

Numerical Simulation of Fire Incidents in Ship Compartments

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Abstract

This study focuses on a ship compartment of a 5000-ton vessel. Utilizing the FDS fire simulation software, a combination of qualitative analysis and dynamic simulation is employed to investigate the progression of a fire incident in the ship compartment after implementing compartmentalization and firefighting measures. The study examines the development of the fire and the phenomenon of re-ignition. Various aspects, such as smoke diffusion patterns, temperature field variations, and CO concentration distributions, are analyzed to understand the changing environmental parameters during a fire incident on board a ship. The results demonstrate that the numerical simulation accurately portrays the re-ignition process within the compartment, providing a highly credible and reliable representation. These findings also serve as valuable references for fire assessment and ship design in the context of ship compartment fires.

Keywords

Fire Numerical Simulation; Fire Backfiring; Ship Cabin Fire.

1. Introduction

Marine fire accidents differ significantly from land-based fire incidents, characterized by rapid fire development, swift propagation, and challenging firefighting conditions. Once a fire erupts in a ship's compartments, it can lead to substantial casualties and extensive property damage due to its potential to escalate quickly, posing a significant level of risk[1]. According to the global maritime total loss accident data compiled by Allianz Global Corporate & Specialty, as shown in Table 1, fire or explosion incidents have accounted for approximately 14% of the total causes in maritime total loss accidents involving vessels with a gross tonnage exceeding 100 tons since 2015 worldwide.

Table 1. Global Maritime Total Loss Accident Cause Statistics

Year Cause	2015	2016	2017	2018	2019	2020	2021	Total
Submergence	66	48	56	33	32	25	32	292
Wrecked	19	22	15	18	9	12	1	96
Fire	9	13	8	12	20	14	8	78
Breakdown	2	10	9	3	3	4	6	37
Hull damage	2	4	5	2	1	1	1	16
Collision	7	2	1	3	3	3	3	22
Other		3		2	3	6	3	17
Total	105	102	94	73	71	65	54	558

After implementing compartmentalization and firefighting measures in the event of a fire outbreak within ship compartments, the air inside the compartments becomes inadequate to sustain the combustion of combustible materials[2]. At this stage, the smoke produced by the fire often contains a significant amount of unburned combustible gas components. If individuals do not have real-time information about the temperature and smoke distribution within the compartment and suddenly open the compartment door, fresh air rushes in. This leads to a wide-scale mixing of hot smoke and fresh air, creating a highly combustible mixture that is prone to intense combustion, resulting in a phenomenon known as fire re-ignition[3-4]. Therefore, studying ship compartment fires helps uncover the development mechanisms of both ship compartment fires and re-ignition phenomena. This knowledge serves the purpose of enhancing ship firefighting and holds significant importance in preventing and combating fires in ship cabin rooms.

To enhance the authenticity of numerical simulation results for ship compartment fires, this study focuses on the compartments of a 5000-ton bulk carrier vessel. The PyroSim pre- and post-processing software, coupled with the Fire Dynamics Simulator (FDS)[5], is employed to construct corresponding geometric models. The control equations for numerical simulation of ship compartment fires are established based on the principles of energy, momentum, and mass conservation. Large Eddy Simulation (LES) is employed as the method of choice for solving these equations, enabling an exploration of the re-ignition phenomenon in ship compartment fires and the patterns of smoke propagation and temperature distribution during the fire incident.

2. Model Construction

2.1. Basic Governing Equations

The development of ship compartment fire incidents is inherently complex, with smoke propagation approximated as three-dimensional unsteady turbulent flow[6-7]. Therefore, an idealized representation of the gases produced by the fire is necessary. As a result, the process of fire development adheres to fundamental principles of physical conservation. The specific governing equations for turbulent flow are as follows:

Mass Conservation Equation: The mass conservation equation represents the principle of mass conservation, stating that the rate of change of mass within a control volume is equal to the net mass flux through its boundaries.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

Momentum Conservation Equation: The momentum conservation equation describes the change in momentum within a control volume due to pressure, viscous forces, gravity, and external forces.

$$\rho \left[\frac{\partial u}{\partial t} + (u \cdot \nabla) u \right] + \nabla p = \rho g + f + \nabla \cdot \tau \quad (2)$$

Energy Conservation Equation: The energy conservation equation accounts for the change in total energy within a control volume due to heat transfer, work done, and internal energy changes.

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h u) = \frac{\partial p}{\partial t} - \nabla \cdot q_r + \dot{q}'''' + \nabla \cdot k \nabla T + \sum (\nabla h_i \rho D_i \nabla Y_i) \quad (3)$$

Species Transport Equation: The species transport equation tracks the change in mass fraction of a specific chemical species within a control volume due to diffusion and chemical reactions.

$$\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho Y_i u) = \nabla \cdot (\rho D_i \nabla Y_i) + \dot{m}_i'' \quad (4)$$

Ideal Gas Law Equation: The ideal gas state equation relates the pressure, volume, and temperature of an ideal gas.

$$p = \frac{\rho R T}{M} = \rho R T \sum_i \left(\frac{Y_i}{M_i} \right) \quad (5)$$

The fundamental governing equations mentioned above constitute the theoretical model used by FDS to simulate the combustion process[8]. FDS accurately describes various state parameters during ship compartment fire incidents based on these theoretical models.

2.2. Establishment of Fire Scenarios

The establishment of fire scenarios within ship compartments is a crucial step in conducting numerical simulations of fire incidents. It directly impacts the accuracy of fire simulation. In this study, the focus is on the development process of ship compartment fires in the crew compartments of a 5000-ton bulk carrier. Based on the layout diagram, each deck compartment is modeled in PyroSim. The constructed model is illustrated in Fig 1.

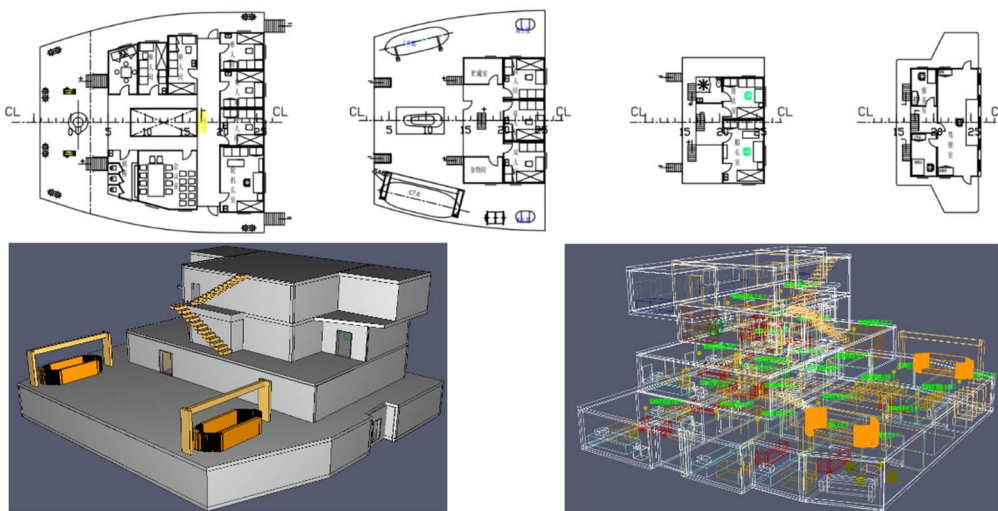


Fig. 1 Ship Compartment Structural Diagram

The chosen grid size for this study is , resulting in a total of 448448 grid cells. The selected fire scenario involves igniting a sofa and indoor furniture made of polyurethane and wood materials from a single ignition point, leading to a significant fire outbreak within the compartment. The initial heat release rate of the ignition source is set at 1500 , with a rapid fire growth factor of 0.04689 , and a smoke yield rate of 0.131 and carbon monoxide yield rate of

0.011, as referenced from the "Concise Tutorial on Fires." Additionally, the fire is set to occur for 250 seconds before the compartment door is closed. At the 2000-second mark, the compartment door is reopened. This specific configuration aims to simulate the phenomenon of re-ignition within the ship compartment after compartmentalization and firefighting measures have been applied.

3. Numerical Simulation Results Analysis

3.1. Fire Heat Release Rate Curve

In fire numerical simulations, the heat release rate curve is commonly utilized to depict the progression of a fire incident. This curve allows us to anticipate the changing trends of crucial parameters within the fire scene, including temperature, smoke release, fire scale, and fire propagation. see Fig. 2.

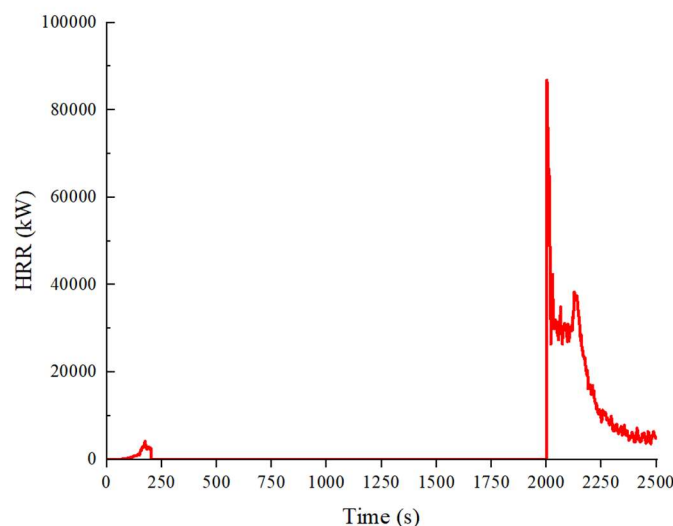


Fig. 2 Heat Release Rate Variation Curve

3.2. Temperature Field Distribution

Temperature data within the compartments will be collected using thermocouples and temperature slices distributed at various locations within the compartments and corridors. Fig 3 presents rainbow-colored temperature distribution maps obtained from temperature slices along the Y-axis and Z-axis at 70s, 250s, 2000s, 2002s, and 2500s. These maps illustrate the temperature variations during the development of the re-ignition phenomenon in the ship compartment fire.

Upon the onset of the fire, a substantial volume of high-temperature smoke is generated. Under the influence of the fire plume, the hot smoke rises and moves upward. Upon reaching the top of the compartment, the smoke spreads outward. Over time, it accumulates near the compartment's ceiling. As the quantity of high-temperature smoke increases, the temperature within the compartment gradually rises. If the compartment door is opened at this point, when the thickness of the hot smoke layer reaches the height of the door, the smoke will start spreading into the corridor.

Throughout this process, despite an overall increase in smoke temperature within the compartment, the top temperature is notably higher than the bottom temperature. Additionally, the rate of temperature change at the top is significantly faster compared to the bottom.

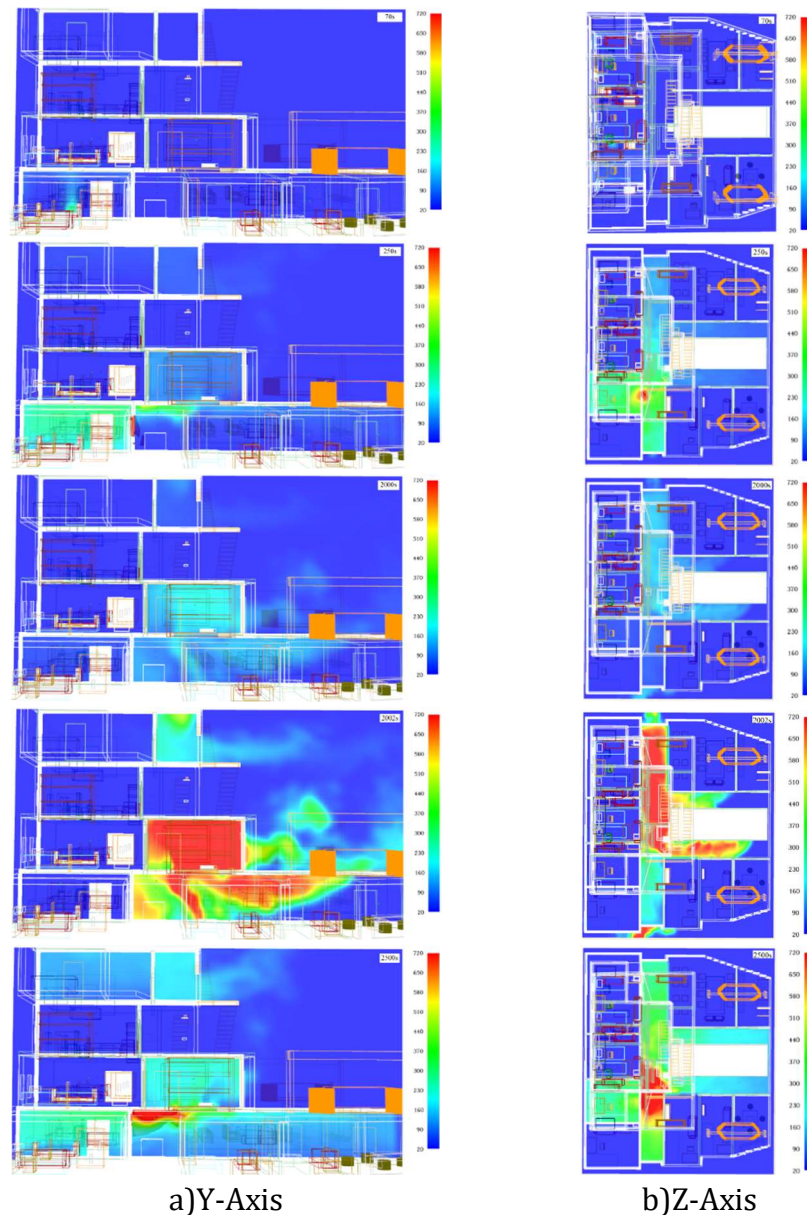


Fig. 3 Temperature Slice Cloud Maps at Different Time Intervals within the Compartment

3.3. CO and Smoke Concentration Analysis

The distribution pattern of CO gas concentration during the fire simulation process is analyzed based on the data obtained from the CO and smoke concentration variation curve shown in Figure 3.4. From the graph, it is evident that the distribution of CO gas concentration in both time and space follows a pattern similar to that of smoke concentration. As depicted in Fig 4, during the initial phase of the ship compartment fire development at 75s, the heat generated by the fire source gradually ignites the sofa within the compartment, leading to a substantial production of CO gas. As the fire spreads and the fire plume expands, CO gas reaches the compartment's ceiling. At 131s, a ceiling jet phenomenon forms as the CO-laden smoke reaches the ceiling. Due to the relatively confined upper space of the compartment, the smoke accumulates at the top, and as its concentration increases, it gradually diffuses downward. This continues until re-ignition occurs, resulting in pronounced fluctuations in both CO and smoke concentrations.

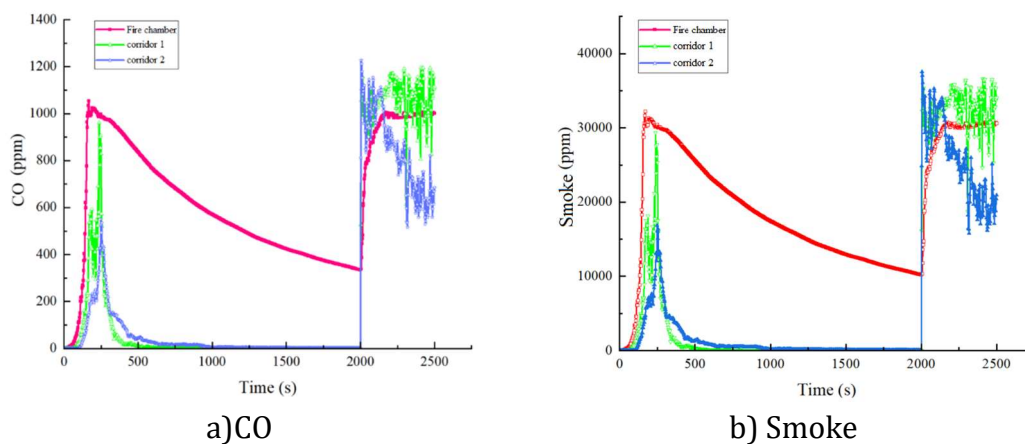


Fig. 4 CO and Smoke Concentration Variation Curves

3.4. Oxygen Concentration Analysis

As shown in Fig 5, the oxygen concentration variation curve illustrates that the fire development during the fire incident results in a significant depletion of oxygen. The oxygen concentration within the compartment of ignition rapidly decreases to 0.06 mol/mol. At 250s, the compartment undergoes attenuation due to compartmentalization and firefighting measures, leading to a decrease in the oxygen content within the ignited compartment as smoldering of the fire source occurs. Simultaneously, the oxygen concentration in the corridor gradually returns to normal levels.

At 2000s, due to the compartment being reopened, fresh air enters the compartment. The occurrence of re-ignition as part of the rekindling phenomenon causes a rapid decrease in oxygen concentration to 0.04 mol/mol near the compartment door in the corridor. Subsequently, the total oxygen content remains relatively stable throughout the subsequent combustion process, indicating the gradual attainment of a dynamic equilibrium in oxygen consumption.

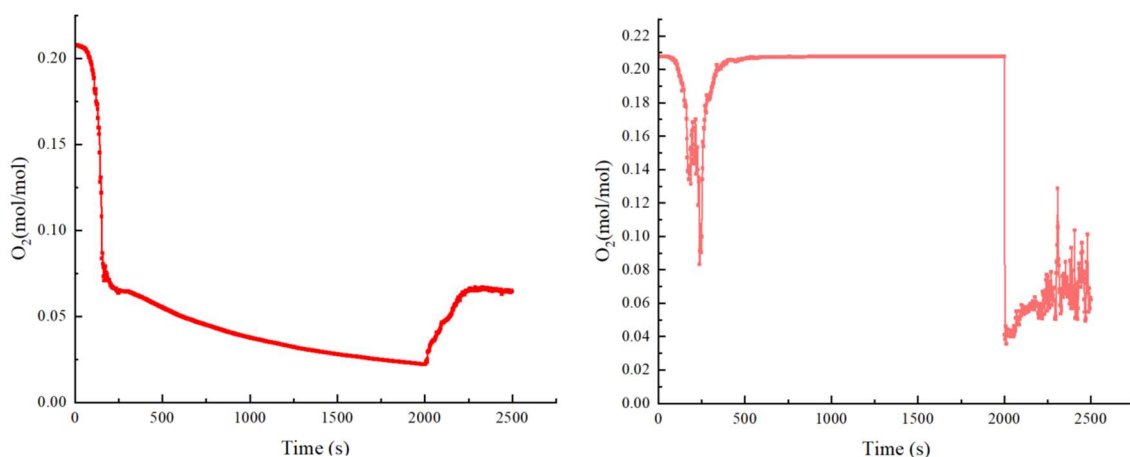


Fig. 5 Oxygen Concentration Variation Curve

4. Conclusion

This paper, based on the application of Large Eddy Simulation (LES) technique using FDS software, has effectively replicated the re-ignition phenomenon observed during compartmentalization and firefighting processes. This has provided insights into the impact of re-ignition, an aspect not easily observable during ship compartment firefighting. The following conclusions have been drawn:

(1) After a compartment experiences a fire, a significant amount of smoke ascends due to buoyancy, forming a fire plume. The smoke rises to the ceiling and then spreads throughout the compartment. It subsequently extends to the corridors, windows, and doors, moving outward to other floors. The smoke initially spreads to adjacent compartments surrounding the ignited compartment and then longitudinally along the corridors.

(2) There exists an inherent correlation between the temperature field, smoke concentration, and flame propagation. The variation in smoke concentration significantly influences the distribution of the temperature field.

(3) The re-ignition phenomenon not only leads to the widespread spread of flames within the compartment but also triggers a sudden and sharp increase in fuel heat release rate. This intensifies both convective and radiative heat transfer, and their mutual reinforcement further escalates the fuel heat release rate.

(4) Accurately monitoring the compartment's internal temperature is an effective means of preventing the occurrence of re-ignition during ship compartment fires. Therefore, in ship design and fire prevention processes, it is advisable to install fire detectors at multiple positions above the compartment. This ensures a precise understanding of temperature variations within the compartment, thereby determining the safety of opening the compartment for firefighting.

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