Numerical simulation of LNG pool fire mitigation

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Abstract

The increasing attention to environmental aspects has promoted the development and adoption of innovative combustion systems. Several economic considerations suggest the utilization of cryogenic fuels such as the liquefied natural gas (LNG). However, several concerns regarding the safety aspects of LNG exist, and in particular, few indications can be found for the individuation and optimization of mitigation systems in the case of accidental release of LNG.

This work has been devoted to the investigation of the effects of mitigation system conditions on LNG pool fire by non-conventional water-based systems. To this aim, two open-source, computational fluid dynamics (CFD) codes, i.e., OpenFoam and fire dynamics simulator (FDS), have been adopted for the characterization of LNG pool fire. The analysis has indicated that the extinguishing capacity is weakly affected by the water particle diameter in the investigated range (particle diameter ≤ 200 μm); thus, the utilization of smaller particles is discouraged by the increased operative costs related to the higher pressure.

Introduction

Liquefied natural gas (LNG) has been widely recognized as one of the most sustainable alternatives among fossil fuels [1-3] due to the elevated mass and energy density, which makes LNG particularly attractive for the propulsion [4]. This trend has promoted the investigation of chemical and physical phenomena occurring at a low temperature either for the direct combustion system or for safety purposes [5].

When accidental releases of LNG to the open atmosphere occur, a boiling pool is formed. In the presence of ignition sources, the fire of the resulting pool represents the most likely scenario [6], which may be in first instance, mitigated (possibly extinguished) by standard procedures, i.e. by means of water-based systems, inertization (N_2 or CO_2 inertization) or solid suppression (application of expanding foams, powders or fibrous solids) [7].

When cryogenic systems are of concern, however, the ultra-low temperature of the pool affects the inefficiency of the cited mitigation technologies. If water sprinkler are adopted, the presence of large water particles increases the evaporation of LNG, thus the severity of the pool fire [8]. Besides, effective inertization by nitrogen or carbon dioxide requires large amount of gases, making this procedure often unstainable technologically and economically [9]. Finally, although the

encouraging results obtained by Suardin et al. [10], further investigations for the development of suitable solid materials are still required due to the inefficacy on the suppression of the LNG vapor dispersion probably caused by the low temperatures involved.
Under this light, this work has been then devoted to the numerical investigation of water mist and water curtain of LNG pool fire mitigation, by means of open-source computational fluid dynamics.

Material and Methods

The combination of combustion models and accurate prediction of evaporation rate for different boundary conditions (e.g., presence of wind, LNG composition or floor material) represents one of the main challenges for the simulation of pool fires [11]. To this aim, liquid and vapor are commonly decoupled in two different systems, i.e., boiling liquid and vapor dispersion. For this reason, a preliminary investigation of the existing evaporation models suitable for cryogenic fluids is necessary. In the recent literature review reported by Nguyen et al. (2017) [12], linear evaporation models (Equation 1) with respect to evaporating species partial pressure (P_{sat}) has been suggested for the estimation of evaporation rate (m_{ev}).

$$m_{ev} = (K_m \cdot M_w \cdot P_{sat}) / (RT) \tag{1}$$

where K_m, M_w, R, and T are the mass transfer coefficient, molecular weight, ideal gas constant, and temperature, respectively. Reed model (Equation 2) has been indicated as the more accurate for the evaluation of K_m with respect to experimental data for cryogenic fluid evaporation [12].

$$K_m \cdot = (0.029\ u^{0.78}) / (d^{0.11} \cdot Sc^{0.67}) \tag{2}$$

where u, d and Sc stand for wind speed at the height of 10 m, pool diameter, and Schmidt number. Reed model considers the M_w as calculated in Equation 3.

$$M_w = [(M_f + M_a) / M_f]^{0.5} \tag{3}$$

in which the subscripts f and a represent the evaporating fuel and air, respectively.
Under these assumptions, the vapor subsystem has been tested by using OpenFoam (OF) and fire dynamics simulator (FDS) software, considering the resulting flux as boundary conditions. Grid dependency analyses have been performed separately for both software by using the cell dimensions reported in Table 1. A base case scenario was defined to this aim, consisting of a cylindrical pool of pure methane at normal boiling temperature (110 K), having a diameter of 1 m, ambient temperature of 295 K, absence of wind, computational domain of 2 m x 2 m x 5 m, simulation time of 80 s.

Table 1. Meshes adopted in this work, where x, y, and z axes are the longitudinal, normal, and lateral directions, respectively.

Mesh name	x_{min} [cm]	y_{min} [cm]	z_{min} [cm]
Mesh 1	5.00	6.25	5.00
Mesh 2	1.33	3.33	1.33
Mesh 3	0.50	1.25	0.50
Mesh 4	0.40	1.00	0.40

Further analyses were performed by applying to the same scenario reported for the base case, with the except of wind speed equal to 5 m/s, water-based mitigation systems characterized by 8 l/ (min m^2), average particle size included in the range 20 – 200 μm, spray angle of 45° with respect to x-z plane, placed at 20 m from the pool center and height of 4 m, in accordance with the scenario experimentally investigated by Liu et al. (2016) [13].

Results and discussion

For the sake of brevity, grid dependency analysis resulting from OF was reported, exclusively (Figure 1), since all the defined meshes satisfy the FDS acceptance criteria [14].

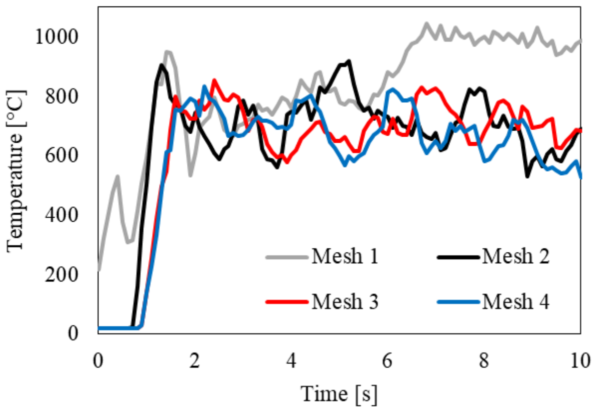

Figure 1. Grid dependency for the base case scenario, as obtained by using OF.

The finest mesh (Mesh 4) was adopted as the benchmark for the comparison of the other meshes reported in Table 1, in terms of temperature trend at the height of 4.5 m above the LNG pool center. Results indicate that Mesh 3 can be utilized for the following investigations, because of a reduced impact on the obtained results and a significant decrease in computational time with respect to Mesh 4. Moreover, OF offers the possibility to considerably reduce the computational cost required for the desired simulation, by implementing a 2-D domain. Hence, considering the investigated boundary conditions, a comparison with the base case scenario simulated in 3-D and 2-D domains was carried out. Since negligible effects on the estimated temperature distribution were found, the 2-D domain was implemented in OF for the following analyses.

The temperature trends with respect to time at the height of 4.5 m above the pool center as estimated by OF and FDS, were compared (Figure 2).

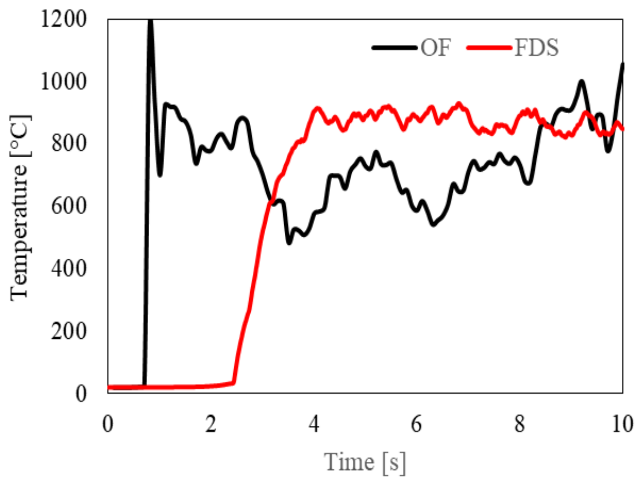

Figure 2. Comparison of temperature Vs time evolution, resulting from OF and FDS for the base case scenario.

It is possible to notice that some meaningful differences are present. In FDS, the temperature increases slowly and reaches the fully developed stage after more than 4 s whereas in the case of OF the rise time is considerably shorter and reaches a pseudo-steady-state in less than 1 s. Furthermore, the temperature fluctuations are much more marked in OF results. Similar trends have been already reported by Almeida et al. (2015) [15], especially for temperature profiles. Besides, Maragkos et al. [16] have reported OF overestimation of the temperature with respect to experimental data. These discrepancies are more pronounced in OF and can be partially attributed to overestimation of air entrainment inside the control volume [15] or shorter mixing time of the reagents [16]. In particular, the latter may lead to greater chemical reactivity and, consequently, to higher temperatures. On the other hand, several examples of validation of FDS models for LNG pool fire [14] and mitigation systems [17] are present in the current literature. For these reasons, FDS was preferred for the following analyses.

Figure 3 shows the temperature distribution with respect to time in case of the activation of the water mist system with average droplets size of 200 µm.

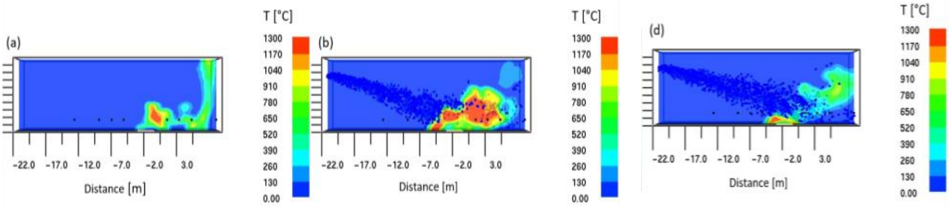

Figure 3. LNG pool fire suppressed by water mist having an average particle diameter of 200 μm at different time.

More specifically, Figure 3.a shows the ignition stage of the pool under the wind effect and the consequent developed of the flame that burns undisturbed until the water mist activation (Figure 3.b). In Figure 3.c, it is observed a general decrease in the temperature filed. More specifically, it decreases from an average value of 1300 °C to 600 °C except for some hot spot zones. The same scenario was investigated by applying a system characterized by particles with an average diameter of 20 μm, but not appreciable differences were obtained.

Conclusions

This work has been devoted to the evaluation of the applicability of mitigation systems to LNG pool fire. Particular attention was posed to the water mist. Significant discrepancies were observed between FDS and OF results, partially attributed to the reduced mixing time of OF, which leads to higher reactivity and temperatures. Negligible effects of the average particle diameter on extinguish efficiency were reported for values included in the range 20 μm ÷ 200 μm. The implementation of water in fine droplets was found to be useful for the reduction of radiative heat flux, promoting the adoption of this strategy to mitigate the LNG pool fire scenarios. The observed efficiency promotes further investigation on water-based mitigation systems, such as water curtain systems, to reduce the risk of second cascading events.

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