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Fire Safety Analysis Onboard Passenger Ships by using Fire Dynamics Simulations: Case Study of a Turkish Domestic Passenger Ship

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Abstract

Fire hazards onboard are a significant cause of accidents, leading to loss of life and property. According to the Global Integrated Shipping Information System database, 6.82 out of every 1000 passenger/Ro-Ro/Ferry ships have reported fire casualties within the category of "serious to very serious", a rate higher than that of other ship types. This study analyzes fire safety on passenger ships through fire dynamics simulations. A Turkish domestic passenger ferry with a capacity of 600 passengers was selected as the case study. The model analyzed fire extinguishing and structural fire protection systems under five scenarios. The heat release rate, total energy, and temperature parameters were also scrutinized. In addition to fire extinguishing systems like sprinklers, structural fire protection systems such as fire-rated bulkheads and decks significantly impact fire safety on passenger ships. During maintenance and operation processes, these components should undergo regular inspections by the crew and technical teams. The key findings of this study are that temperatures in the engine room increase extremely to around 500 °C in the early stages and application of neither structural nor active (extinguishing etc.) fire protection systems together led to fatal consequences onboard passenger ships.

Keywords: Passenger ships, Fire safety, Fire dynamics simulation, Field modeling

1. Introduction

No ship can operate with 100% safety or be completely error-free. Hazard classification and risk evaluation are primarily focused on assessing risk levels and identifying the greatest fire hazards on board. Properly conducted analyses can reduce failure risk to an acceptable level and enhance ship reliability under critical conditions. Therefore, risk assessment applications are of great importance to safeguard system reliability in ships. A thorough analysis of historical ship incident data can inform amendments to regulations and decrease theoretical accident risk. Maritime safety is not only of primary environmental importance but also has a considerable commercial aspect. An obvious safety level is a critical component of the package offered by operators to their customers [1].

onboard fires are among the main ship accidents, leading to loss of life and property. If a fire on board is not extinguished, it can lead to catastrophic consequences, total actual loss, and severe victimization. The data was collected from the Global Integrated Shipping Information System (GISIS), a database provided by the International Maritime Organization (IMO), containing casualty and incident data reported by IMO member states. We analyzed various types of ships reporting serious and very serious fire casualties from January 2000 to December 2022 [2]. In GISIS, fire casualty reports are classified into four categories: very serious, serious, less serious, and unspecified. Total loss of the ship and/or loss of life can be defined as very serious fire casualties. Serious fire casualties are fatalities to ships that do not qualify as "dreadful fire casualties" and which involve a fire and/or explosion, resulting in immobilization

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of main engines, extensive accommodation damage, severe structural damage, etc. In this study, only very serious and serious reported casualties were investigated. The serious and very serious fire incidents of different types of ships between January 2000 and December 2022 are listed in Table 1.

Table 1. *Reported serious and very serious fire casualties between 2000 and 2022 for different ship types [2]*

Ship types	Total	Percentage
Tanker	78	24.1%
Ro-Ro/Ferry/Pass.	54	16.7%
General cargo	45	13.9%
Fishing vessel	43	13.3%
Bulk/Ore carrier	34	10.5%
Others	30	9.3%
Container	30	9.3%
Tug/Supply vessel	9	2.8%

Ro-Ro/Ferry/Passenger ships accounted for 16.7% of marine casualties globally from 2000 to 2022. However, one must consider not only the number of incidents but also the incidence rate. The average occurrence rates of ship types that recorded serious and very serious fire fatalities between 2000 and 2022 are shown in Table 2. The average rate describes the number of fire casualties per 1,000 ship over 22 years. It is calculated by dividing the casualty numbers by the average number of ships. The average incidence rate of fire casualties for Ro-Ro/Ferry/Passenger ships from 2000 to 2022 is 6.82, meaning that, on average, 6.82 out of every 1000 such ships reported serious or very serious fire fatalities. During the same period, the average incidence rate for all other ship groups was 3.58. Therefore, the incidence rate of Ro-Ro/Ferry/Passenger ships is almost twice that of all other ship types.

Table 2. *The incidence rates and numbers of different ship types reporting serious and very serious fire casualties between 2000 and 2022*

Ship types	Average incidence rate	Average number of ships
Ro-Ro/Ferry/Pass.	6.82	7907
Tanker	5.42	14380
General cargo	2.53	17784
Fishing vessel	1.86	23000
Bulk/Ore carrier	2.63	12941
Container	5.38	5574
Tug/Supply vessel	0.43	20804

Given the high frequency of fire incidents on passenger ships, this study analyzes passenger ship fire safety from the perspective of fire dynamics simulations. As a case study, we meticulously examine a Turkish Domestic Passenger Ferry, namely SH SUTLUCE (IMO: 9564009), with a capacity of 600 passengers belonging to the Sehir Hatlari passenger ship fleet. Sehir Hatlari operates public sea transportation services in İstanbul, 933 daily trips, and transports 40 million passengers annually, offering a crucial alternative for transportation [3].

Although the literature review section investigates the fire safety onboard passenger ships in terms of regulations, modeling, risk assessment, evacuation, and performance-based design perspectives, the fire safety measurement of the Sehir Hatlari fleet reveals a research gap in the literature. In this study, fire dynamics simulation tools are used to assess the fire safety of one passenger vessel from the Sehir Hatlari fleet.

Fire safety onboard passenger ships is profoundly affected not only by fire extinguishing systems such as sprinklers but also by the presence of structural fire protection systems such as fire-rated bulkheads and decks. To reduce fire hazard risk, fire compartmentation and extinguishing systems significantly affect temperature spread in crucial compartments such as engine rooms. It is of paramount importance to ensure the proper installation of these systems with appropriate materials, paying special attention to their stability. During the maintenance and operation of passenger ships, regular inspections of the fire protection systems by both the crew and technical teams are imperative.

The aims of this study are as follows:

• Outline strategies for mitigating fire risk, particularly on passenger ships, with a case study on Sehir Hatlari.

• Simulate fire dynamics, including fire protection active and structural systems, in a passenger ship and analyze engine room fires due to the fatality and risk of these fires.

• Observe the outcomes of fire protection systems, for instance, extinguishing and structural systems, in the fire dynamics simulation,

• Develop a risk framework for onboard fire casualties, especially on passenger ships, to minimize their occurrence.

• Determine the variables that contribute to onboard fire casualties, particularly on passenger ships, thereby expanding our understanding of these phenomena and supporting new approaches to preventing onboard fires.

2. Literature Review

The literature review is analyzed in detail in terms of fire safety regulation onboard ships, fire modeling, fire protection systems such as extinguishing systems, and performance-based design depending on fire dynamics simulations and evacuations in the literature review section.

Ships are protected against fire hazards through the regulations of the IMO's International Convention for the Safety of Life at Sea (SOLAS) [4,5]. The well-known SOLAS convention was first established in 1914 after the Titanic disaster. Its main purpose was to set the minimum safety requirements onboard. Then, the SOLAS convention was constantly amended after the major accidents that highlighted new safety aspects onboard. Chapter II-2 of SOLAS governs fire safety onboard. The regulations provide all fire safety provisions, starting with division and separation by thermal and structural boundaries, and then continuing with restrictions on combustible materials and fire detection systems at the origin of fires. In the event of a fire incident, the regulations cover containment and extinction procedures at the fire's origin. The regulations also ensure the availability of fire-extinguishing appliances and minimize ignition possibilities, thus protecting the means of escape and firefighting through special provisions [4].

Fires that occur in restricted spaces, such as compartments within buildings, ships, and airplanes, are referred to as "compartment fires". This typically starts slight and then expands to involve a significant fuel source, becoming influenced by the compartment's boundaries [6]. Various fire models have been developed and are continually being refined and validated to predict compartment fire consequences [7]. There are two types of models available: deterministic and probabilistic. Deterministic models allow for a "single possible development", while probabilistic models attempt to investigate a range of potential developments. Over the years, deterministic models have gained popularity among fire safety engineers primarily because they provide numbers that are readily usable, often taking a conservative approach [8]. Initial semi-empirical and basic analytical models, or hand-calculation models, laid the foundation for deterministic fire models. Zone models, the earliest generation and most widely used types of fire models, were developed as a result of this evolution. The ability to solve the fundamental conservation equations of mass, energy, and momentum has facilitated advances in Computational Fluid Dynamics (CFD) modeling to enable the simulation of fire phenomena from first principles. Field or CFD modeling is an approach that has shown efficacy in addressing a range of fire safety issues [9].

An innovative simulation method to examine the propagation rule of ship cabin fire and smoke, with model validation performed using a miniature model, is presented [10]. The fire smoke flow characteristics in closed ship cabins, which lay a theoretical basis for firefighting in ship cabins, were analyzed and verified [11]. The Fire Dynamics Simulator (FDS) tool, equipped with a Large Eddy Simulation (LES) turbulence model, was used to model a full-scale cabin fire experiment designed by the U.S. Coast Guard [12]. FDS could calculate the precise temperature distribution in the cabin sections. Fire scenarios are considered rather than a formal risk modeling process. The machinery room of the target ship was used for the fire simulation [13]. Fire suppression models are studied using reinforcement-learning techniques to aim at fire extinguishing nozzles [14]. A general overview of machine learning and specific techniques being explored for performing low-cost, high-fidelity fire predictions are offered [15]. A comprehensive study [16] delves into the structural strength of fire protection installation systems, providing valuable guidelines for the appropriate implementation of fire-related systems in ship compartments. The fire safety of multilayer and monolayer engine rooms using three-dimensional numerical simulations has been investigated [17]. Fire incidents in the ship engine room were numerically analyzed in terms of temperature and smoke based on OpenFOAM, and the main factors such as fire position, fire area, and ventilation situation factors were investigated to determine the temperature distribution and smoke propagation in the engine room [18]. From the perspective of passenger evacuation, [19] displays a non-monotonic relationship between the peak heat release rate (HRR) and the required safe egress time by combining fire dynamics and evacuation simulations. Wang et al. [20] studied the ship evacuation route assignment approach and added new parameters to simulate human performance under special circumstances, such as lifting, trimming, and ship motions. The suppression of a pool fire in an engine room under different ventilation conditions has been studied depending on the fire extinguishing situation of the spray equipment [21].

3. Materials and Methods

3.1. Fire Modeling

Generally, there are two types of deterministic models: zone and field models. The former rely mostly on empirical correlations between specific variables derived from laboratory-scale experiments. Zone models are subdivided into one-layer, two-layer, and HVAC models, depending on the type of problem they are attempting to solve. Field models assume fewer empirical relations and attempt to solve the governing conservation equations (mass, momentum, and enthalpy) using numerical techniques.

One-layer models attempt to calculate smoke movement in regions remote from the fire and can handle large, complex buildings with numerous floors and rooms. On the other hand, two-layer models are limited to fires in small enclosures (with no vertical shafts) and consider smoke movement in the immediate vicinity of the fire. The HVAC models calculate smoke spread by HVAC systems and are theoretically similar to the one-layer models. Various types of computer fire models are illustrated in Figure 1 [8].

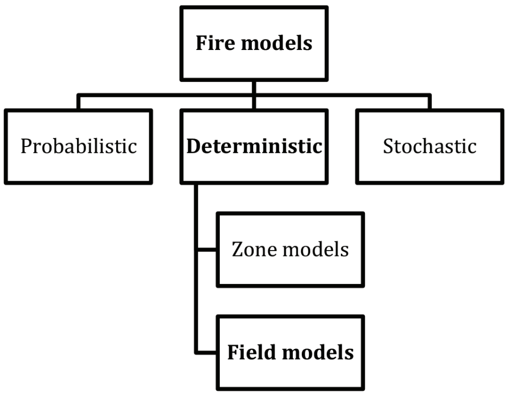

Figure 1. *Types of computer fire models*

This study employs a field model for fire modeling. Field (or CFD) models split the domain into multiple smaller control volumes to calculate the flow. With advancements in computer science, field models have become increasingly common and are now extensively used [8]. The conservation laws of mass, momentum, energy, and species concentrations are applied to each of these control volumes. Solving the equations, along with the equation of state, provides predictions of fluid flow properties with an accuracy level that is dependent on the size and number of control volumes considered. Figure 2 depicts the two layers and plumes in a room fire, divided by field models into small control volumes [22]. Fire scenario outcomes onboard passenger ships were numerically predicted by comparing the zone and field models and concluded that the role of the zone model is significant in the early design phase of passenger ships [23].

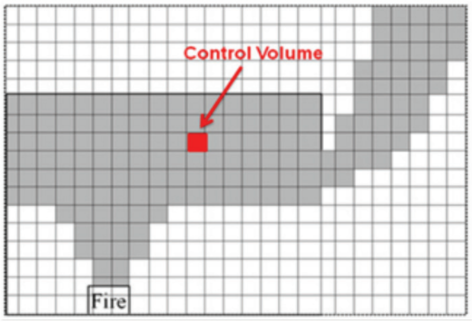

Figure 2. *The two layers and plumes in a room fire as divided by field models into small control volumes*

The transport equations for mass, momentum, and energy are given as [24]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial t}(\rho u_i) = 0 \tag{1}$$

Is the continuity Equation,

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + F_i \tag{2}$$

is the momentum equation, where u_i is the velocity and ρ is the variable density, noting that the density in a combusting flow is dependent on pressure, temperature, and species concentration, p is the pressure, F_i represents the body forces including gravity and τ_{ij} is the viscous stress tensor defined as follows:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \tag{3}$$

The transport equations for species k can be written as:

$$\frac{\partial}{\partial t}(\rho Y_k) + \frac{\partial}{\partial x_i}(\rho u_i Y_k) = \frac{\partial}{\partial x_i}\left(\rho D_k \frac{\partial Y_k}{\partial x_i}\right) + \dot{\omega}_k \tag{4}$$

where Y_k is the mass fraction of a species k, D_k is the species diffusion coefficient in (m^2/s) which is usually considered a single value for all the involved species and $\dot{\omega}_k$ is the source or sink term representing the generation or destruction of a species due to chemical reactions. The energy equations in their simplified form can be written as:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left[\frac{\mu}{\sigma_h}\frac{\partial h}{x_i}\right] + \frac{\partial P}{\partial t} + S_{rad} \tag{5}$$

The HRR (also known as energy release rate) is a crucial time-varying parameter that provides a quantitative description of a design fire. The major fire properties, including smoke layer height, gas temperature, and plume velocity, are all within its control. HRR, measured in kW and plotted against time, represents the size of the fire and its potential damage. The fuel mass loss rate (MLR in kg/s) and the effective heat of combustion for the burning fuel (Δhc in kJ/kg) can be multiplied to obtain the HRR of combustion (HRR in kW); HRR = MLR · Δhc [25].

3.2. Case Study of a Turkish Domestic Passenger Ship

Sehir Hatlari provides vital public sea transportation services in İstanbul, offering a crucial alternative to public transportation. The Sehir Hatlari fleet comprises 28 passenger vessels, categorized on the basis of passenger capacity into five classes: 2100, 1800, 1500, 700, and 600 passengers. A review of the fleet reveals that the vessels were built between 1973 and 2005, and the newer vessels have a smaller capacity than the older ones. According to [26], the change in capacity is related to the operational expenses of the vessels and the occupancy rate of the lines. The propulsion system alternatives of passenger ships used in public transportation, such as Sehir Hatlari, are analyzed in terms of fuel consumption and investment costs [27]. In addition to passenger vessels, Sehir Hatlari has invested in Sea Taxis, which offer private sea transportation with a capacity of 6-10 passengers.

In this study SH SUTLUCE passenger vessel from İstanbul's Sehir Hatlari fleet, which has the lowest passenger capacity, was chosen for research. The specifications are provided in Table 3 and a photograph of SH SUTLUCE is depicted in Figure 3 [28].

Table 3. *Technical specifications of the SH SUTLUCE (IMO: 9564009)*

Building year	2009
Passenger capacity	600
Gross tonnage (ton)	175.4
Net tonnage (ton)	69.2
Length overall (m)	41.97
Beam (m)	8.5
Depth (m)	2.8
Freeboard (m)	0.754
Main engine type	D16C-BMH VOLVO PENTA
Power	2X641BHP

Figure 3. *Six hundred passenger capacity vessels SH SUTLUCE (IMO: 9564009)*

In general, the structure of a whole passenger ship is very complex for modeling all details in a model. In the first step, this study focuses on the lower deck of selected passenger vessels depending on [29] that evaluates 20 common risks in ship engine rooms, and fire risk appears among the five most significant hazards. The detailed shapes of each piece of equipment in this deck are irregular. Therefore, since the FDS tool is used for investigating the fire within the vessel and cuboid meshes are used for building the physical model, the structure information of the actual deck should be simplified as follows:

a) The intricate layout of the deck: most of these small pieces of equipment are disregarded while creating the numerical model because they may not have a significant impact on the spread of the fire.

b) Explosibility: Because the deck contains a lot of small equipment, such as gas bombs, oil tanks, and high-pressure containers, an explosive phenomenon might easily occur when a fire starts. This could make the fire more destructive. To simplify the calculation, this would be disregarded because of the complexity of explosibility.

c) The impact of human activity on the spread of the fire: during the early stages of the fire's development within the deck, people's movements have very little bearing on the distribution of flow. Human action can therefore be disregarded. However, because of human interference, the fire's course will be unpredictable in its later stages. The consequences of human behavior are not discussed in this study.

d) The ignitability of the fuel system is disregarded in order to streamline the model computation.

3.3. Boundary and Initial Conditions for the Simulations of the Case Study

In this case, the simplified structure and the final model are shown in Figure 4. The overall length of the model is 41.1 m, width is 8.5 m, and height is 2.8 m. The entire deck is separated by fire-rated bulkheads into four main zones: helm station, engine room, mechanical and electrical workshop, and warehouses. The length between each fire-rated bulkhead is 4.3 m. Two diesel engines are in the center of the engine room. In each fire, the rated bulkheads have three door openings. In addition, ladder and service openings are modeled on the basis of the current situation of the passenger ship. The study assumes that the openings are stable and do not change during the life of the vessel. In this control volume, the boundary conditions and mesh figure for the case of fire dynamics simulation are depicted in Figure 5.

The fire source is located in the center of the engine room and its cuboid dimension is 1 m*1 m*0.25 m. Therefore, the maximum heat release rate is 3460 kW [30]. The fire during its growth stage and during its decay period can be described by a t2 curve. The methane reaction is used in fire modeling, and the specific heat of combustion is determined as 50 MJ/kg [31,32]. The well-known very LES is used based on the

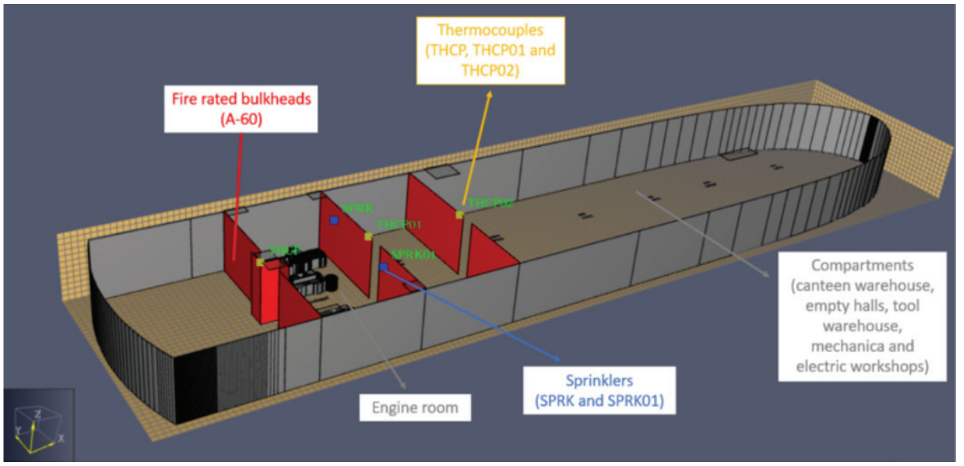

***Figure 4.** Geometric model structure of the lower deck of SH SUTLUCE*

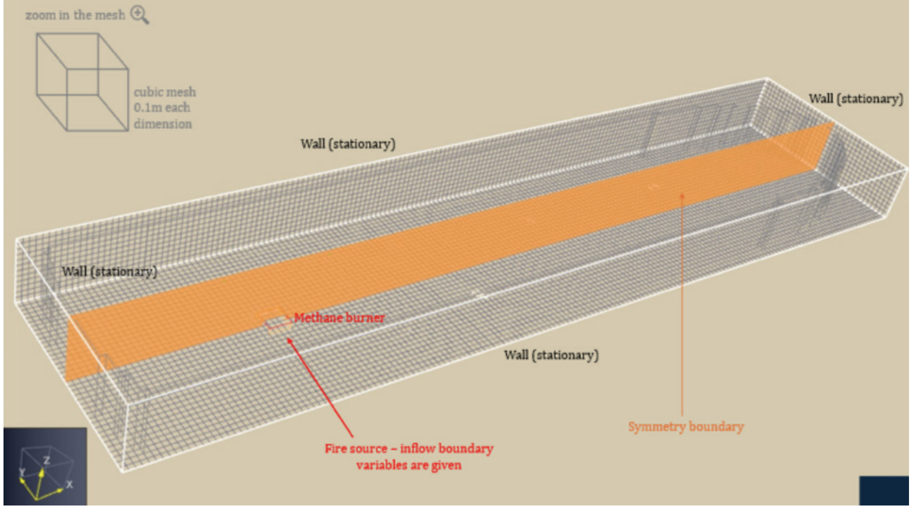

***Figure 5.** Boundary conditions and mesh figure for the case of fire simulation*

concept of filtering a larger part of turbulent fluctuations compared with the standard LES [33]. It can be concluded that the VLES model has better predictions of the swirling flow field for both the mean and root mean results than the LES model [34].

From the perspective of fire protection systems, extinguisher systems such as sprinklers and structural systems such as fire-rated bulkheads & decks are concentrated in this study. On the other hand, fire detection and alarm systems are ignored to simulate. The sprinklers are of generic industrial type, and the activation temperature is 93.33 °C. To determine the arrangement of sprinklers, the geometrical shape method is used. The geometrical shape method is the simplest and most widely used spacing method because it provides the highest uniformity for the system [35]. In conclusion, the main parameters of the fire simulation are given in Table 4.

3.4. Experimental Validation and Mesh Dependency

Before running the fire dynamics simulations of the case study, the parameters mentioned in the previous section must be validated and verified by an experimental study. Steckler et al. [36] conducted several fire tests inside a compartment to study fire-induced flows. The experimental data gathered from these fire tests were used as part of the validation for fire dynamics simulations. The data indicate non-spreading fires in small compartments. A series of 45 experiments were conducted to investigate fire-induced flows in a compartment 2.8 m * 2.8 m in plane and 2.18 m in height. The 0.3 m diameter burner was supplied with commercial grade methane at fixed rates, producing a constant fire strength of 62.9 kW. The model of the Steckler et al. [36] experiment is depicted in Figure 6. Depending on the burner type and geometry of the case study, experiments are performed as a validation study [36].

Table 4. *The main parameters of fire simulations*

	Reaction	Methane
Fire source	Maximum heat release rate	3460 kW
	Specific heat of combustion	50 MJ/kg
	Original volume of the fire	1 m*1 m*0.25 m
Fire rated bulkheads	Material	Steel
	Thickness	0.01 m
Fire extinguishing system	Type	Generic industrial
	Arrangement method	Geometric shape method
	Quantity	1, 2 or 4 (depends on scenarios)
	Activation temperature	93.33 °C

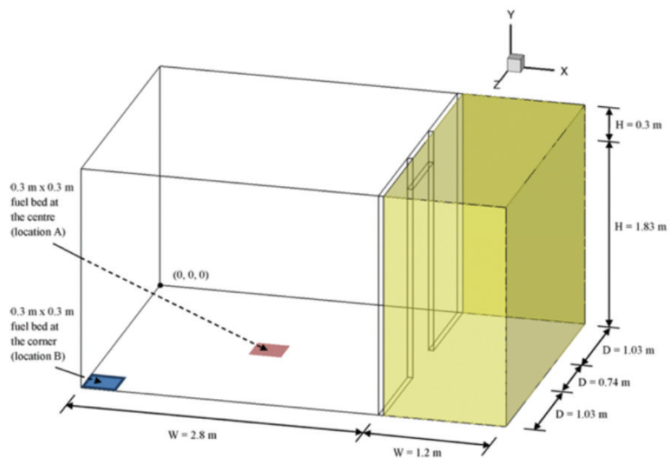

Figure 6. *Model of Steckler experiment*

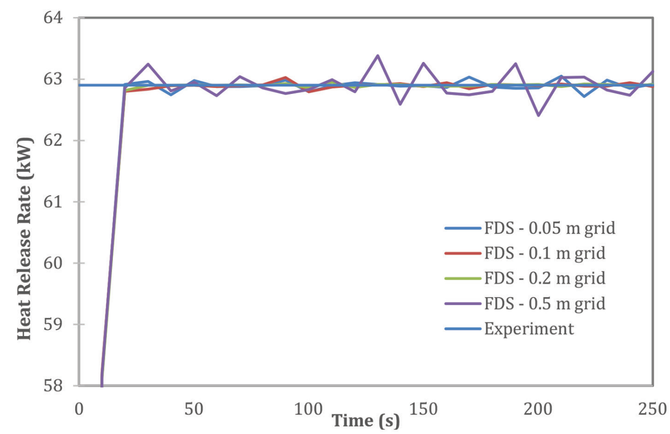

Figure 7. *Heat release rate results of the experiment and fire dynamic simulations*

Initially, comparison of heat release rate between fire dynamics simulations with 4 different mesh sizes and experiment are given in Figure 7. In fire dynamics simulations, heat release rate is zero at time zero and significantly increases to around 60 kW at approximately 20 seconds. Experiment and FDS results are validated in terms of heat release rate and mesh sizes at heat release rate are not affected mainly.

In the model, 19 thermocouples are placed at heights from 0 to 1.8 m from bottom to top. To validate the model and running mesh dependencies, temperatures on these thermocouples for experiments and fire dynamics simulations are illustrated in Figure 8. Differences in temperatures between the experiment and FDS results are approximately 10%. Because of the grid resolution, the grid size was selected as 0.1 m according to Figure 8.

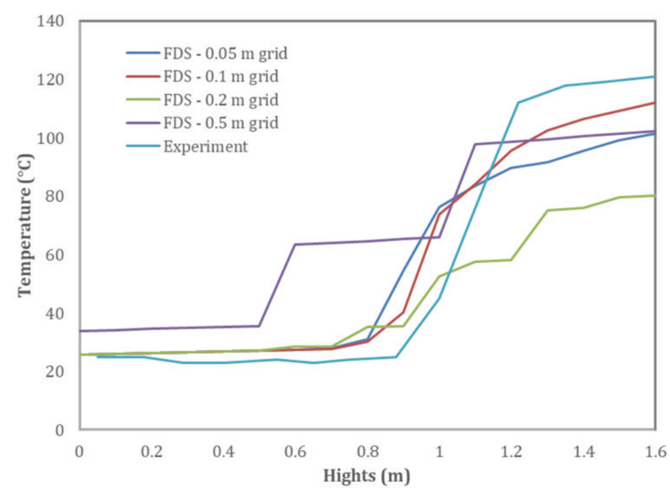

Figure 8. *Temperatures of thermocouples in experiments and fire dynamics simulations with different mesh sizes*

The simulation results match well with the experimental data; despite some initial differences, these are reasonable because of the response time of the temperature sensor used in the experiment. The recorded values are delayed from the true temperature during the early stages of the fire because of the extremely high rate of temperature increase. As the temperature increase rate decreases, the variations disappear.

In addition to the grid resolution of Steckler experiments, the characteristic fire diameter (D^*) is calculated according to Equation 6 [37]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \tag{6}$$

where $\dot{Q}$ is the total heat release rate of the fire, ρ_∞ is the air density (kg/m^3), c_p is the air specific heat (kJ/kg·K), g is the gravitational constant (m/s^2) and T_∞ is the ambient temperature (K). Depending on the calculation, D^* is calculated as a 0.1 m grid size that is aligned with the Steckler experiment results.

4. Results of Fire Dynamics Simulations

In order to analyze fire safety onboard passenger ships in the case of SH SUTLUCE, several scenarios are derived in terms of fire fatality level. Table 5 shows the details of the fire simulation scenarios. Scenario 1 is divided into three main categories depending on the quantity and arrangement of sprinklers. To determine the end time of the simulation, each scenario was run up to the stabilization point; therefore, the end time was specified as 280, 480, and 300 s for Scenarios 1, 2, and 3, respectively. In each scenario, simulations were run until the heat release rate, temperature, and pressure parameters stabilized.s

Heat release rate - time graphs for each scenario are illustrated in Figure 9. In the first few seconds, the heat release rates increase dramatically for all scenarios and continue fluctuating at roughly the same level as the determined maximum heat release rate in the simulation; 3460 kW.

The total energy of the control volume is another crucial factor in fire dynamics simulations. In Figure 10, the total energy and time charts are analyzed for each scenario. Similar to the heat release rate, the total energy dramatically increases with the ignition of the fire in the compartment. After almost 50 s for all scenarios, the average total energy converges to zero. In the worst scenario, this convergence starts mainly after 100 s, and the total energy is approximately doubled compared to other scenarios at 50 s.

In the scenarios, thermocouples were placed into the mid-top of each fire-rated bulkhead in the lower deck. Figure 11 demonstrates the location of thermocouples in the lower deck. The measured temperatures on the thermocouples are given in Figure 12. THCP1 is the most critical one that reaches more than 500 °C for all scenarios except the worst one. Fire-rated bulkheads cause closed compartments, which leads to a temperature increase in THCP1. At the end of the simulation, THCP1 stabilizes at approximately 400 °C for each scenario. THCP2 reaches at 250 °C in only scenario 2 and in other cases; THCP2 fluctuates below 150 °C. Lastly, same graph characteristic is shown for TCHP3 with fluctuating at almost 120 °C.

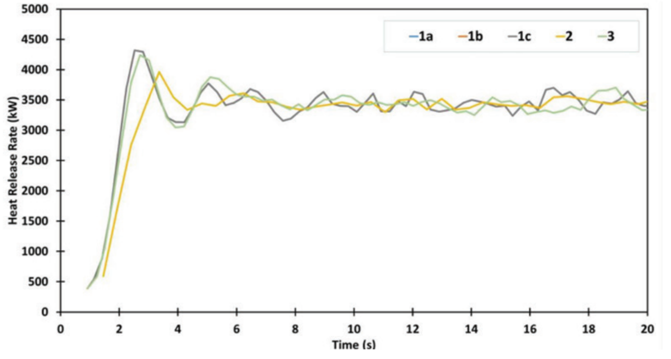

Figure 9. *Heat release rates of three different scenarios*

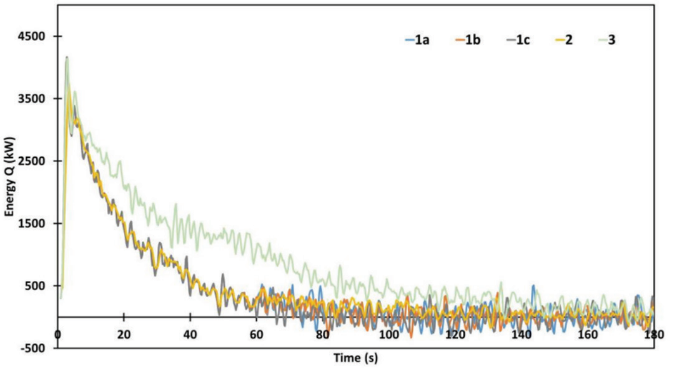

Figure 10. *Total energy (Q) of three different scenarios*

Table 5. *Scenarios of the fire simulations*

Scenarios	Fire extinguishing system (sprinklers)	Fire-rated bulkheads & decks	Number of sprinklers nozzles	Simulation time (s)	Scenario fatality
Scenario 1a	Yes	Yes	1	280	Best
Scenario 1b	Yes	Yes	2	280	Best
Scenario 1c	Yes	Yes	4	280	Best
Scenario 2	No	Yes	-	480	Medium
Scenario 3	No	No	-	300	Worst

In the three best scenarios, the arrangement and number of sprinklers are derived from each scenario. Figure 13 presents the arrangements of the sprinklers in the engine room. The arrangement of sprinklers is determined according to the geometrical shape method, and Scenarios 1a, 1b, and 1c have one, two, and four sprinklers, respectively. In Figure 14, the temperature change of sprinkler nozzles for the scenarios is illustrated. In Scenarios 1b and 1c, the temperature can reach 160 °C even though Scenario 1a has a maximum nozzle temperature of 180 °C. The characteristics of the graphs are the same due to the selection of the same fire source and sprinkler type as generic industrial. For this case, Scenario 1b, which includes two sprinkler nozzles, can be selected as the best fire-extinguishing sprinkler arrangement.

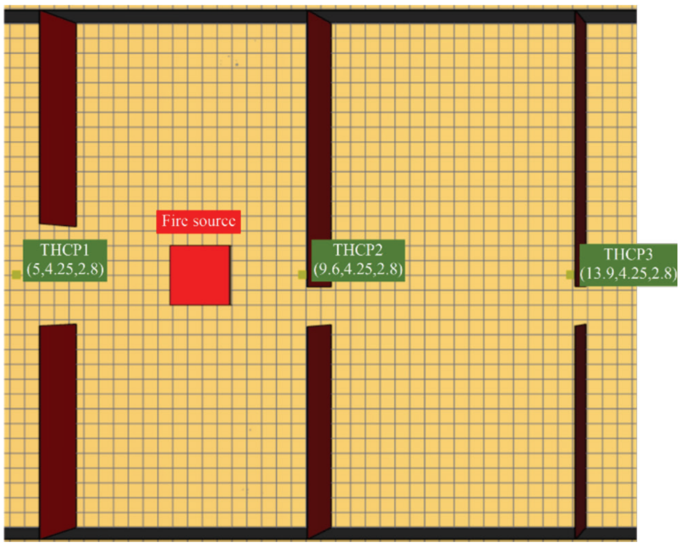

Figure 11. *Arrangement of thermocouples in the lower deck*

The temperature distribution on y=4.25 m at t=50 s for all scenarios is depicted in Figure 15. Time is selected depending on the activation of the sprinklers. In the scenarios, sprinklers break out after the 50s. In only Scenario 3, temperature along the ship length is distributed, and other zones such as workshop areas and warehouses in the lower deck are affected by the fire in the engine room. This indicates that fire-rated bulkheads play a crucial role in compartmentation even though only 50 s last. Figure 16 represents the temperature distribution at y=4.25 and t=150 s along the lower deck for the scenarios. This figure states that even though the time goes to 100 s, the temperature of the sprinkler included scenarios is almost the same as in Figure 12. However, the temperature of other zones increases dramatically to almost 300 °C in Scenario 3, which lacks fire-rated bulkheads. In addition, differences between scenario 3 and others last the same until the end of the simulation.

In Figures 17 and 18, the temperature distribution on the fire-rated bulkhead located at x=5.4 m is given at time 100 s and 250 s, respectively. This bulkhead is crucial in terms of fire safety because it separates the engine room from the helm station. In these figures, the positive effect of sprinklers is shown when comparing Scenarios 1c and 2.

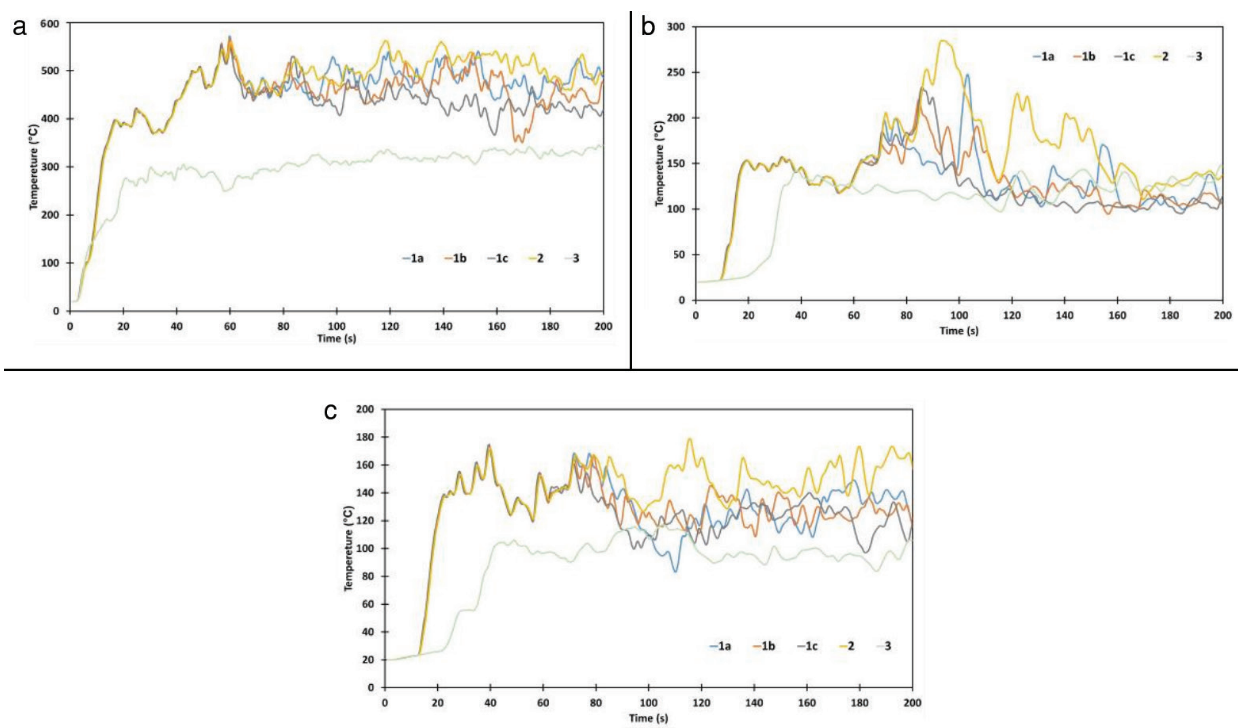

Figure 12. *Temperature change of the thermocouples in each scenario: a) THCP1, b) THCP2, and c) THCP3*

Lastly, the fire-rated deck is placed at z=2.8 m along the vessel. Figure 19 represents the temperature change on the z=2.8 m plane at 100 and 200 s, respectively. This plane in the z direction is a significant obstacle for spreading fire along the ship vertically. If this fire-rated deck collapses because of the temperature increase, passenger compartments would be in danger in terms of fire safety.

In conclusion, similar studies were compared with the results of this study. Azzi [38] investigated cabin, large space, and corridor fire scenarios onboard passenger ships using a CFD tool called a field model. The models for the scenarios provided in the study are considered to examine results similar to those of this study in terms of temperature [38]. Kang et al. [13] used computational fire simulations in the early stage of ship design, including fire suppression systems in the engine room and field model. Similar to our study, this work shows the effect of the extinguishing system on the temperature [13]. Wang et al. [39] investigated the vertical distribution profile of the temperature in a sealed ship engine room and found that the temperature gradient in the vertical direction is slightly smaller than that in a compartment with openings similar to our study. In summary, the CFD results in this study are aligned with similar studies and contribute to the literature by simulating the entire deck, including the engine room and other technical compartments together, and using both extinguishing and structural fire protection systems in the simulation.

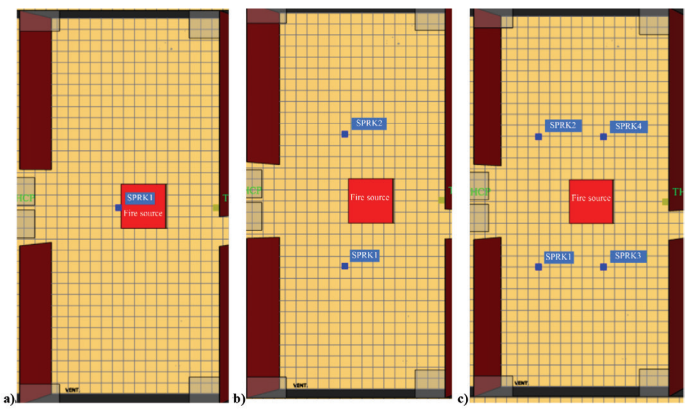

__Figure 13.__ Arrangement of the sprinklers in the engine room scenarios a) 1a, b) 1b, c) 1c

5. Conclusion and Recommendations

In this study, fire safety onboard passenger ships was examined using a fire-specific CFD tool called fire dynamics simulation. The case study specifically focuses on analyzing the engine room fire of a 600-passenger passenger ship operated by Sehir Hatlari, a governmental organization responsible for public marine transportation in İstanbul, which transports 40 million passengers annually. Simulation scenarios are called best, medium, and worst according to fire incident severity, and the scenarios vary depending on active and structural fire protection systems. Active fire protection systems are selected as generic industrial sprinklers, and structural fire protection systems are selected as fire-rated bulkheads and decks. Additionally,

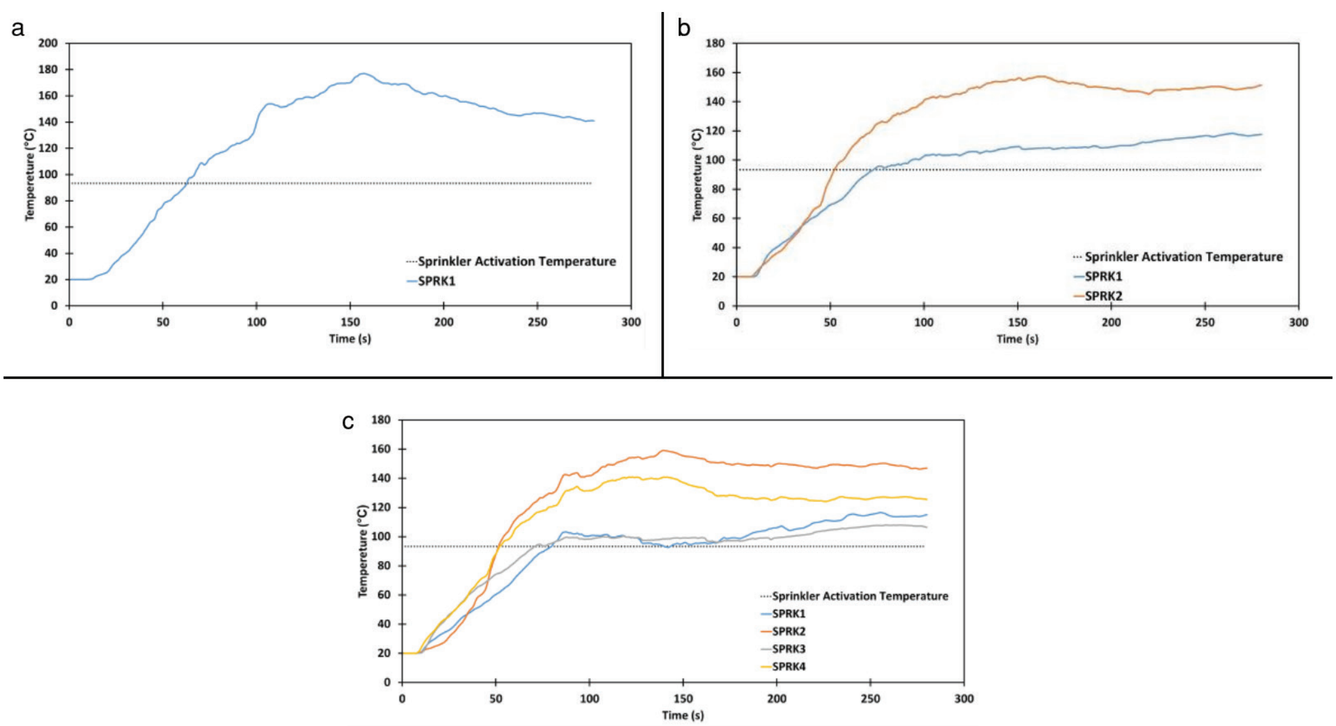

***Figure 14.** Temperature change of sprinklers in the scenarios a) 1a, b) 1b, c) 1c*

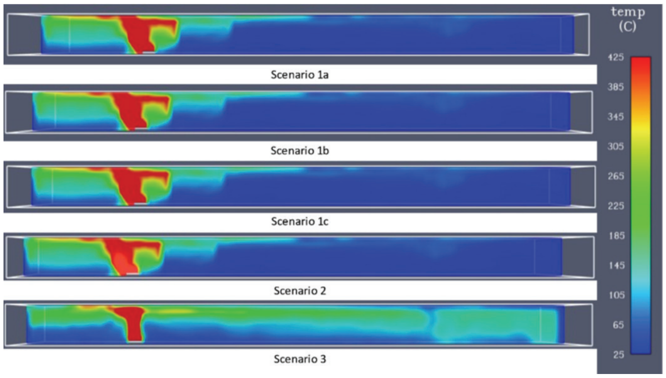

Figure 15. *Temperature distribution at y=4.25 m at t=50 s for all scenarios*

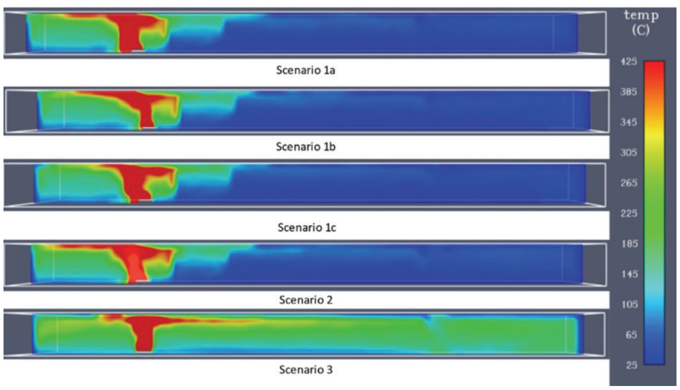

Figure 16. *Temperature distribution on y=4.25 m at t=150 s for all scenarios*

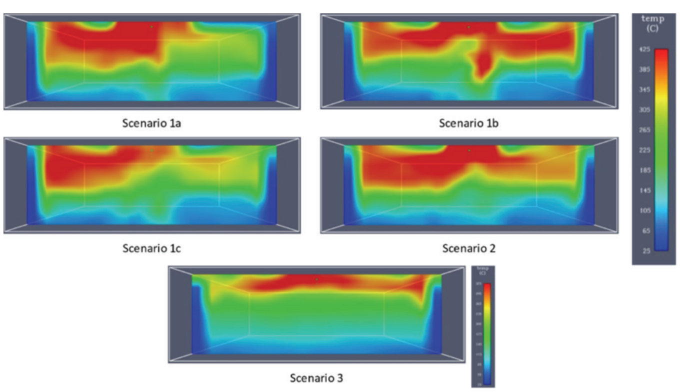

Figure 17. *Temperature distribution on x=5.4m at t=100s for all scenarios*

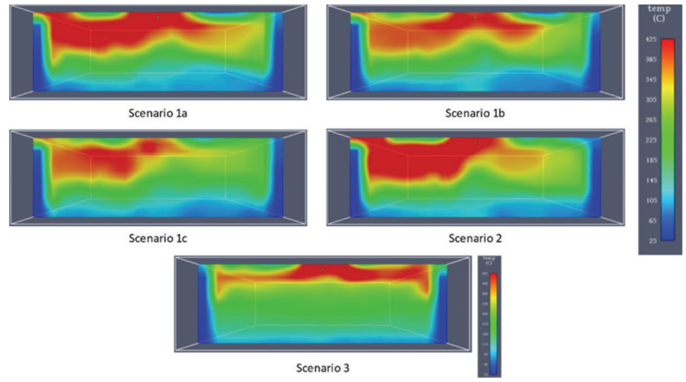

Figure 18. *Temperature distribution on x=5.4 m at t=250 s for all scenarios*

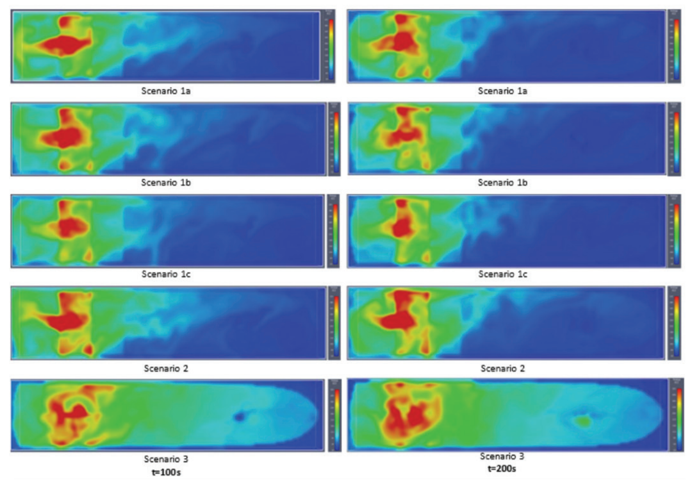

Figure 19. *Temperature distribution on z=2.8 m at t=100 s and t=200 s for all scenarios*

in the best scenario, the number and arrangement of sprinklers diversify into three sub-cases with one, two, and four sprinklers in the engine room. The cubic grids were selected as 0.1 m in each dimension.

The findings derived from the fire dynamics simulations underscore the critical role played by the protection systems in impeding the spread of fire across passenger ships. Also, this study provides a novelty to the marine safety literature by applying fire dynamics simulation to a domestic passenger ship. The key findings of this study are that temperatures in the engine room increase extremely to around 500 °C in the early stages and application of neither structural nor active (extinguishing etc.) fire protection systems together led to fatal consequences onboard passenger ships.

For future research, the following are recommended:

• The inclusion of other compartments to the fire dynamics simulation, such as atriums, upper decks, galleries, etc., is suggested.

• The selection of different types of fire origin within the control volume can give more diversified results.

• Exploration of diverse sprinkler types and activation temperatures should be included in scenarios involving malfunctioning systems.

In addition to the above recommendations, human factor analysis can be added to the study for future research. The evacuation model and fire detection system design are affected directly by human factors. For the evacuation modeling, a simulation tool dedicated to the fire safety industry called PathFinder is advised to be integrated. In addition, performance-based fire safety analysis onboard passenger ships is a developing research area, and fire dynamics simulations can be applied to other ship types such as Ro-Ro, container, and tanker. Lastly, smoke propagation can be added to the study, including the materials that led to the smoke in the control volume. For instance, antiskid coatings can be considered for smoke concentration and implicit evacuation.

The authors believe that undertaking these suggested investigations can yield valuable insights and contribute to the enhancement of fire safety measures on passenger ships.

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Authorship Contributions

Concept design: T. Aycı, B. Barlas, and A. Ölçer, Data Collection or Processing: T. Aycı, B. Barlas, and A. Ölçer, Analysis or Interpretation: T. Aycı, Literature Review: T. Aycı, B. Barlas, and A. Ölçer, Writing, Reviewing and Editing: T. Aycı, B. Barlas, and A. Ölçer.

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