CFD simulation to predict the thermal radiation of large LNG pool fires

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Abstract

Flame temperature \( T \), surface emissive power \( SEP \) of Liquefied Natural Gas (LNG) pool fires (\( d = 1 \) m, 6.1 m, 30 m) are investigated by CFD (Computational Fluid Dynamics) simulation and compared with experimental results. Time averaged flame temperatures of \( T = 1320 \text{ K} \), \( T = 1298 \text{ K} \) and \( T = 1281 \text{ K} \) are obtained. Surface emissive power \( (SEP) \) of 55 kW/m\(^2\), 130 kW/m\(^2\) and 230 kW/m\(^2\) are predicted.

1 Introduction

Accidental fires in process industries often occur as pool fires which are hazardous to people and adjacent objects due to thermal radiation, largely sooting plumes and formation of other combustion products (1; 2; 3). Pool fires are turbulent non-premixed fires burning over a horizontal pool. In addition to experimental pool fire tests numerical investigation of those fires using Computational Fluid Dynamics (CFD) codes becomes more important. The Surface Emissive Power \( (SEP) \) is a key parameter to characterize thermal radiation emitted by a fire. Beside the \( SEP \) the temperatures \( T \) and irradiances \( E \) of pool fires are of particular interest. To predict the thermal radiation from LNG (\( d = 1 \) m, 6.1 m, 30 m) pool fires CFD methods are used and the CFD results are compared with experiments.

2 Characteristics of pool fires

Pool fires are turbulent non-premixed fires burning over a horizontal pool (4; 5; 6). Pool fires can be divided into two- or three non-continuous zones, but until now these length can be calculated with large uncertainty only. Directly over the pool rim exists a luminous clear burning zone (\( H_{cl} \) in Fig. 1), which is not covered with black smoke and has beside hot spots the largest surface emissive power \( SEP_{ma} \) of a fire. In the pulsation zone (\( H_{pul} \) in Fig. 1) the flame front is still connected to the flame basis but it is a less efficient combustion zone of a flame. Due to large eddies of intaken air radial and axial pulsation occurs and formation of black soot can be observed. In the top region the plume zone (\( H_{P} \) in Fig. 1) a non-continuous segregated flame is observed.

3 Thermal radiation models

A widely used thermal radiation model is the Solid Flame Model (SFM, Fig. 2) (7), from which several modifications exists (8). In the classical case a flame is postulated as a cylinder with circular base, with a homogeneous temperature of \( T = 1173 \text{ K} \) on flame surface, a emissivity of \( \varepsilon_f = 0.95 \) for hydrocarbon pool fires a specific emission of 100 kW/m\(^2\) is obtained by the following equation:
\[ \overline{SEP}_{SFM}^{ma} = \tau_0 (T^4 - T_a^4) \]  

(1)

\[ E = \varphi_{E,F} \tau_{at} \alpha_r \overline{SEP} \]  

(3)

Beside the semi-empirical models according to Mudan (10), Fay (5) and Raj (6) especially the model OSRAMO II (11; 12) and OSRAMO III (3; 11) which contain mainly quantities with physical meaning are to be noted.

4 CFD simulation

In CFD simulation a domain is represented by a 3-D hexahedral block structured mesh (Fig. 4) (13; 14). The fuel is assumed to be already evaporated and the fuel vapor entering the domain from inlet has a constant temperature of \( T = T_b \) and an experimentally determined constant mass flux (15). The inlet is surrounded by a low rim and an adiabatic ground area. The remaining boundary conditions are set as "pressure outlet" in a relative wide distance from the pool to achieve open boundary conditions. With increasing axial and vertical distance from the pool cell size increases.

The time step vary depending on sufficient convergence from \( t = 10^{-6} \) s to \( t = 10^{-4} \) s depending on Courant-Friederich-Levy (CFL) criterion. Large Eddy Simulation (LES) is used for modeling turbulence (16; 17). In the pool fire simulations presented here, the following sub models are used:

- Assumed pdf approach with laminar flamelets containing up to 21 species and elementary reactions (18; 19; 20).
- Moos-Brookes soot model (21).
- Discrete Ordinates model for radiation (22; 23; 24).

The coupling between thermal radiation and soot reactions is described by a weighed sum of gray gases approach (25; 26).

The governing equations were solved with an iterativ solution method with either coupled or segregated solvers, e.g. the pressure correction methods SIMPLE (Semi-Implicit Methods for Pressure Linked Equations).
The starting and boundary conditions are listed in Tab.1-2.

Tab. 1: Starting conditions of CFD pool fire simulation

<table>
<thead>
<tr>
<th>starting conditions</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass fraction N₂</td>
<td>0.743</td>
</tr>
<tr>
<td>mass fraction O₂</td>
<td>0.231</td>
</tr>
<tr>
<td>mass fraction Ar</td>
<td>0.012</td>
</tr>
<tr>
<td>mass fraction CO₂</td>
<td>0.001</td>
</tr>
<tr>
<td>mass fraction H₂O</td>
<td>0.013</td>
</tr>
<tr>
<td>p_a</td>
<td>1013.25 hPa</td>
</tr>
<tr>
<td>p - p_a</td>
<td>0</td>
</tr>
<tr>
<td>flow velocity</td>
<td>0</td>
</tr>
<tr>
<td>temperature</td>
<td>298 K</td>
</tr>
<tr>
<td>gravitational acceleration</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>mixing fraction f</td>
<td>f = 0</td>
</tr>
</tbody>
</table>

Tab. 2: Boundary conditions of CFD pool fire simulation

<table>
<thead>
<tr>
<th>boundary conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>upper end face</td>
<td>p = p_a</td>
</tr>
<tr>
<td>+ lateral area</td>
<td>298 K</td>
</tr>
<tr>
<td>“pressure outlet”</td>
<td>open boundary conditions</td>
</tr>
<tr>
<td>lower end face</td>
<td>adiabatic</td>
</tr>
<tr>
<td>+ pool rim</td>
<td>heat flux to pool rim</td>
</tr>
<tr>
<td>“wall”</td>
<td>̇q = 0</td>
</tr>
<tr>
<td>pool “mass flow inlet”</td>
<td>experimentally determined</td>
</tr>
<tr>
<td></td>
<td>p = p_a, T = T_b</td>
</tr>
</tbody>
</table>

The main purpose is to determine the temperature T, Surface Emissive Power (SEP). The simulations are started with an two equation model based on the eddy viscosity hypothesis like \( k - \epsilon \) with a buoyancy correction term to reach a certain flame height which refers to the developing stage of the fire. Assuming the flame to be developed, further simulation is continued by using LES. CFD simulation is carried out with commercial software ANSYS FLUENT 12 (27).

5 Results and Discussion

5.1 Flame temperature

With CFD simulation instantaneous temperature fields of LNG pool fires can be predicted. In both fields (Fig. 5-6) pulsation of the flame is visible. Inside the observed vortices a significant higher instantaneous temperatures \((1800 \text{ K} < T < 2161 \text{ K})\) then in the adjacent area. \((1400 \text{ K} < T < 1800 \text{ K})\).

![Fig. 5: CFD predicted instantaneous temperature field of a LNG pool fire (d = 30 m) \(t = t_0\)](image)

The vortices cool down in the higher flame region where temperatures of \( T < 1400 \text{ K} \) are obtained. The maximum temperatures accure above the pool rim, but
not directly at the center line. The simulation shows broken off vortices with temperatures $T < 650 \text{ K}$ until a heights of 90 m.

With CFD simulation also time averaged flame temperatures can be predicted. The maximum time averaged temperature is located at center line above the pool rim (Fig. 7). The time averaged maximum flame temperatures of LNG pool fires decrease with increasing pool diameter (Tab. 3).

![Fig. 7: CFD predicted time averaged temperature field of a LNG pool fire (d = 30 m)](image)

Fig. 7: CFD predicted time averaged temperature field of a LNG pool fire (d = 30 m)

<table>
<thead>
<tr>
<th>pool diameter [m]</th>
<th>$T_{max}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1320</td>
</tr>
<tr>
<td>6.1</td>
<td>1298</td>
</tr>
<tr>
<td>30</td>
<td>1281</td>
</tr>
</tbody>
</table>

Tab. 3: Maximum time averaged flame temperatures of LNG pool fires

The time averaged flame temperatures of LNG pool fires are up to 50 K higher, then those of other hydrocarbon pool fires e.g. JP-4 (Tab. 4).

![Tab. 4: Maximum time averaged flame temperatures of JP-4 pool fires](image)

Tab. 4: Maximum time averaged flame temperatures of JP-4 pool fires

<table>
<thead>
<tr>
<th>pool diameter [m]</th>
<th>$T_{max}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1300</td>
</tr>
<tr>
<td>8</td>
<td>1280</td>
</tr>
<tr>
<td>16</td>
<td>1250</td>
</tr>
<tr>
<td>25</td>
<td>1230</td>
</tr>
</tbody>
</table>

5.2 Surface emissive power

The $SEP$ is a derived quantity and its value depends on flame surface and flame shape. Especially the value of the flame height, but also atmospheric transmission and general experimental errors are import. The $SEP$ of a fire can be obtained by CFD simulation in three ways. In the first way the $SEP$ is predicted by radiative heat flux $q_{out}$ leaving each grid cell placed on the flame surface $A_F$. The value of $q_{out}$ can be obtained by calculating the component of radiative flux $q_{rad}$ that is normal ($\vec{n} \perp A_F$) to the cell surfaces which define the flame surface $A_F$:

$$SEP = q_{out} = (1 - \epsilon_t) q_{in} + \epsilon_t \sigma T^4, \quad (4)$$

with $q_{in}$

$$q_{in} = \int L \vec{s} \cdot \vec{n} < 0 \ d\Omega. \quad (5)$$

To get the $SEP$ at the flame surface it is necessary to determine a surface $A_F$ which presents a realistic shape of the flame. One possibility is an isosurface of temperature ($T > T_a$).

The procedure can be described as follows:

- An instantaneous flame surface $A_{F, CFD}$ is defined as an isosurface of temperature (interior wall).
- The CFD calculated heat flux $q_{out}(t)$ is averaged over the isosurface $A_{F, CFD}$ for each time interval $\Delta t$ (an usual value is $\Delta t = 0.1 \text{ s}$) to evaluate area averaged heat flux $\langle q_{out}(t) \rangle$.
- The heat flux $\langle q_{out}(t) \rangle$ is averaged over the steady burning time ($t \approx 10 \text{ s}$) which results in a time averaged heat flux $\langle q_{out}(t) \rangle \equiv SEP_{CFD}$. It is assumed that a steady state burning time of 10 s shows real burning behaviour.

![Fig. 8: CFD predicted instantaneous SEP for an isosurface $T = 500 \text{ K}$ of a LNG pool fire (d = 30 m)](image)

Fig. 8 shows the instantaneous $SEP$, depending in general on pool diameter and fuel, calculated by using
an isosurface of temperature \( T = 500 \) K for LNG pool fire.

Time averaged \( SEP \) is determined: \( SEP = 55 \) kW/m\(^2\) (\( d = 1 \) m), \( SEP = 130 \) kW/m\(^2\) (\( d = 6.1 \) m) and \( SEP = 230 \) kW/m\(^2\) (\( d = 30 \) m). The maximum specific emissivity \( SEP_{\text{max}} \) accounts for 301 kW/m\(^2\) thus being much higher than time averaged \( SEP \).

The mass burning rates of LNG pool fires are by factor 2.3 higher in comparison with other hydrocarbon pool fires. The measured mass burning rates are in comparison with calculated (over thermal back flow) mass burning rates by factor 2.5 smaller. This effects are caused by higher absorption coefficient of LNG vapor. For kryogenic liquids the air entrainment leads to an additional increase of the mass burning rate due to the large temperature difference. CFD simulation shows an temperature increase of the originally cold LNG vapor short above the pool surface.

### 6 Conclusion

With CFD simulation instantaneous and time averaged flame temperatures \( T, \bar{T} \), specific emissions \( SEP, \bar{SEP} \) can be predicted. The about 50 K higher instantaneous and time averaged flame temperatures are caused by the higher mass burning rate of LNG pool fires in comparison with other hydrocarbon pool fires. This facts can be explained by the mass burning rates which are in comparison with other hydrocarbon pool fires much higher caused by the temperature difference between boiling point and ambient temperature. To determine the maximum of \( SEP \) as a function of the pool diameter further investigation with pool diameters \( d > 35 \) m should be done.

### Acknowledgements

The authors thank Max-Buchner-Forschungsstiftung for financial support.

LaTable

### References


