Three-dimensional Numerical Simulation of Smoke Motion in Fire of the Ship Engine Room with Multilayer Structure

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1 Introduction

The engine room is the power source of a ship at a particularly exposed location. Therefore, it requires additional safety considerations. The crew, complex equipment, and the fuel oil in the limited space [1] represent a fire potential. The characteristic of a possible fire in the engine room is that the fire spreads quickly, it is difficult to extinguish it, and it is hard to evacuate people from the area. However, the flame and the high temperature in a fire are not the most dangerous factors for the crew. The smoke and the poisonous gases are the main reasons for death of people by suffocation [2].

Figure 1 presents the structure diagram of a typical engine room. It is divided into three layers by two steel platforms (A and B) built as stiffened panels. The two layers are connected by inclined ladders. The whole engine room is divided into multi-sub-regions containing the diesel engine, the diesel generators and the supporting platforms. Since the whole space is divided into the structures of multilayer and multiple sub-regions, the structure can be considered as a multilayer structure; otherwise, it represents a monolayer structure.

The fire in the ship engine room is being extensively researched in recent years. Particularly the laws of smoke movement have provoked the fire researchers’ attention. The relation of the smoke movement and the physical dimension of the space has been studied by the US College of Naval Research (2000). The results of this research were compared with simulation result by the CFDRC [3]. The temperature character of the smoke in the enclosed cabin was studied earlier by LU Shouxiang [4] resulting in the improvement of the two-zone model. ZOU...
2 Mathematical model

2.1 Governing equations

The tensor form of turbulent combustion governing equations can be found in reference [8]. By choosing the spatial filter operation it follows:

\[ \bar{f}(x) = \int f(x') F(x - x') dx' \]  

where \( F \) is the filter. The article applies the box filter as shown:

\[ F(x) = \begin{cases} \frac{1}{\Delta^3} & \text{if } |x| \leq \Delta/2, i = 1, 2, 3 \\ 0 & \text{otherwise} \end{cases} \]  

(2)

where \((x_1, x_2, x_3)\) are the spatial coordinates of the location \(X\).

The filtering of the instantaneous balance equations leads to the following equations:

Conservation of Mass

\[ \frac{\partial}{\partial t} \bar{\rho} + \frac{\partial}{\partial x_i} (\bar{\rho} \bar{u}_i) = 0 \]  

(3)

Conservation of Momentum

\[ \frac{\partial}{\partial t} \bar{\rho} \bar{u}_i + \frac{\partial}{\partial x_j} (\bar{\rho} \bar{u}_i \bar{u}_j) = -\frac{\partial}{\partial x_i} \bar{p} + \frac{\partial}{\partial x_j} (\bar{\tau}_{ij} - \rho \bar{u}_i \bar{u}_j) \]  

(4)

Conservation of Energy

\[ \frac{\partial}{\partial t} \bar{\rho} \bar{e} + \frac{\partial}{\partial x_i} (\bar{\rho} \bar{e} \bar{u}_i) = \frac{\partial}{\partial x_i} \bar{q} - \frac{\partial}{\partial x_i} (\rho \sum_{k=1}^{N} V_k \bar{Y}_k) \]  

(5)

Chemical species

\[ \frac{\partial}{\partial t} \bar{\rho} \bar{Y}_k + \frac{\partial}{\partial x_i} (\bar{\rho} \bar{Y}_k \bar{u}_i) = \frac{\partial}{\partial x_i} \bar{V}_k - \rho \bar{u}_i \bar{Y}_k + \bar{\omega}_k \]  

(6)

where \( \frac{\partial}{\partial t} \bar{p} = \frac{\partial}{\partial t} \bar{\rho} + \bar{u}_i \frac{\partial}{\partial x_i} \bar{\rho} \), \( \bar{p} \) is the density, \( \bar{u}_i \) is the three dimensional velocity, \( \bar{v} \) is the pressure, \( \bar{\tau} \) is the stress tensor, \( \bar{h} \) is the enthalpy, \( \bar{h}_j \) is the sensible enthalpy, \( \bar{\omega}_k \) is the reaction rate of species \( k \), \( \bar{\lambda} \) is coefficient of heat conductivity, \( \bar{V}_k \) is the i-component of the diffusion velocity \( V_k \) of species \( k \), \( \bar{Y}_k \) is the mass fractions of species \( k \).

In the governing equations, the unresolved momentum fluxes are expressed according to the Boussinesq assumption as follows:

\[ \bar{\tau}_{ij} = \frac{\partial}{\partial x_j} \bar{u}_i - \frac{\partial}{\partial x_i} \bar{u}_j \]  

(7)

\[ \bar{v}_i = C_r \bar{\lambda} \bar{V}_i \bar{S}_D \bar{S}_n \bar{S}_{n}^{ij} \]  

(8)

\[ \bar{S}_V = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \]  

(9)

where \( \bar{\tau}_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_j \bar{u}_i \) is the subgrid stress, \( \bar{v}_i \) the subgrid scale viscosity, \( C_r \) the model constant, \( l_i \) is the turbulence integral length scale.

The unresolved scalar fluxes are described using a gradient assumption as it is shown:

\[ \bar{u}_i \bar{Y}_k - \bar{\bar{u}} \bar{Y}_k = \frac{\bar{v}_i}{\bar{S}_c} \frac{\partial \bar{Y}_k}{\partial x_i} \]  

(10)

where \( \bar{S}_c \) is a subgrid scale Schmidt number.
2.2 Mixture fraction combustion model and radiative heat transfer

Let us consider a simple, one-step reaction of fuel and oxygen:

\[
C_nH_{2n+2}O \rightarrow v_c CO_2 + v_{H_2O}H_2O + v_{CO}CO + v_S S + v_M M
\]

where the additional product species can be specified as some number of moles of an average molecular weight species M, v is the stoichiometric coefficient, S is soot.

The mixture fraction, Z, can be defined in terms of the mass fraction of fuel and the carbon-carrying products of combustion [9] as follows:

\[
Z = Y_F + \frac{W_F}{xW_{CO}}Y_{CO} + \frac{W_{H_2O}}{xW_S}Y_S
\]

where \(Y\) denotes the mass fractions, \(W\) the molar mass. The mixture fraction \(Z\) can be resolved into the following components:

\[
Z_1 = Y_F
\]

\[
Z_2 = \frac{W_F}{xW_{CO}}Y_{CO} + \frac{W_{H_2O}}{xW_S}Y_S
\]

At the burner surface, \(Z_1\) is assigned to the mass fraction of fuel and the carbon-carrying products of combustion, while the mass fraction of the species in the mixture \(Z_1, Z_2\) are found by means of [10]:

\[
Y_F = Y_F^i Z_1, \quad Y_{H_2O} = \frac{v_{H_2O}W_{H_2O}}{W_F}Y_F^i Z_2,
\]

\[
Y_{CO} = \frac{v_{CO}W_{CO}}{W_F}Y_F^i Z_2, \quad Y_S = \frac{W_{H_2O}Y_F^i Z_2}{W_S},
\]

\[
Y_{O_2} = \frac{v_{O_2}W_{O_2}}{W_F}Y_F^i Z_2,
\]

\[
Y_{CO_2} = \frac{v_{CO_2}W_{CO_2}}{W_F}Y_F^i Z_2
\]

The stoichiometric coefficients are defined:

\[
v_{CO} = \frac{a}{2}, \quad v_{H_2O} = \frac{y - X_H v_s}{2}, \quad v_{O_2} = v_{CO} + \frac{v_{H_2O} - z}{2}, \quad v_{CO_2} = \frac{W_{CO_2}y_{CO_2}}{W_F}, \quad v_{CO_2} = x - v_{CO} - (1 - X_H)v_s, \quad v_{O_2} = \frac{W_{O_2}y_{O_2}}{W_S} = b
\]

For radiative heat transfer, it is supposed that the smoke is non-scattering in the ship engine room fire, and the radiative transport equation (RTE) is solved [11]. The absorption coefficient is calculated by using the RADCAL narrow-band model of Grosshandler and the RTE is solved by using the FDS software [12].

3 Boundary conditions and simulation example

3.1 Physical model

The article considers an engine room of a bulk carrier (Figure 2). Its longitudinal section with the platforms and the appropriate equipment is presented in Figure 2(a), the location of equipment on the E/R floor, the piping layout, and the platforms B and A are presented in Figure 2(b), Figure 2(c) and Figure 2(d), respectively.

Due to the very complex structure of the engine room and irregular shapes of some of the equipment (Figure 2), the geometry of the space has to be simplified. In spite of that, the flame process of fire development in the engine room cannot be fully simulated with respect to the restrictions of the applied FDS software. For the needs of simulation the engine room has been simplified as listed below:

1. The irregular shapes of the engine room are simplified to the cuboid combinations.
2. The small equipment is ignored in the process of building the physical model.
3. The destructiveness of the fire in the engine room caused by possible explosive phenomena increases due to the large amount of the fuel and oil in the tanks and other high-pressure vessels. However, the explosive phenomena and explosibility are neglected due to the high complexity of the problem.
4. The movement of the people in the engine room under fire is small and the effect of human action on the flow distribution at the beginning of the fire can be ignored. On the other hand, the human interventions during the fire development have uncertain effects. Since the main research interest of the article is the smoke movement, the factor of the human intervention will be ignored.
5. The fuel system in the ship engine room is very harmful in the fire. Anyway, in order to simplify this complex calculation, the ignitability of the fuel system is not to be considered.

The simplified model of the structure is shown in Figure 3. The length of the engine room is 21.6 m, the width is 32 m, and the height is 22.8 m. The whole space is divided into zone 1, zone 2, and zone 3 by platform A and platform B. One diesel engine is placed in the centre of zone 1, and three diesel generators are placed in the front of zone 2. Four marine fans are set on the upper deck B; they are used for distribution of air in the engine room through the air pipe; the open section of the air pipe is 1×1 m². Two doors and one door are set on the right side of platform A and platform B respectively. The parameters of equipment and boundary conditions can be found in Table 1.
Figure 2  The plan of the ship engine room
Slika 2  Nacrt brodske strojarnice
The parameters of the major equipment and the boundary setting

<table>
<thead>
<tr>
<th>Category</th>
<th>Diesel engine</th>
<th>Diesel generator</th>
<th>Fan (intake)</th>
<th>The area of cabin door</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>4.57×8.1×8.2 m³</td>
<td>1.8×4.6×2 m³</td>
<td>1 m²</td>
<td>15×2 m²</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>40 °C</td>
<td>35 °C</td>
<td>3 m/s</td>
<td></td>
</tr>
</tbody>
</table>

The initial environment temperature is supposed to be 30 degrees. The pressure free boundary is applied for the marine fans and cabin doors. The wall of the engine room has the heat transfer characterized by the density of 7570 kg/m³ and the specific heat is taken as 470 J/(kg.K). The heat conductivity changes with temperature [14]. The overall simulation time is 1200 s. The simulation of the fire development process of the engine room when the marine fans stopped working and the cabin doors are closed takes 160 s. However, during the 1000 s the marine fans will restart.

3.2 Fire source

The fuel leakage from the fuel system is the main cause of the fire in the engine room of a ship [13]. In the article, diesel oil (Table 2) is selected as fuel and the oil pool fire as the fire source [6]. The 3.13×4×0.02 m³ oil pool is located near the diesel engine, and its volume is 3.13×4×0.02 m³. The maximum heat release rate is 34680.4 kW, which has been determined using [10]. The heat release rate follows the change of $Q = 0.2t^2$ [6].

3.3 Meshing and boundary condition

The mesh structure of the ship engine room is divided into two parts. Below the upper deck is Mesh1 and above the upper deck is Mesh2; the whole space is divided into rectangular mesh of 108×160×84(Mesh1)+35×36×30(Mesh2)=1489320 elements by using the length of the side of 0.1 m.

The second-order finite difference method is used for spatial dispersion of the governing equation and the combustion model. The explicit second-order estimate alignment method is used to disperse the flow variable. The explicit second-order Runge-
Kutta method is used to disperse the time variable. The whole computation is based on the high performance computing system, which has 12 computing nodes; the change of the distribution of smoke with iso-concentration and the height of smoke layer are studied.

The distribution of smoke in the multilayer structure and in the monolayer structure with 0.0001 kg/m³ isoconcentration at t=300 s is used as shown in Figure 4(a) and Figure 4(b) respectively. The concentration of 0.0001 kg/m³ is high, as can be seen from the simulation result [6]. The rise of the hot smoke formation, the plume, from the flame zone due to thermal buoyancy happens, and the ceiling jet is formed beneath the ceiling. Because of the effect of the platform in the multilayer structure, the strength of the ceiling jet will be increased. The large area of zone 3 in Figure 4(a) is filled with high concentration of smoke, but in Figure 4(b) it is confined to the space above of the fire source, and consequently does not spread sufficiently. Therefore, under the effect of the swirl and the ceiling jet in the multilayer structure, the spread velocity and the spread area of smoke in the multilayer structure are obviously greater than those in the monolayer structure. The consequence is that the harmfulness of fire in the multilayer structure is higher.

The change of the height of the smoke layer with time in zone 1, zone 2, zone 3 of the multilayer and monolayer structure is shown in Figure 5. The height of smoke z is determined by using the sectional measurement method; the value of z is in [0, 6.3] [6.41, 11.38] [11.41, 16.4], so the first time the height value is 6.3 m and 11.38 m in zone 1 and zone 2, respectively. This means that the smoke spread has not reached the height. Since the air enters into the engine room from the marine fans, the wind speed is diffuse and asymmetric in the wind propagation process. Due to the gradient of the density in fire thermal field, the height of the smoke layer in the monolayer structure has certain fluctuations, compared with the multilayer structure. However, since the air enters into the engine room by using the air pile in the multilayer structure, the distance of free propagation is short, the degree of diffusion is small, and thus the smoke movement has certain stability.

It is obvious from Figure 5 and Figure 6 that the height variation of the smoke layer is continuous in the monolayer structure. In other words, when the smoke layer drops to the bottom in zone 3, the smoke will began to spread in zone 2, and then the smoke will appeared in zone 1. The whole space is filled up by smoke in 200 s in the monolayer structure, and the height of the smoke layer drops to zone 1 in 165 s, the zone 1 is filled up within 35 s. However, the height variation of the smoke layer is non-continuous in the multilayer structure, when the smoke layer has not reached
the bottom of zone 3, the smoke has begun to spread in zone 2 and zone 1. Moreover, the height of the smoke layer in zone 1 has the trend of a gradual decrease within the multilayer structure, and it provides effective time for the crew evacuation.

5 Conclusion

The article elaborates the idea of subdivision of a ship engine room in multilayer and monolayer structures particularly applied to the structural characteristics of the ship engine room. The smoke movement is simulated in three-dimensions by employing large eddy simulation. The concluding remarks referring to the analysis presented in the article are the following:

(1) The harmfulness of fire in the multilayer structure is higher than it is in the case of the monolayer structure. At the same time, the results of the traditional research process show significant deviations.

(2) The smoke spread velocity and the spread area of smoke in the multilayer structure are evidently greater than in the case of the monolayer structure.

(3) The height of the smoke layer in the monolayer structure has certain fluctuations. The zone 1 is quickly filled up within 35 s. However, the height of the smoke layer in zone 1 decreases slowly.

References