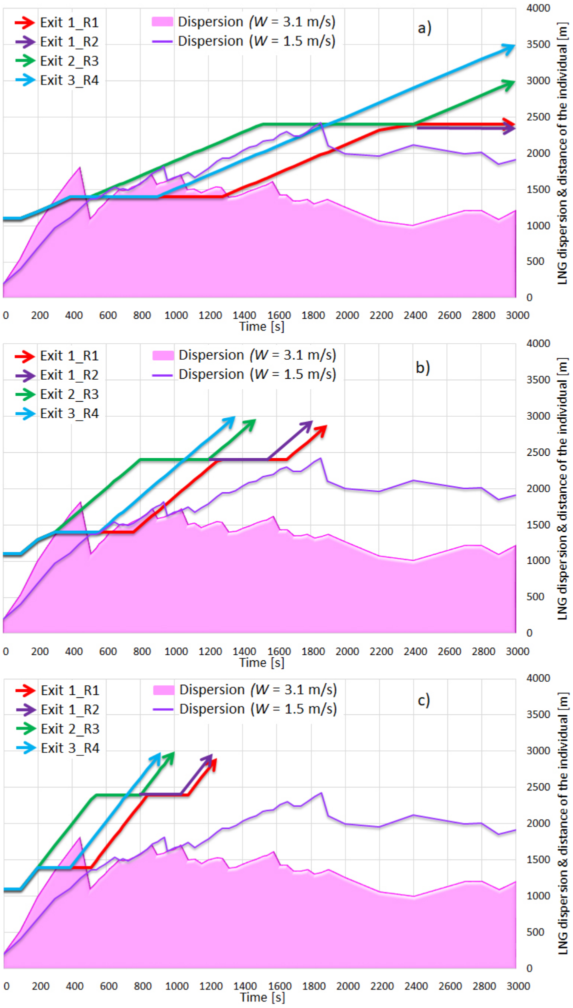

Fig. 8. *The impact of LNG vapor dispersion on evacuation routes in influenced area at two different wind speeds and walking speeds: a) 1 m/s, b) 2 m/s, and c) 3 m/s*

where F_oF_i, is frequency of fatality, $f_{eo,j}$ frequency of event outcome j, $P_{fat,i,j}$ probability of fatality at location i produced by event outcome j, and:

$$F_oF_i = \sum_j f_{eo,j} \cdot P_{fat,i,j}, \tag{2}$$

where $P_{unr,i,j}$ is probability of choosing an unsafe route, $P_{ws,i,j}$ is probability of wind speed, and $P_{wd,i,j}$ is probability of wind direction, (related to the wind rose) at location i produced by event outcome j.

Table 1. *Number of safe evacuation routes*

Wind direction and speed		Total number of safe evacuation routes	Probability of choosing unsafe route
N	1.5 m/s	6	0.50
	3.1 m/s	2	0.83
	5.1 m/s	0	1.00
	8.2 m/s	12	0.00
E	1.5 m/s	9	0.25
	3.1 m/s	1	0.92
	5.1 m/s	0	1.00
	8.2 m/s	0	1.00
W	1.5 m/s	9	0.25
	3.1 m/s	2	0.83
	5.1 m/s	0	1.00
	8.2 m/s	0	1.00
NE	1.5 m/s	5	0.58
	3.1 m/s	2	0.83
	5.1 m/s	12	0.00
	8.2 m/s	12	0.00
NW	1.5 m/s	5	0.58
	3.1 m/s	2	0.83
	5.1 m/s	12	0.00
	8.2 m/s	12	0.00

Table 2. *Probability of choosing unsafe route*

Advanced evacuation model	Not Implemented	Implemented
Probability of choosing unsafe route	0.57	0.25

These analyses and data are of great help in programming and modifying Dijkstra's algorithm with the goal of building a sophisticated model for evacuating people, as well as in defining the rules in Fuzzy logic that are usually used in technologically advanced evacuation models.

The model validation is generally applied to qualitatively and quantitatively compare the model predictions with the experimental datum. So far, researchers have conducted several field trials (Maplin Sands, Burro, Coyote, Falcon, Thorney Island) and three sets of wind tunnel tests (CHRC, BA-Hamburg, BA-TNO) with small-case spill data to analyze the LNG vapor dispersion [25]. Our investigation is based on a conservative and extremely large-scale instantaneous spill of LNG on the water surface as a worst-case scenario. In this case, there is a difficulty making a parallel or substantiated comparison between the analytical results from our model and the existing experimental data and consequently validating them due to physical limitations in the models and the lack of validation with large-scale spill data.

4 CONCLUSION

Conducting simulations which show the impact of the accident on the environment as well as the evacuation travel under the existing routes, from different aspects, enables the creation of databases which provide us with comparable conclusions that might lead to a selection of the safest and fastest evacuation route and exit. By using Dijkstra's algorithm for solving the shortest and safest evacuation route problem we are able to calculate and avoid a hazardous location through blocking the affected area from the evaporated and dispersed LNG, and provide an updated evacuation route. It upgrades the technologically advanced evacuation models in terms of making the system more intelligent and automated. Thus, making a potential mistake during selection of an evacuation route would be minimized, which is not the case in situations where the evacuation route is selected without having at the planners' disposal data and information regarding the effects of the accident on the surrounding environment. The benefits from creating and conducting such simulations, databases and analyses for LNG leakage accidents is utilized by creators of new evacuation models as well as LNG terminals (extant or planned), that need to decrease both the individual and societal risk through decreasing the value of probability of fatality; i.e., the probability of choosing the unsafe route.

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