A Large Eddy Simulation of LNG Pool Fire on Board a Chemical/Oil Tanker

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ABSTRACT
The air pollution from maritime transportation has become one of the major environmental concerns. The liquefied natural gas (LNG) has better environmental performance compared to conventional ship fuels. Therefore, the use of LNG as ship fuel has recently gained more attention in the maritime industry. On the other hand, LNG as a fuel can have high risks of explosion and fire on ships. Among the various LNG ship fires, the pool fire is the most common phenomenon. Therefore, this study focuses on the LNG pool fire on board a chemical/oil tanker with different pool aspect ratios. Also, the effects of wind speed on the flame characteristics are investigated. The LNG pool fire on board a chemical/oil tanker is studied by using large eddy simulation approach and Fire Dynamic Simulator (FDS) code, numerically. The results show that the flame characteristics are affected markedly by the pool aspect ratio and wind speed. While the aspect ratio increases, the mean flame height reduces, whereas the heat flux values increases. It is also found that the heat flux values increase with the wind speed.

KEYWORDS: LNG pool fire; pool aspect ratio; wind speed; CFD; large eddy simulation.
INTRODUCTION

International Maritime Organization (IMO), MARPOL Annex VI sets progressive stricter emission limits to control the emissions from ships, including NOx and SOx emissions which have adverse effects on both the environment and human health [1, 2]. LNG as a ship fuel can be an alternative to adapt the environmental regulations, since it eliminates almost all emissions of SOx and particulate matter, reduce NOx emissions by up to 80% and reduce CO2 emissions by 15-25% [3-5]. However, handling or transporting this flammable and explosive substance, LNG especially under high pressures may lead severe fire accidents. Ergin and Sülüs investigated the engine room fire for a chemical tanker and presented the effects of the openings on the fire development [6]. The pool fire is the most common phenomenon among the various LNG ship fires such as jet fire, flash fire and fire ball [7, 8]. Therefore, the pool fire has become the subject of many papers.

The pool shape in the majority of the pool fire studies is circular, hence the existing correlations based on the circular pool assumptions. There are a limited number of studies which considers the effects of the pool aspect ratio on the fire characteristics in the literature. The experimental study on the asymmetric plume in a channel was conducted by Fan et al. [9] and it has been found that the heat flux increases with the aspect ratio due to the enhancement in the perimeter and a proportional increase in the air entrainment. Hu et al. [10] studied the burning behaviour of the square pool fires which are optical-thin under the cross-air flows. It has been reported that the burning rate changes with the pool diameter and the magnitude of the cross-air flows. Ji et al. [11] investigated experimentally the effects of the sidewall and aspect ratio on the flame characteristics and the burning rate of the n-heptane pool fires. The non-monotonic distribution of the burning rate was obtained by increasing the distance from the sidewall, but the burning rate increased with the pool aspect ratio. Jiang et al. [12] conducted several experiments to obtain a correlation for the burning rate of the rectangular pool fires. It has been shown that the correlation gives satisfactory results for n-heptane and gasoline pool fires and also reported that the small wind speed does not affect the burning rate significantly. Tang et al. [13] studied the radiative heat flux characteristics and mean flame height of the medium-scale rectangular pool fires and claimed that the atmospheric pressure has a low effect on the mean flame height, and also the slight difference was observed in flame radiation fraction. Tang et al. [14] scrutinized the flame pulsation characteristics of the rectangular pool fires for two different atmospheric pressures and different aspect ratios. The flame pulsation characteristics are slightly affected by the ambient pressure. However, it increases as the aspect ratio increases. Fan et al. [15] investigated the sidewall effects with various aspect ratios of the rectangular pool fires on the flame characteristics. It has been found that an increase in the aspect ratio causes an increase in the heat release rate due to the enlargement of the pool perimeter.

The present study investigates the flame characteristics of the LNG pool fire and heat fluxes on board a chemical/oil tanker for different pool aspect ratios and wind speeds, numerically. Four different pool aspect ratios, AR=1, 2, 4 and 8 and also a round pool (AR=0) are considered. The wind speed has been taken as 0 and 3 m/s. In order to calculate the flame characteristics and heat flux values of the fire on board a chemical/oil tanker, a genuine model is developed, and the governing equations are solved by using FDS code and the large eddy simulation approach. A brief explanation of the numerical model is given in the following section. The third section presents the findings of the study and discussions of the results. The last section, conclusions gives the major findings of the present study.

NUMERICAL MODEL

FDS code which is highly validated and widely used code to solve the low Mach number fire dynamic problems is also used in this study. FDS employs Large Eddy Simulation (LES) approach and the governing equations discretized by the second-order central difference method except for the thermal radiation [16]. In computations, Deardorff turbulence viscosity model is used. As a combustion model, the Mixing-Controlled Fast Chemistry model is used. The pool fires are classified as radiation (D>0.2 m) or conduction-controlled (D<0.2 m), since the pool fire which is investigated in the present study has the diameter larger than 0.2 m, it can be classified as radiation-controlled. Therefore, the radiation effects are also considered in the present study. FDS uses the radiative transport equation by considering the absorbing, emitting and scattering of the medium and the equation is discretized using finite volume method [17]. The computational domain of the study is shown in Fig. 1. The “stair stepping” method is used to generate the ship form, and the obstacles with LNG tanks on board ship are modelled as rectangular blocks. In order to obtain appropriate height of the computational domain, the correlation given by Heskestad [18] (Eq. 1) is used as an initial guess for the height of the domain to cover the complete flame.

\[ L = 0.235Q^{0.25} - 1.02D \] (1)
where \( L \) is the mean flame height (m), \( \dot{Q} \) is the energy release rate (kW/m\(^2\)) and \( D \) is the pool diameter (m).

The top and sides of the computational domain are set as open boundaries, only the bottom of the computational domain is the wall with no slip condition. The wind is blowing through the inlet without any oblique and leaves the domain from the outlet. The uniform distributions of the variables are used as the boundary conditions at the inlet and outlet of the domain. The ambient temperature and pressure are set to 20\(^\circ\)C and 1 atm, respectively. LNG includes mainly Methane (93.94\%), Ethane (4.8\%), Propane (0.81\%), Nitrogen (0.25\%) and Butane (0.2\%) and the heat of combustion value of LNG is 50 MJ/kg. The material of the ship, LNG tanks, and obstacles are steel with density 7850 kg/m\(^3\), thermal conductivity 45.8 W/(m K) and specific heat 0.46 kJ/(kg K). The effects of four different AR values (AR=0.0, 1.0, 2.0, 4.0 and 8.0) and two different wind speeds (\( V_w \)=0 and 3 m/s) on the flame height, plume velocity, plume temperature and heat flux values are investigated.

Three different grids are employed in the solution of the problem and the heat flux values are used to assess the desired grid resolution. Since LES intrinsically depends on the grid resolution, a final grid independent resolution does not exist. Therefore, the desired resolution is determined among three different grids. The resolved parts of Grid 2 (309x146x78) and Grid 3 (420x227x110) are found to be satisfactory to obtain the results, however, the resolution of Grid 1 (211x114x55) is found as inadequate. Therefore, Grid 2 is used in the solution.

RESULTS AND DISCUSSION

This section presents the calculated flame heights, vertical velocity values, temperature distributions and heat flux values for different pool aspect ratios and wind speeds. To obtain the fully developed results, the adequate computational time is specified as 30 s. The time step is determined by satisfying the CFL (Courant, Friedrichs, Lewy) condition, this parameter is set automatically by FDS [19]. Fig. 2 shows the instantaneous flame heights of the pool fire for different pool aspect ratios when \( t \) equals 30 s. The instantaneous flame heights for the round pool (AR=0) and the square pool fire (AR=1) are found similar. As can be clearly seen from Fig. 2, the flame height decreases while the aspect ratio increases.
Fig. 2. Instantaneous flame heights of the pool fire at \( t=30 \) s. (a) \( AR=0 \), (b) \( AR=1 \), (c) \( AR=2 \), (d) \( AR=4 \) and (e) \( AR=8 \).

Fig. 3 shows the vertical plume velocity distributions at the centreline of the burner for different pool aspect ratios and wind speeds. As can be seen from Fig. 3a, the velocity firstly increases, it reaches its maximum value, and then stays nearly constant along the centreline of the burner. The mean flame height decreases as the aspect ratio increases, since the flame height is significantly affected by the side entrainment of the pool shape. Hence the plume velocity decreases when the aspect ratio increases. The velocity distribution for the round pool (\( AR=0 \)) is almost same as that for the pool aspect ratio, \( AR=2 \). The vertical velocity starts to oscillate at the certain distance above the burner. This distance becomes shorter when the aspect ratio increases. It can be seen from Fig. 3a that the amplitude of the velocity increases as the aspect ratio increases.

The flame characteristics are considerably affected by the wind speed. The flame is not only affected by the wind, but also by the obstacles, which are located in front of the pool. A recirculation region occurs behind the obstacles and it affects the vertical velocity and the temperature distributions. Since the flame height decreases with the increasing aspect ratio, relatively shorter flames will be less affected by the wind speed. Therefore, opposite trend is obtained for the wind velocity, \( V_w=3 \) m/s, the velocity values along the centreline of the burner increase as the pool aspect ratio increases (see, Fig. 3b). For the wind velocity, \( V_w=3 \) m/s, the velocity first increases sharply, reaches its maximum value and then decreases along the centreline of the burner (see, Fig. 3b). The maximum vertical velocity value decreases almost 50 % when the wind velocity increases from 0 to 3 m/s. The velocity values for the round pool are smaller than that of the square and rectangular pools.

Fig. 4 shows the plume temperature distribution along the centreline of the burner for different aspect ratios and wind velocities. For no wind (\( V_w=0 \) m/s) case, the plume temperature first increases sharply, reaches its maximum value and then decreases. The maximum temperature values are obtained at the persistent region of the flame as expected, and temperatures begin to decrease at the intermittent region of the flame as combustion reactions diminish and the cooling effect of the air became more dominant. The maximum temperature is almost same for all the aspect ratios, since the physical characteristics of the pool fire change with the size of the fire, and the temperature usually increases due to reduction in thermal radiation loss from the fire. The wind speed affects the temperature distribution significantly (see, Fig. 4ab). For the wind speed, \( V_w=3 \) m/s, the temperature
first rises very sharply, reaches its maximum value and then decreases sharply. On the other hand, the lowest temperatures occur for the case with round pool. The temperature distribution has a similar phenomenon as the vertical velocity distribution. The effect of wind speed is relatively small for the shortest flame length. Hence the plume temperatures decrease with decreasing pool aspect ratio.

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**Fig. 3.** Velocity distribution at the centreline of the burner. (a) $V_w=0.0 \text{ m/s (no wind)}$, (b) $V_w=3 \text{ m/s}$

![Image](The sum of the heat fluxes by radiation, conduction and convection gives the total heat flux from flame to the fuel bed [20, 21] and the calculated heat flux values on the fuel bed for different aspect ratios and the wind speeds are presented in Fig. 5. Since the wind entrains the flame through the short side of the pool, the flame became more turbulent. Hence the heat flux values increase when the pool aspect ratio increases [22]. There is a sharp increase when the pool aspect ratio is small. Since the pool fire has the asymptotic burning rate for the large aspect ratios. On the other hand, the heat transfer characteristics, flame shape and turbulence mechanism are affected by the wind. The wind contributes the air-fuel mixing and that causes an improvement on the combustion efficiency and hence the burning rate [23]. Therefore, the heat flux values are increased with the wind speed.)

**Fig. 4.** Temperature distribution at the centreline of the burner. (a) $V_w=0.0 \text{ m/s (no wind)}$, (b) $V_w=3 \text{ m/s}$

![Image](The sum of the heat fluxes by radiation, conduction and convection gives the total heat flux from flame to the fuel bed [20, 21] and the calculated heat flux values on the fuel bed for different aspect ratios and the wind speeds are presented in Fig. 5. Since the wind entrains the flame through the short side of the pool, the flame became more turbulent. Hence the heat flux values increase when the pool aspect ratio increases [22]. There is a sharp increase when the pool aspect ratio is small. Since the pool fire has the asymptotic burning rate for the large aspect ratios. On the other hand, the heat transfer characteristics, flame shape and turbulence mechanism are affected by the wind. The wind contributes the air-fuel mixing and that causes an improvement on the combustion efficiency and hence the burning rate [23]. Therefore, the heat flux values are increased with the wind speed.)

**Fig. 5.** Heat flux values on the burner plate for different aspect ratios.
CONCLUSIONS

This study investigates the LNG pool fire on board a chemical/oil tanker by using large eddy simulation approach. The effects of different pool aspect ratios and wind speeds on the flame characteristics, plume velocities, plume temperatures and heat fluxes are obtained, numerically. The solution of the governing equations is obtained by using Fire Dynamic Simulator (FDS) code. The major findings include:

- The flame height decreases while the pool aspect ratio and the heat flux values increase, since the flame height is significantly affected by the side entrainment of the pool shape.
- The pool fire that has a high aspect ratio is relatively less affected by the wind and recirculation region occurred due to the obstacles on board ship. Therefore, the temperature and vertical velocity values increase with the aspect ratio.
- The wind speed increases the combustion efficiency. As a result of this, the burning rate and heat flux values increase.

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