Predicting Large-Scale LNG Pool Fires Using FireFOAM

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Abstract The open source computational fluid dynamics (CFD) code FireFOAM has been used to study a range of liquefied natural gas (LNG) pool fires on land and water. The studied pool diameters range from 14 to 400 m and involve cross winds from 1.6 to 9.6 m/s. The code uses the extended Eddy Dissipation Concept (EDC) and a newly developed soot model based on the smoke point concept in the large eddy simulation (LES) framework. The trend of fire behaviour change with diameter is analysed. For the first four cases where full scale test data is available, comparison between the predictions and measurements are carried out. Analysis is conducted for all cases to investigate the change of flame length, tilt angle and surface emissive power with LNG pool diameters.

Key words: LNG fire; Cross wind; Large eddy simulation; Extended eddy dissipation concept

1 Introduction

The international commitment to reduce emissions of greenhouse gases has led to a dramatic increase in the use of natural gas (NG) in recent years. This trend is expected to continue since NG is considered as a vital resource in the search for a sustainable energy future. As Europe is deficient in NG resource, the demands need to be met by growing import in the form of liquefied natural gas (LNG). The capacity of LNG to yield large volume of gas (a ration of $\approx 600:1$ at standard temperature and pressure) has made it an extremely important component of the NG industry but also necessitates high safety standards in its handling. This has led to renewed interest in LNG safety from the energy security and reliability standpoint. While the safety of NG has received considerable attention, the same cannot be claimed for LNG. Some research was carried out in the 80s, when LNG importation to Europe was in its infancy, mainly to provide the necessary data for ship operations and onshore tankage as perceived by operating companies then. Relatively little has been carried out ever since either in Europe or internationally. The main hazard of LNG is the flammable vapour which can diffuse to kilometres, or be ignited resulting in fire and explosions. LNG pool fires can extend to hundreds of meters, giving rise to relatively large fire height normally about 1.2~3 times its diameter [1]. Its high temperature and radiative heat could bring direct injuries or fatalities to people and damages to facilities. So LNG pool fire is of special concern for safety. In an expert panel convened in the US to rank the need for research on LNG and suggest future research priorities to determine the public safety impact of an LNG spill, large fire phenomena was ranked as having the highest priority [2].

A series of LNG pool fire tests [3-14] have been performed on land or water with pool diameters ranging from about 2 m to 56 m. Some key fire parameters such as flame height, surface emissive power (SEP), etc. were measured in these tests. Surface emissive power is of particular importance for LNG fire risk assessment. It has been shown experimentally that for almost all hydrocarbon pool fires, e.g. butane, gasoline, kerosene, JP8 and liquefied petroleum gas, SEP does not increase monotonically with the pool diameter. The same was assumed for LNG but has not been supported by any experiment evidence until the recent Sandia tests [14], which was funded by a multi-million dollars investment of the US Department of Energy. However, as reported by Blanchat et al. [14], the two tests conducted had actually burning diameters of 21 and 56 m (in an 83-m spill). The trend in the data from these tests indicate that the SEPs for LNG fires on water level off at about ~280-290 kW/m² and might be expected for spreading pools with diameters in the range of 100 m.

Large scale LNG tests are technically difficult to perform and prohibitively costly. Semi-empirical models such as the solid flame model (SFM) are widely used. Such models assume the fire as a circular cylinder (vertical or tilted) of diameter equal to the base diameter of the fire and axial length representing the visible plume of the fire. To calculate radiation heat flux at a given location with SFM, the Surface Emissive Power (SEP) calculated from experiments and the view factor should both be known [2]. This is indeed one of the limitations of SFM. In the conventional SFM, the smoke obscuration that tends to reduce radiation is not accounted for. A variant of SFM for large hydrocarbon pool fires is the "two-zone" model of McGrattan et al. [15], which assumes that the lower luminous region is the only radiating surface and upper fire plume is obscured by opaque smoke. A "three-zone" semi-empirical approach that accounts for the variation of the SEP with height was proposed by Raj [16]. In spite of theses improvements, SFM and its variants are semi-empirical approaches based on existing experimental SEP and fail to properly account for the combustion dynamics of large LNG fires. Computational fluid dynamics (CFD) techniques with robust combustion and soot models, and validated from existing pool fire tests data offer a viable alternative to provide reliable assessment of the thermal radiative hazards for LNG installations.

The present study is motivated by the above background and takes advantage of a recently modified version of FireFOAM¹, an LES based CFD solver within the OpenFOAM toolbox. A series of simulations are carried out for LNG pool fires with diameters ranging from 20m to 400m.

2 Numerical modeling

The FireFOAM code solves the spatial filtered and Favre averaged reactive Navier-Stokes equations in the LES framework. The one-equation eddy viscosity model of Menon et al. [17] is used for the sub-gris scale (SGS) stress in terms of the resolved velocity field and predicting the turbulent viscosity, turbulent kenetic energy and its dissipation rate etc. For combustion, the extended EDC developed by Chen et al. [18] is used. It assumes infinitely fast chemistry occuring in the fine structure region and calculates the filtered reaction rate by accounting for turbulent diffusion from the fine structure to its surrounding fluid in the same computational cell. The smoke-point based soot model also developed by Chen[19] is used for soot formation and oxidation. It should be noted that the laminar smoke point height of methane cannot be measured since the flame becomes turbulent before it emits smoke. Methane may even play a role in suppressing soot formation if it is included in fuel mixtures as indicated by Markstein [20]. However, Lautenberger [21] assigned a smoke point height of 29cm and subsequently used by Beji [22] and Yao [23]. This value is believed to be estimated by Tewarson [29] from the comparison of radiant fraction between methane and ethane flame. The same value is hence adopted in the present study.

It is acknowledged that LNG fires with diamaters less than 30m can be considered as optically thin while larger LNG fires are optically thick. However, as an approxiamtion before an optically thick

¹ http://www.fmglobal.com/page.aspx?id=04010400

model is implemented, thermal radition in all cases are computed using the Optically-Thin-Assumption (OTA) model of Winters [24]. The total absorption coefficient is calculated as the sum of the component gas and soot absorption coefficients. The former is evaluated by the RADCAL program [25] while the later is computed following Prateep et al. [26], $\kappa_s \approx 1226 f_v T$, where f_v, T are soot volume fraction and gas temperature, respectively.



Fig.1 Schematic of the computational domain.

Case	Pool diameter	Cylinder size	Burning rate	Wind speed	Remarks
No.	М	$(D \times H) m^2$	$kg/(m^2.s)$	m/s	Kenlarks
1	14	80 imes 200	0.22	0	Raj et al. [6]
2	21	200×100	0.14	4.8	Blanchat et al. [14]
3	35	300×100	0.14	9.6	Nedelka et al. [13]
4	56	300×300	0.22	1.6	Blanchat et al. [14]
5	100	800 imes 500	0.14	1.6	Hypothetical LNG fire on
					land
6	100	800 × 500	0.22	1.6	Hypothetical LNG fire on
					water
7	200	1600 × 1000	0.14	1.6	Hypothetical LNG fire on
					land
8	200	1600 × 1000	0.22	1.6	Hypothetical LNG fire on
					water
9	400	3200×2000	0.14	1.6	Hypothetical LNG fire on
			0.14		land
10	400	3200 × 2000	0.22	1.6	Hypothetical LNG fire on
					water

Table 1 Operating conditions for the LNG fires simulated

Within the OpenFoam toolbox[27], the governing equations are discretized with the finite volume technique on a non-uniform grid. The time derivative is discretized using the backward time scheme with second order accuracy while the central differencing scheme with second order accuracy is utilized to discretize both the diffusion and gradient terms. The Gauss limited linear differencing scheme is employed to evaluate the convection term in order to maintain the total variation diminishing (TVD) characteristics. For the source term, the implicit scheme is adopted. Additionally, during the inner and outer loop iterations for every timestep, the PIMPLE algorithm, which is a combination of pressure implicit with splitting of operators (PISO) and semi-implicit methods for pressure-linked equations (SIMPLE), is involved to update the field variables.

LNG Fire Simulation

Numerical simulations were carried out for LNG pool fires with different diameters ranging from 14m to 400m. The computational domain is a cylinder as shown in Fig.1 while the height and diameter are changed from case to case dependently on the pool diameter. Although it is possible to dynamically calculating the mass burning rates of LNG pool fires, this requires a pool evaporation model. For simplicity, the pool fire mass burning rates are set according to experimental measurements for Cases 1 to 3. While for the other cases with larger than 35 m, the mass burning rate is set as 0.14 kg/m².s for LNG fire on land and 0.22 kg/m².s on water following Chamberlain[28]. The pool inlet temperature is set to LNG boiling temperature 111.67K. The atmospheric wind profile, which varies from case to case, is imposed from left to right direction. The wall boundary is set around the pool on the cylinder bottom while open boundaries are used for the sides. Non-uniform meshes were employed with finer grid points clustered near the burner centre and the grid density gradually reducing in the outward radial and verticaly upward directions. The initial and boundary conditions for all the 10 cases considered are summarised in Table 1.



Fig. 2 The predicted transient temperature and soot volume fraction contours for LNG pool fire (a and b for the 35m fire; c and d for the 100 m fire)

3 Results and discussions

3.1 Charateristics of flow field

Figure 2 presents the predicted transient temperature and soot volume fraction in Cases 3 and 6, the former is the 21m LNG fire tested by Gaz de France [13] and the later is a hypothetical 100 m diameter LNG pool fire on water. The predicted soot volume fraction is presented in ppm but but unfortunately there was no measurement of soot available for comparison. It is well known that the

shape of the fire plume e.g. flame length and tilt angle are dependent on the speed of the cross wind and fire buoyancy. Cross wind causes the fire plume to tilt, reducing its vertical height, as shown in Fig.2 (a) and (c).

In the presence of cross winds, more oxygen is entrained into the fire plume. This enhances the combustion intensity. On the other hand, the wind also promotes convective heat transfer between the fire plume and surrounding air, resulting in the fire plume being cooled down more quickly. Hence, there is competition between enhanced combustion intensity and convective cooling. In Fig.2 (b), on the "upwind" surface of the fire plume, less soot is observed, which is attributed to more entrained oxygen enhancing the oxidation of soot. As the chemistry of soot formation is much slower than that of the gas phase, there is also relatively less time for soot formation. However, this effect of "enhanced" soot oxidation is not evident near the "downwind" surface which is probably due to the dilution of the fresh air by the combustion products blown over from the upwind. It should also be noted that this region with higher soot concentration is not located directly above the pool surface but a little further downstream from the edge of the pool. The predicted soot volume fraction is less than 3.0 ppm. If the pool size is increased, as shown in Fig.2(d), stronger fire buoyancy weakens the effect of cross wind, resulting in decrease in the flame tilt angle and the higher soot concentration region is seen to be almost directly above the pool surface in the downwind direction. Certainly cross wind causes the soot to accumulate more on the downwind side.

3.2 Flame length and tilt angle

Figure 3 compares the predicted and measured flame length versus pool diameter. The predictions are in good agreement with the data. For LNG fire with the burning rate of 0.14kg/m².s (on land) or 0.22kg/m².s (on water), the flame length increases with pool diameter, because large pool size reduces the ability of entrained air to mix with the fuel in its centre. For fires with the same pool diameter, the fire on water with larger burning rate has slightly longer flame length.



Fig. 3 The predicted flame length L vs pool diameter D.

Figure 4 presents the calculated tilt angle of the LNG fire plume plotted against pool diameter. With the help of cross wind, the LNG fire tilts and continuously pulsates, which increases the difficulties of tilt angle measurement for large-scale LNG fire. In all the cases consideredtaken into account in this paper, the tilt angle was only measured only inin the 21m LNG pool fire experiments in Phoenix. The was the tilt angle measured to be around 50°. Currently the averagepredicted tilt angle of is calculated to be 57.8° is in reasonably good agreement with the measured value of 50°, slightly greater than the experimental value. At the same wind speed, the tilt angle decreases with increasing pool diameter due to stronger buoyancy and relatively smaller portion of the fire plume circumstances facing the wind which leads to reduced wind loading on the overall fire plume. There is little difference between the predicted tilt angles of LNG fires on land and water with the same diameter, implying that burning rate

has little difference on the tilt angle. The results clearly show a large and abrupt jump of 40 degree when the pool diameter decreases from 35 to 56 m. This is thought to be likely caused by the insufficiently large computational domain in the 56m fire predictions conducted by Chen [19]. This particular simulation will be re-run before the presentation at the conference.



Fig. 4 The predicted tilt angle of LNG fire plume axis vs pool diameter D.

3.3 Surface emissive power (SEP)

The SEP is determined from the averaged flame emissivity over the entire flame. It can be expressed as

$$SEP = e_F \sigma T_F^4 \tag{1}$$

where e_F and T_F are the averaged emissivity and temperature over the whole flame, respectively. σ denotes the Stefan-Boltzmann constant, 5.67×10^{-8} W/m²K⁴. Averaged flame temperature T_F could be expressed as

$$T_F = \frac{\sum_{cell} \tilde{T}_{cell} dV_{cell}}{\sum_{cell} dV_{cell}} \bigg|_{\tilde{Y}_s + \tilde{Y}_{ref} \ge 0}$$
(2)

where $Y_{ref} = Y_{fu} - \frac{Y_{O_2}}{s}$. Note that the weight of volume is introduced here for the averaging process. The subscript *cell* refers to the local variable on a cell inside the flame envelope. Similarly, e_F could be written as

$$e_F = 1 - \exp\left(-\kappa_F L_b\right) \tag{3}$$

$$\kappa_{F} = \frac{\sum_{cell} \kappa_{cell} dV_{cell}}{\sum_{cell} dV_{cell}} \bigg|_{\bar{Y}_{s} + \bar{Y}_{ref} \ge 0}$$
(4)

where L_{b} is the beam length for the entire flame, expressed as

$$L_b = \frac{4\pi D^2 L}{4\pi D L + \pi D^2} \tag{5}$$

where D and L are the pool diameter and flame length, respectively.

Figure 5 compares the predicted and measured SEPs. The predictions for the fires with diameters of 14m, 21m, 35m and 56m are in reasonably good agreement with the measurements. The largest discrepancy which happened in the case of the 35m fire is still less than 12%.

It is known that with the increase of pool diameter, less air could reach the centre to support combustion. Therefore, under the high temperature and radiation, the gaseous methane in the core region is cracked into soot, which has the effect of shielding the radiant heat from the fire. Additionally, some soot particles can escape from the fire before it is completely burnt. They cool rapidly and absorb heat from the fire, which further reduces its thermal radiation hazards on the surroundings. It is generally expected that the variation of the SEP for LNG fires against the pool diameter will follow similar trends of other hydrocarbon pool fires, i.e. firstly increases with pool diameter and then decreases with the increase in smoke shielding. From the 10 cases considered here, the SEP reached its maximum value of 325.6 kW/m^2 for LNG fire on land and 310 kW/m^2 for that on water when the pool diameter is 100m. The predicted SEPs decrease with further increase in the pool diameter. It needs to be specially pointed out that the surface emissive power for LNG fire on land is slightly bigger than that on water, when the pool diameter is kept same. This is thought to be the higher predicted soot concentration associated with the high mass burning rate on water which results in increasing thermal radiation blockage by soot.



Fig. 5 The predicted surface emissive power of LNG fire plume vs pool diameter D.

4 Conclusions

The following conclusions can be drawn from the present numerical simulations of 10 LNG pool fires with diameters ranging from 14 m to 400 m.

- (1) The presence of a cross wind will cause the LNG fire to tilt, resulting in reduction in vertical flame height.
- (2) The flame length increases with the pool diameter. For the same pool diameter, the fire on water which has larger mass burning rate also has longer flame length.
- (3) For the same pool diameter, the surface emissive power for the fire on land is slightly bigger than that on water.

(4) From the 10 cases simulated here, it is seen that the surface emissive power peaks at 325.6 kW/m² for LNG fire on land and 310 kW/m² for that on water. With further increase in the pool diameter, the surface emissive power starts to decease. This is in line with the trends demonstrated by large scale fire tests for other heavier hydrocarbon pool fires. However, it should be clarified that, further numerical simulations for a range of diameters between the range of 60 to 100 m will need to be conducted to further establish the exact diameter at which the surface emissive power peaks for LNG fire.

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