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

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The article at the beginning defines multilayer and monolayer structure based on the structural characteristics of ship engine room. The smoke filling motions in multilayer and monolayer structures are studied by employing filtered balance equations and the Smagorinsky subgrid-scale model. The article investigates the distribution of smoke with iso-concentration and the height of smoke layer. The research indicates that the spread speed and the spread area of smoke in the multilayer structure are greater than in the monolayer structure. The height variation of smoke layer is non-continuous in the multilayer structure and continuous in monolayer structure. The height of smoke layer decreased slowly within zone 1 in the multilayer structure, but the smoke fills the zone 1 more quickly in the monolayer structure. The examples demonstrate that the shortcomings of the structural hypothesis in traditional method badly affect the research results. The article suggests improvements for research of fires in ship.

Keywords: *fire, multilayer structure, ship engine room, smoke filling, the large eddy simulation.*

Trodimenzionalna numerička simulacija kretanja dima u slučaju požara u brodskoj strojarnici s višeslojnom strukturom

Izvorni znanstveni rad

Članak na početku definira zamisao o višeslojnim i jednoslojnim strukturnim svojstvima brodske strojarnice. Za proučavanje širenja dima u višeslojnim i jednoslojnim strukturama korištena je jednadžba filtrirane ravnoteže i Smagorinskijev model. Članak dalje proučava raspodjelu dima iste koncentracije te visine slojeva dima. Pokazuje se da su brzina širenja i površina širenja dima u višeslojnim strukturama veće nego u jednoslojnim strukturama. Promjene slojeva dima po visini su za višeslojne strukture diskontinuirane, a kontinuirane za jednoslojne strukture. Kod višeslojnih se struktura visina slojeva dima u području 1 smanjuje polako dok se kod jednoslojnih struktura smanjuje brže. Primjeri ukazuju da nedostatci strukturne hipoteze kod primjene tradicionalnoga pristupa izazivaju znatna odstupanja. Članak stoga predlaže poboljšanja za izučavanje požara na brodovima.

Ključne riječi: *brodska strojarnica, požar, simulacija velikih vrtloga, širenje dima, višeslojne strukture.*

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

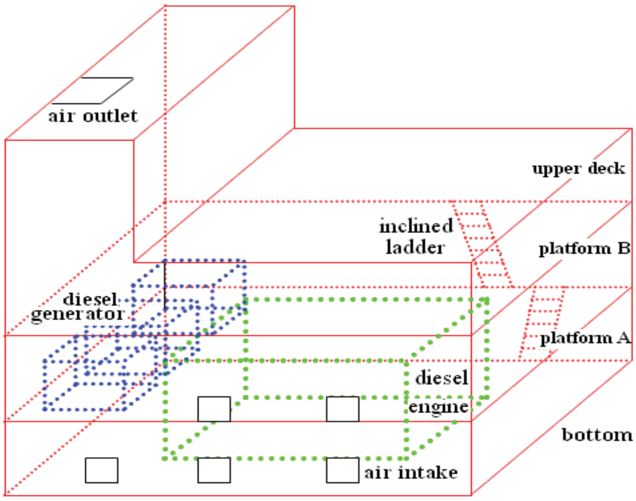


Figure 1 **The structure diagram of a typical engine room**
Slika 1 **Struktura tipične strojarnice**

Gaowan [5] studied the smoke movement in large cabin space, and investigated the law of smoke filling by using simulation methods and experimenting. The smoke movements in the case of engine room fire and flashover are numerically simulated by SU Shichuan and WANG Liang [6, 7]. The traditional research of the smoke movement in case of fire in the ship engine room normally assumes engine rooms with smooth walls, without any equipment arrangement inside, ignoring the non-uniform distribution of ventilation in the cabin, very similarly to fire investigation in enclosed chambers in buildings. However, the presence of the piping and of the diesel engine between the different layers in the multilayer structure, together with the platforms A and B have effects on the smoke flow, flame spread and radial absorption (Figure 1). Therefore, the complexity of the space structure and the presence of different layers determine the fire characteristics in the ship engine room, which are very different from those in case of a single compartment fire.

The article considers the engine room fire in ships by modelling with multilayer and monolayer structures. The three-dimensional smoke movement is simulated by using the filtered balance equations and Smagorinsky subgrid-scale model. The article investigates the characteristic of smoke distribution with iso-concentration and the height of smoke layer in multilayer and monolayer structures. The article also considers the rule of smoke filling and points to shortcomings of the traditional research methods with respect to the one presented in the article.

2 Mathematical model

2.1 Governing equations

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

$$\bar{f}(x) = \int f(x')F(x-x')dx' \tag{1}$$

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

$$F(X) = F(x_1,x_2,x_3)\begin{cases} 1/\Delta^3 & if\ |x_i| \le \Delta/2, i=1,2,3 \\ 0 & otherwise \end{cases} \tag{2}$$

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

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_i}\left(\bar{\rho}\tilde{u}_i\right) = 0 \tag{3}$$

Conservation of Momentum

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{u}_i) + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{u}_j) + \frac{\partial \bar{p}}{\partial x_j} = \frac{\partial}{\partial x_i}[\tau_{ij} - \bar{\rho}(\widetilde{u_i u_j} - \tilde{u}_i\tilde{u}_j)] \tag{4}$$

Conservation of Energy

$$\begin{aligned} &\frac{\partial}{\partial t}(\bar{\rho}\tilde{h}_s) + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{h}_s) = \bar{\dot{\omega}}_k + \overline{\frac{Dp}{Dt}} + \frac{\partial}{\partial x_i}[\overline{\lambda\frac{\partial T}{\partial x_i}} - \\ &-\bar{\rho}(\widetilde{u_i h_s} - \tilde{u}_i\tilde{h}_s)] + \overline{\tau_{ij}\frac{\partial u_i}{\partial x_i}} - \frac{\partial}{\partial x_i}(\overline{\rho\sum_{k=1}^{N}V_{k,i}Y_k h_{s,k}}) \end{aligned} \tag{5}$$

Chemical species

$$\frac{\partial(\bar{\rho}\tilde{Y}_k)}{\partial t} + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{Y}_k) = -\frac{\partial}{\partial x_i}[\overline{V_{k,i}Y_k} - \bar{\rho}(\widetilde{u_i Y_k} - \tilde{u}_i\tilde{Y}_k)] + \bar{\dot{\omega}}_k \quad k=1,N \tag{6}$$

where $\overline{\frac{Dp}{Dt}} = \frac{\partial \bar{p}}{\partial t} + \overline{u_i\frac{\partial p}{\partial x_i}}$, ρ is the density, u_i is the three dimensional velocity, p is the pressure, τ_{ij} is the stress tensor, h is the enthalpy, $h_{s,k}$ is the sensible enthalpy, $\dot{\omega}_k$ is the reaction rate of species k, λ is coefficient of heat conductivity, $V_{k,i}$ is the i- component of the diffusion velocity V_k of species k, 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:

$$\varsigma_{ij} - \frac{\delta_{ij}}{3}\varsigma_{kk} = -2\nu_t\bar{S}_{ij} \tag{7}$$

$$\nu_t = C_s^2\Delta^{4/3}l_t^{2/3}(2\bar{S}_{ij}\bar{S}_{ij})^{1/2} \tag{8}$$

$$\tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial\tilde{u}_i}{\partial x_j} + \frac{\partial\tilde{u}_j}{\partial x_i}\right) \tag{9}$$

where $\varsigma_{ij} = \overline{\bar{u}_i\bar{u}_j} - \bar{\bar{u}}_i\bar{\bar{u}}_j$ is the subgrid stress, ν_t the subgrid scale viscosity, C_S the model constant, l_t is the turbulence integral length scale.

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

$$\widetilde{u_i Y_k} - \tilde{u}_i\tilde{Y}_k = -\frac{\nu_t}{Sc_k}\frac{\partial\tilde{Y}_k}{\partial x_i} \tag{10}$$

where Sc_k 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:

$$C_xH_yO_zM_b + v_{o_2}O_2 \rightarrow v_{co_2}CO_2 + v_{H_2O}H_2O + \\ + v_{co}CO + v_sS + v_{N_2}N_2 + v_M M \tag{11}$$

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:

$$Z = Y_F + \frac{W_F}{xW_{CO_2}}Y_{CO_2} + \frac{W_F}{xW_{CO}}Y_{CO} + \frac{W_F}{xW_S}Y_S \tag{12}$$

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

$$Z_1 = Y_F \tag{13}$$

$$Z_2 = \frac{W_F}{XW_{CO_2}}Y_{CO_2} + \frac{W_F}{XW_{CO}}Y_{CO} + \frac{W_F}{XW_S}Y_S \tag{14}$$

At the burner surface, Z_1 is assigned to the mass flux of fuel, while the mass flux for Z_2 is zero. If a reaction occurs, Z_1 is converted to Z_2 representing the conversion of fuel to products.

The mass fractions of the species in the mixture $Y_k(Z_1, Z_2)$ are found by means of [10]:

$$Y_F = Y_F^I Z_1, \quad Y_{H_2O} = \frac{v_{H_2O}W_{H_2O}}{W_F}Y_F^I Z_2, \\ Y_{N_2} = (1-Z)Y_{N_2}^\infty + Y_{N_2}^I Z_1 + \frac{v_{N_2}W_{N_2}}{W_F}Y_F^I Z_2 \tag{15}$$

$$Y_{CO} = \frac{v_{CO}W_{CO}}{W_F}Y_F^I Z_2, \quad Y_S = \frac{v_s W_s}{W_F}Y_F^I Z_2, \\ Y_{O_2} = (1-Z)Y_{O_2}^\infty - \frac{v_{O_2}W_{O_2}}{W_F}Y_F^I Z_2, \tag{16}$$

$$Y_{CO_2} = \frac{v_{CO_2}W_{CO_2}}{W_F}Y_F^I Z_2, \quad Y_M = \frac{v_M W_M}{W_F}Y_F^I Z_2 \tag{17}$$

The stoichiometric coefficients are defined:

$$v_{N_2} = \frac{a}{2}, \quad v_{H_2O} = \frac{y}{2} - X_H v_s, \quad v_{O_2} = v_{co_2} + \frac{v_{co} + v_{H_2O} - z}{2} \tag{18}$$

$$v_{CO} = \frac{W_F}{W_{CO}}y_{co}, \quad v_{CO_2} = x - v_{co} - (1-X_H)v_s, \\ v_s = \frac{W_F}{W_S}y_S, \quad v_M = b \tag{19}$$

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 vessel. 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 m^2 0.5×0.5 m^2. 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.

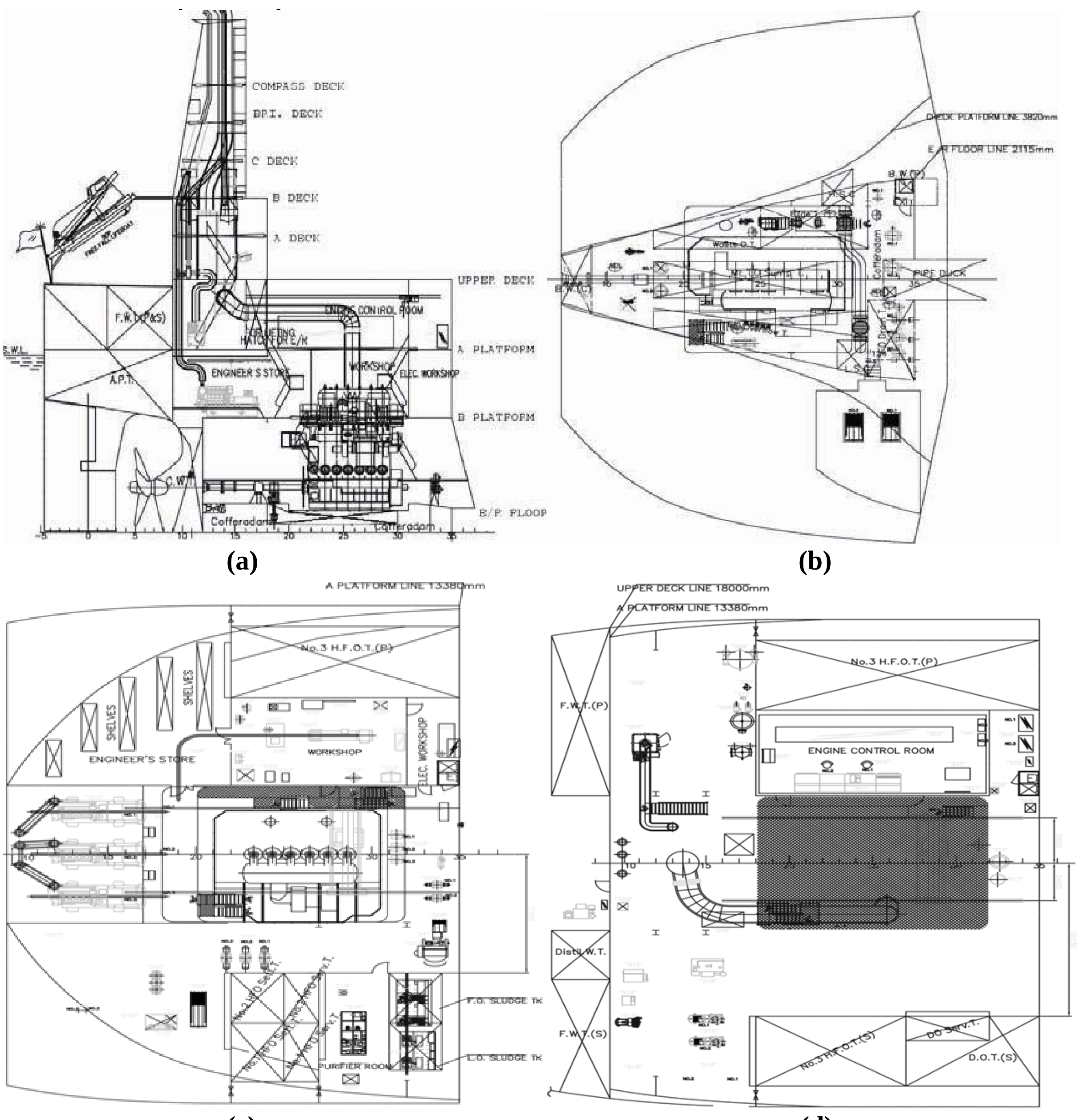
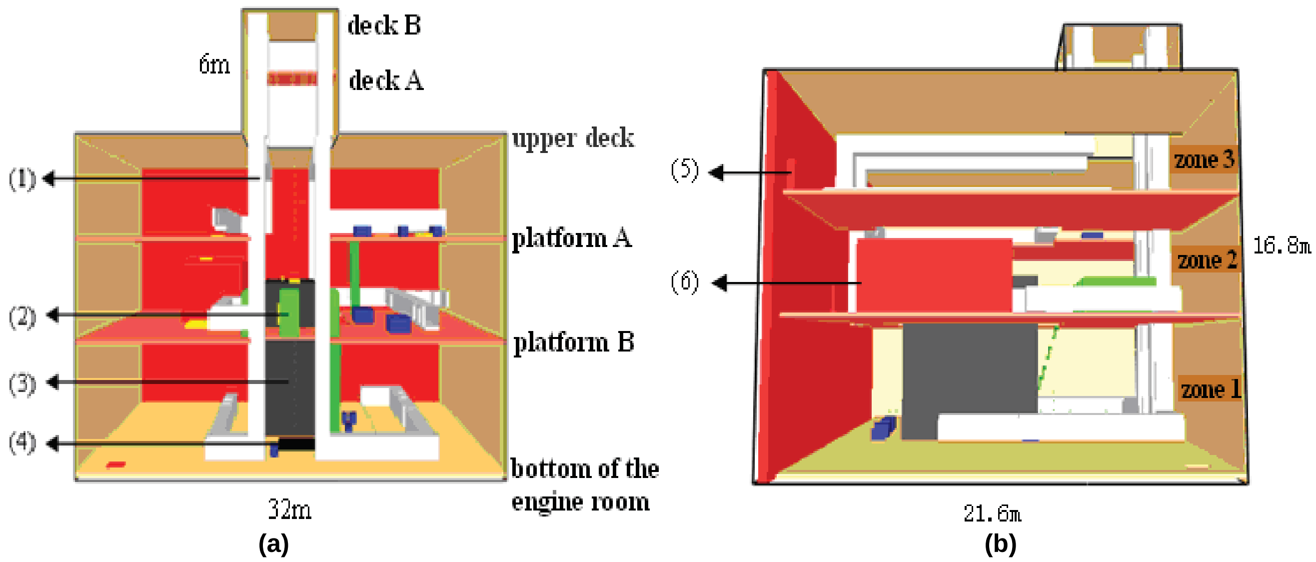


Figure 2 **The plan of the ship engine room**
Slika 2 **Nacrt brodske strojarnice**



Notes: (1) air pipe; (2) diesel generator; (3) diesel engine; (4) fire source; (5) cabin door; (6) mechanical workshop

Figure 3 **Distribution of the multilayer geometric structure model**
Slika 3 **Raspodjela modela višeslojne geometrijske strukture**

Table 1 **The parameters of the major equipment and the boundary setting**
Tablica 1 **Parametri važnije opreme i određivanje rubova**

Category	Diesel engine		Diesel generator		Fan (intake)		The area of cabin door
	Volume	Surface temperature	Volume	Surface temperature	Area	Velocity	
Parameter	4.57×8.1×8.2 m^3	40 ^{0}C	1.8×4.6×2 m^3	35 ^{0}C	1 m^2	3 m/s	1.5×2 m^2

Table 2 **Properties of diesel oil**
Tablica 2 **Svojstva dizelskog ulja**

Heat of combustion	Density	Gradual burning rate	Chemistry burning rate	Convective heat transfer coefficient	Radiation heat coefficient	Effective absorption coefficient
41	940	35	0.9	0.6	0.3	1.7

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 m^3 oil pool is located near the diesel engine. and its volume is 3.13×4×0.02 m^3. 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].

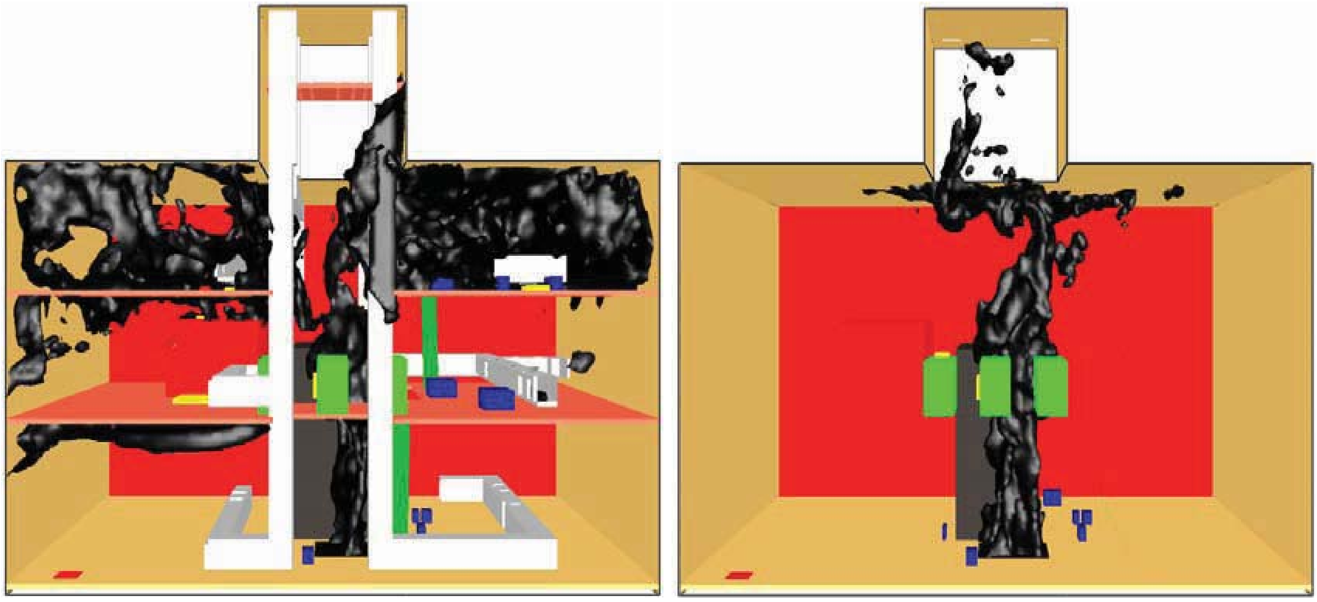
3.3 Meshing and boundary condition

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 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/m^3 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.

4 Consequence and analysis

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-



(a) multilayer structure (b) monolayer structure

Figure 4 **The 0.0001 kg/m³ equivalent distribution of the smoke concentration**
Slika 4 **Ekvivalentna razdioba koncentracije dima iznosa 0,0001 kg/m³**

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, zone3 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 directly 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

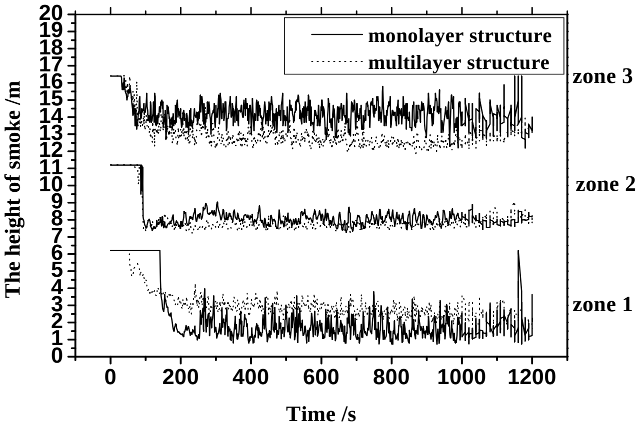


Figure 5 **The height of the smoke layer**
Slika 5 **Visina dimnog sloja**

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

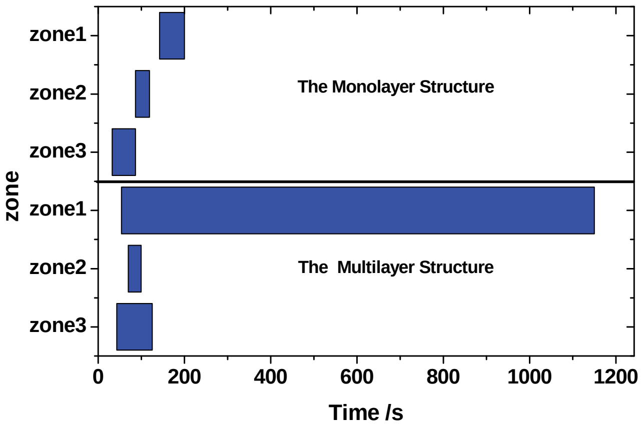


Figure 6 **The time segment of the change of the smoke layer in every zone**
Slika 6 **Dijelovi vremena promjena dimnog sloja u svakoj zoni**

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.

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