Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000925

Research Article

Evaluation on fire incident of electric vehicle spaces onboard ferries with using fire dynamics simulations

Tolga AYCI[1,*], Baris BARLAS[1], Aykut I. OLCER[2]

[1]*Department of Naval Architecture and Marine Engineering, Istanbul Technical University, Istanbul, 34467, Türkiye*
[2]*Department of Maritime Energy Management, World Maritime University, Malmö, 211 18, Sweden*

ARTICLE INFO

Article history
Received: 09 January 2024
Revised: 11 May 2024
Accepted: 13 May 2024

Keywords:
Electric Vehicles; Fire Dynamics Simulation; Fire Onboard Ferry; Fire Safety

ABSTRACT

This study brings a unique perspective of electric vehicles (EVs) transportation via maritime with using performance-based design of fire safety management. In the recent years, due to the increase of production and transportation of EVs, this study is highlighted the fire safety management. The integration of electric vehicles (EVs) into maritime transport, particularly via ships and ferries, brings about unique challenges, notably concerning fire safety management. Given the increasing prevalence of EVs and their potential fire hazards, it's crucial to address these risks comprehensively. The fire safety management of electric vehicles in ferry transport is dealt with, as this form of maritime transport is becoming increasingly important due to the increased production of this type of vehicle, which develops a complex chemical reaction mechanism and dangerous properties such as initial exothermal temperature, self-heating speed, pressure increase speed, etc. Therefore, relevant rules and regulations should be considered to ensure a safe journey. This study brings novelty to the fire safety analysis of EVs transportation onboard ships with using performance-based design and fire dynamics simulation tools to predict temperature level of the case incident. The Fire Dynamic Simulator was used for the simulations for the prediction of temperature distributions during an electric vehicle fire inside a ferry. The presented case study demonstrates how fire simulations could predict conditions for performance-based design of ferries that transport electric vehicles. Depending on simulations, temperature at initial times approximately 40s of fire incidents caused by EVs is around 1200°C and this cause severe results in terms of life and asset safety. In conclusion, this paper presents a brief insight to find an effective method for simulating and mitigating EV fires on ships to ensure crew safety and minimize fire damage.

Cite this article as: Ayci T, Barlas B, Olcer AI. Evaluation on fire incident of electric vehicle spaces onboard ferries with using fire dynamics simulations. J Ther Eng 2025;11(2):434−447.

***Corresponding author.**
*E-mail address: aycit@itu.edu.tr

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University Press, İstanbul, Turkey

INTRODUCTION

No ship can operate with 100% safety or be completely error-free. Hazard recognition and risk analysis are primarily focused on assessing risk levels and identifying the greatest fire hazards on board. Properly conducted analyses can reduce fire risks to an acceptable level and enhance ship reliability in serious circumstances. Therefore, risk assessment applications are at great importance to safeguard the system reliability in ships. A thorough analysis of historical ship incident data can inform amendments to regulations and decrease the theoretical accident risk [1].

It is well known that onboard fires are among the main ship accidents, leading to loss of life and property. If fire on board is not extinguished, it can lead to catastrophic consequences, total actual loss, and severe victims. Various types of ships reporting fire casualties from January 2000 to December 2022 is analyzed using Global Integrated Shipping Information System (GISIS) database provided by International Maritime Organization (IMO) [2]. In this study, only very serious and serious reported fire casualties are investigated. The serious and very serious fire casualties of different types of ships between January 2000 and December 2022 are given in Figure 1. Totally, 323 serious and very serious fire incidents occurred in this selected period. Even though fires onboard tanker is the most critical due to the high fire risk level with 24.1%, afterwards Ro-Ro/Ferry/Passenger ship types have 16.7% fire casualty percentage among all types of ship.

Electric vehicle (EV) markets are growing exponentially as sales exceeded 10 million cars in 2022 globally and the percentage of EVs in total car sales increased three and a half times in three years, from around 4% in 2020 to 14% in 2022. EV sales are expected to continue strongly through in the coming years. Figure 2 depicts the parabolic growth of the global sales volume of EVs between 2016 and 2023 [3]. As the growth trend in EV sales continues exponentially, sales number of EV globally overtakes 30 million quantities within the recent years [4].

In the world, almost 80 million vehicles are produced annually and approximately 40% of the vehicles are transported via marine transportation. For the near future projection, both produced vehicles and marine transportation ratio on vehicle are assumed to be doubled [4]. Therefore, a part of the vehicle transportation via marine, EV takes a crucial role depending on exponential growth on EVs global sales. Among the risks such as floating, grounding, structural failures or collisions, fire safety takes a significant place to be considered due to the fact that EVs or charging stations led to fire incidents onboard ships. Lithium-ion batteries, commonly used in EVs, have the potential to catch fire under adverse conditions, posing serious risks to both passengers and crew Based on this risk assessment, the subject of fire safety onboard ships that transport EVs reveals as a challenging and paramount issue to be analyzed and solved. This study is focusing on the issue from the perspective of fire dynamics simulations.

Lithium-ion batteries have the potential to catch fire under adverse conditions due to exposure to the conditions of energy creation, storage, and use. Although rare, fires and accidents caused by these batteries can be very

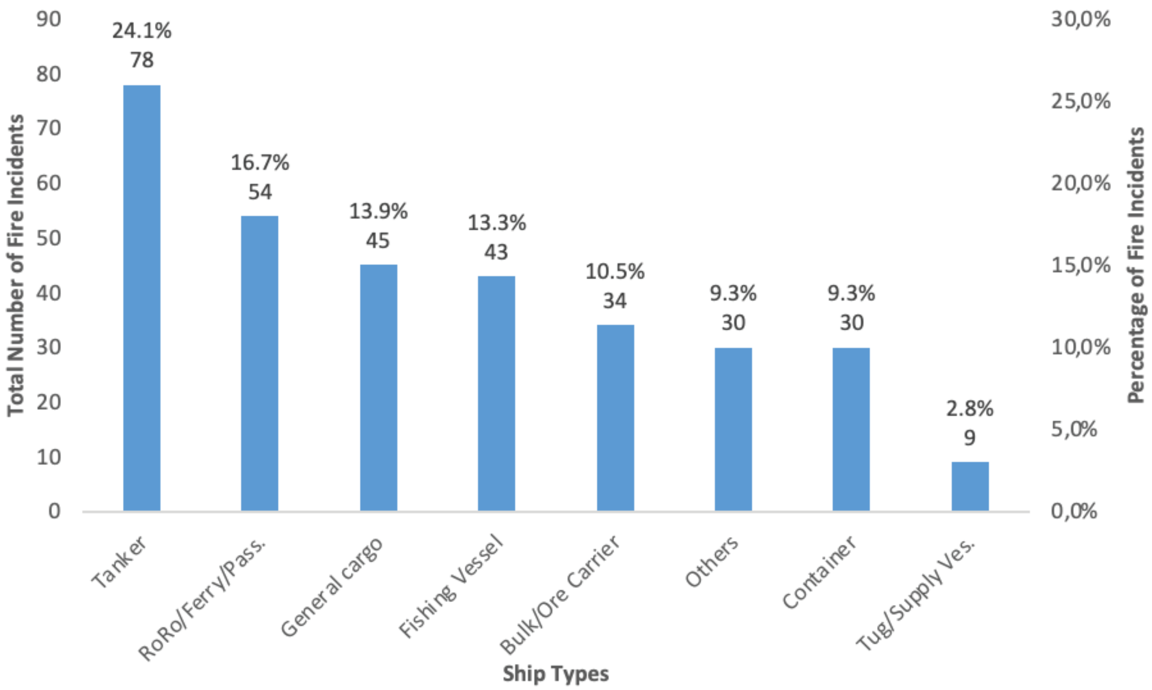

Figure 1. Reported serious and very serious fire casualties between 2000 and 2022 for different ship types.

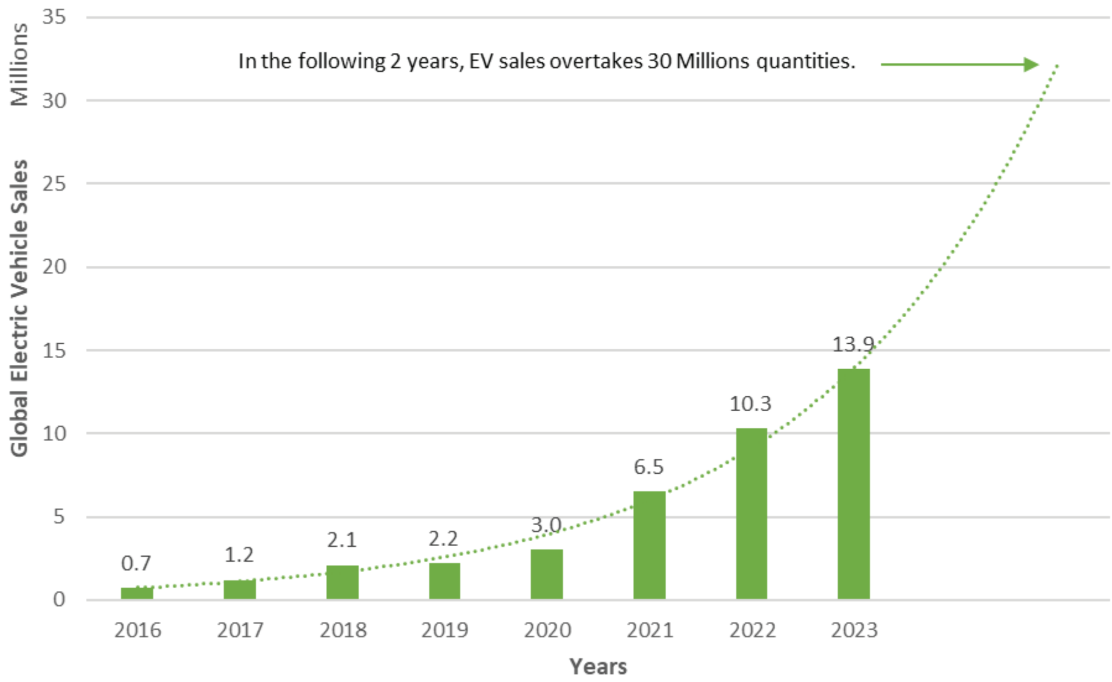

Figure 2. Global electric vehicle sales, 2016-2023 (adopted from https://www.iea.org/data-and-statistics/charts/electric-car-sales-2016-2023, IEA, 2023).

dangerous. Therefore, it is important to take every precaution to prevent lithium-ion battery fires. When Li-ion cells generate more heat than they are able to effectively dissipate, they may experience thermal runaway, which is the rapid, uncontrollable release of heat energy that could cause fire or explosion.

There have been many reports of EV fires in the last few years. When an EV is involved in a fire, investigating the incident often reveals the battery as the primary cause. The safety of transporting EVs is a major concern for the shipping and insurance companies since some accidents have been reported owing to the thermal runaway of EVs [5]. Also, there are also some fire accidents of EVs occurring globally as reported by the general media. For example, a fire on a ferry carrying almost 3,000 cars off the coast of the Dutch island of Ameland has left one sailor dead and 22 other crew members hurt in July 2023 [6]. Therefore, if a fire accident occurs on the deck, the fire may spread to other combustible materials and eventually cause serious consequences, so the transportation of EVs by ship should be handled carefully.

From the perspective of novelty of the study is that applications of performance-based design and fire dynamics simulation tools to the EVs spaces onboard RoPax ships with a case study provide the prediction of temperature levels along the enclosed space. In the lens of the statistics shown in Figure 1 and 2, this study examines the fire safety of electrical vehicle spaces of ferries. The aims of the study are as follows:

- Performance-based fire safety design on ships includes electrical vehicles,
- Outline strategies for mitigating fire risk, particularly on electrical vehicle spaces on vessels,
- Simulate fire dynamics inside the control volume and track crucial components such as temperature.

The literature review is detailed analyzed in terms of fire safety regulation onboard ships, fire modelling and performance-based design depending on fire dynamics simulations in the next section. In summary, fire regulation onboard ships are mainly based on the Safety of Life at Sea (SOLAS) in Chapter II-2. Additionally, UK Government, Maritime & Coastguard Agency and Nippon Kaiji Kyokai are published guidelines for the specifically EVs and its transportation via maritime. Fire modelling with fire dynamics simulations is the main part of the literature review section. Among the probabilistic, deterministic, and stochastic fire modelling approaches, deterministic ones as field and zone models are examined in details and mathematical equations of field model selected for the case study is given. Lastly, the fire dynamics simulations for specifically passenger ships, Ro-Ro vessels and Ro-Pax vessels including EVs spaces are reviewed literately.

LITERATURE REVIEW

Fire Safety Regulations

Ships are protected against fire hazards through the regulations of the IMO's International Convention for the

Safety of Life at Sea (SOLAS) [7, 8]. The well-known SOLAS convention was first established in 1914 after the Titanic disaster. Its main purpose was to set minimum safety requirements onboard. Then, SOLAS convention was constantly amended after the major accidents that highlighted new safety aspects onboard. Chapter II-2 of SOLAS governs fire safety on-board. 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, protecting the means of escape and firefighting through special provisions [7]. In the recent years, UK Government, Maritime & Coastguard Agency published marine guidance note with the title of Electric Vehicles Onboard Passenger Ro-Ro Ferries and this guide facilitate safe carriage and charging operations of electrified vehicles being transported onboard roll-on roll-off passenger (Ro-pax) ferries [9]. Also, Nippon Kaiji Kyokai called as ClassNK released Guidelines for the Safe Transportation of Electric Vehicles document from the perspective of Lloyds [10].

Fire Modelling

Salem [11] investigated fire engineering tools in consequence analysis, demonstrated transfer from a perspective approach to assess the fire safety design of ships to a performance-based approach. This new method leverages scientific and technological advancements and encourages innovation. However, using this type of approaches requires fire engineering tools to execute consequence analysis, which is the cornerstone of the risk investigation techniques. While most of these tools were developed for simulating fire and smoke propagation in building, there is some doubt about the applicability of these models for simulating compartment fires onboard ships.

This paper estimates the currently available fire modelling tools through a series of comprehensive comparisons between representative zone models and a benchmark field model in fire scenarios that involve typical ship layouts. Fires that occur in confined spaces, such as compartments within buildings, ships, and airplanes, are referred to as "compartment fires." A compartment fire typically starts small and then expands to involve a significant fuel source, becoming influenced by the compartment's boundaries. The fire's hot combustion products rise, entraining additional air and forming a discrete, hot, smoky upper layer below the ceiling. This layer deepens as the fire lasts to burn. Once the hot layer accesses the soffit level of a vent, smoke begins to spread out from the compartment into the rest of the structure [12]. Wang and Su [13] define multilayer and monolayer structure based on the structural characteristics of ship engine room.

Smoke and toxic gases and vapours usually occur together at fires, and it is difficult to distinguish clearly which product of combustion is responsible for the harmful effects. Smoke is a type of particulate matter that consists of very fine solid particles and condensed vapour. It makes up the majority of the visible products of combustion that are observed during a fire. Gas, on the other hand, is a product of combustion that remains in a gaseous state even when cooled to normal building temperatures. Vapour is also a product of combustion, but it is initially produced as a gas and then reverts to a solid or liquid state at normal temperatures. As vapours migrate away from the fire, they gradually condense on cool surfaces. Carbon monoxide is typically produced in large quantities during building fires due to the presence of carbon in the chemical structure of most organic materials. However, materials containing nitrogen, such as acrylic fiber, nylon, wool, and urea-formaldehyde foam, can also produce hazardous amounts of HCN in addition to CO. As a result, the resulting atmosphere from the combustion of these materials could be more toxic than that of an equal amount of material whose primary toxic product is CO. Materials that contain a high proportion of chlorine, such as PVC, can be extremely hazardous in fires as they produce both HCl and CO [14].

Once started a fire can spread in three ways: convection, conduction, and radiation. Convection is the most hazardous way in which fire can spread through a property. In an enclosed space, the heat generated by a fire becomes trapped when it hits the ceiling due to the natural rising of heat. The heat then travels horizontally, causing the fire to spread throughout the entire area. Conduction refers to the spread of fire through direct contact between materials. Some materials are better conductors of heat than others such as metals. Radiation transfers heat via electromagnetic waves in the air. Heat transmits in every direction until it reaches an object which absorbs it.

There are three types of fire models available: probabilistic, deterministic, and stochastic. 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 [15]. The journey of deterministic fire models started with semi empirical and simple analytical models. This development conducted to the progress of zone models, and the most popular types of fire models. Progress in Computational Fluid Dynamics (CFD) modelling made it possible to model fire phenomena, by solving the basic conservation equations of mass, energy, and momentum, proven to be successful in solving a variety of fire safety problems [16]. In general, there are two types of deterministic models: zone models 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,

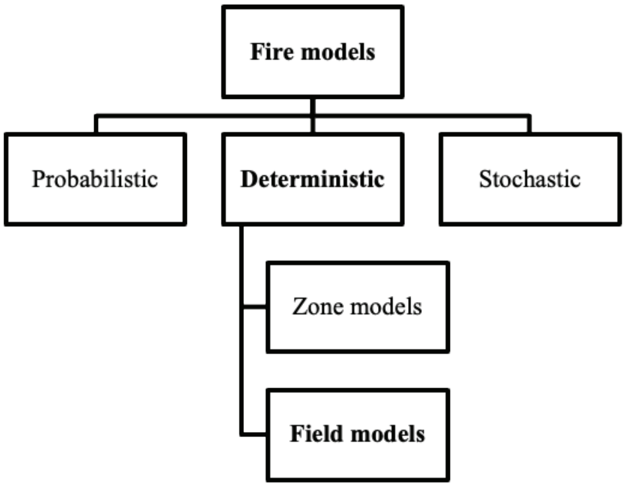

Figure 3. Fire model types.

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. Two- layer models, on the other hand, 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 one-layer models. Numerous types of fire models are illustrated in Figure 3 [15].

The heat release from a fire is an indication of its intensity. It can be stated as the fire load, which is the energy content of the flammable resources capable of burning in a fire [17]. Equation-1 can be used to estimate the total fire load, Q [kJ]:

$$Q = M\Delta H_c = q\, A_f \tag{1}$$

where, M [kg] is the total mass of the combustible materials; ΔH_c [kJ/kg] is the materials' heat of combustion; q [kJ/m^2] is the fire load density, and A_f [m^2] is the floor area. The fire load is calculated by Equation-2 [18].

$$q = (1/A_f)\sum_i^n M_i\, \Delta H_{ci} \tag{2}$$

where, n is the number of combustible materials; M_i [kg] is the mass of the combustible material i; and ΔH_{ci} [kJ/kg] is the heat of combustion of material i. The total mass of the available combustible materials per unit floor area ($\sum_i^n M_i/A_f$) expresses the so-called fuel load density FL [kg/m^2]. The heat release rate Q [kW] is calculated by Equation-3 [17]:

$$\dot{Q} = \dot{m}\Delta H_c \tag{3}$$

where, $\dot{m}$ [kg/s] is the mass burning rate of the combustible mass M. In a ventilation-controlled fire, the rate of combustion of the fuel is moderated by the rate of inflow of air and the rate of heat release is determined by the amount of oxygen available. The heat release rate of such fires is given by Equation-4 [17].

$$\dot{Q}_v = \dot{m}_{air}\Delta H_c/r_s \tag{4}$$

where, $\dot{m}_{air}$ is the mass flow rate of air into ventilation openings, and r_s is the stoichiometric air/fuel ratio. $\dot{m}_{air}$ depends on the area and the height of the ventilation openings via Equation-5 as follow [17]:

$$\dot{m}_{air} = 0.5\, A_0\sqrt{H_0} \tag{5}$$

principally, whether $\dot{m}_{air}$ / $\dot{m}$ < r_s, the fire is ventilation-controlled; otherwise, it is fuel-controlled [10].

An innovative simulation method to estimate the spreading rule of ship compartment fire and smoke presented with model verification carried out based on a miniature model [19]. Mathematical models, integrating ventilation network, field model, and zone model of ship fire will be established to characterize ship compartment fire scenarios. The development of this hybrid field-zone-net simulation technology can offer a comprehensive dynamic simulation of plume scene features. This hybrid simulation technology presents a new method for calculating the overall characteristics of compartment fires, laying the foundation for research into ship fire initiation, development, and the temporal migration [20] analyzed and verified the flow characteristics in closed ship cabins, laying a hypothetical basis for firefighting in ship cabins. As an emergency measure, extinguishing a ship fire in a closed cabin effectively halts the fire. Initially, it is crucial to organize personal evacuation quickly and prevent the fire's spread. This study, which uses a small-sized ship cabin as the research subject and heptane as the ignition fuel, examines the smoke characteristics in closed compartments theoretically and designs a physical parameter model of fire smoke based on MATLAB. The research is predicated on a constant heptane mass loss rate, which somewhat deviates from an actual fire in an enclosed space. Ship cabin fires differ from other types of fire because cabin-surrounding bulkheads are typically made of steel which is a good conductor of heat. The heat produced by the fire can be conducted through the steel bulkhead to other cabins, and the hot bulkhead can heat up the cabin's air through radiation and convection. Investigating the law of temperature increase in the steel cabin during a fire could significantly inform the fireproofing design of the cabin. Fire Dynamics Simulator (FDS), equipped with a Large Eddy Simulation (LES) turbulence model, are used to simulate a full-scale cabin fire experiment designed [21]. FDS could predict accurate temperature distribution in the cabin's middle and top sections, but the cold layer temperature affected by incoming air was moderately predicted by FDS.

Even though all ships being built according to fire safety rules and regulations, ship fire accidents still occur. Dynamic fire simulations can provide insights into heat and smoke tendencies and behaviors based on cause, location, and environmental conditions. While numerous frameworks and fire safety schemes exist, suitable fire simulation frameworks should accommodate the increasing data availability at each stage of the ship design process. Consequently, fire scenarios are considered rather than a formal risk modelling process. The machinery room of the target ship has been utilized for the fire simulation [22]. From the perspective of fire extinguishing systems, [23] studied fire suppression models by using reinforcement-learning technique to aim of fire extinguishing nozzle and [24] investigated the effect of initial water temperature on the cooling performance of a water mist fire suppression system.

Lastly, design of fire methodology for vehicle spaces onboard ships is widely analyzed with a case study, a realistic closed-type cargo space of a Ro–Ro passenger ship, accommodating 38 cars and 11 heavy goods vehicles (HGVs) with using fire dynamics simulation [25]. As a result of the study, temperatures in the vehicle spaces are reaching to approximately 800°C.

MATERIALS AND METHODS

In this study, one ship is selected as a case study for simulating fire dynamics. In the case, the capacity of the vessel are 800 passengers, 90 cars and 60 trucks. Table 1 indicates the technical specifications of the vessel below. In general, the structure of a whole ship is very complex to simulate all detailed information in a model. In the first step, this study focuses on electrical vehicles space onboard ship. Mainly, the detailed shapes of each equipment in this deck are irregular. Therefore, FDS software is used for investigating the fire and cube-shaped grids are used, the structure information of the real deck should be streamlined as follows:

a) The complex structure in the deck: as some small equipment or electrical vehicles have a small effect on the flame spread, most of these components are ignored during development of numerical model. Electrical vehicles in the compartments simplify with two cubic fire sources.
b) Explosibility: There are many small equipment and devices within the compartments, so they can easily cause explosions in the event of a fire. This can increase the destructive power of fire. However, due to the complex nature of explosives, this will be omitted to simplify the calculations.
c) Human impact on fire development: For the whole fire spreading process within the deck; in the early stages, the movement of people has small effect on the flow distribution. Therefore, the impact of human actions will be ignored.
d) Active fire protection systems such as fire extinguishing sprinklers, detections are ignored in this study.

Table 1. Technical specifications of the case study vessel

Ship type	ROPAX
Length (m)	146
Beam (m)	22
Depth (m)	14
Draught (m)	6,26
Gross tonnage (t)	6.825
Deadweight tonnage (t)	3.790
Capacity	800 passengers
	90 cars
	60 trucks

For the CFD simulations, it is necessary to assume some initial conditions of external and internal parameters. For the environment, it is assumed that the air temperature is 20°C, ambient pressure is 1013 hPa, and relative air humidity is 40%. A propane gas burner is taken as the combustion material [26]. The well-known Very-Large Eddy Simulation (V-LES) is used based on the concept of filtering a larger part of turbulent fluctuations compared to the standard LES [27]. It can be concluded that VLES model has better predictions of the swirling flow field for both the mean and the root mean results than the LES models [28]. Therefore, maximum heat release rate is 7000 kW per EV [29]. The fire in its growth stage and during its decay period can be described by a t2 curve and total simulation time is taken as 1000s. Geometry of the ship is simplified and determined the length of 145m, the width of 23m and the height of 5m. Instead of the complex geometry of the EV, two cuboid fire sources geometry are determined 4x3x2 m3 depending on vehicles geometry. Each fire source is combusted at the beginning of the simulation.

To select the grid resolution for the fire dynamics simulation, it's essential to consider the non-dimensional ratio of the characteristic fire diameter (D^*) to the nominal size of a grid cell (dx). This ratio helps determine the appropriate resolution of the computational grid. The greater the ratio, the finer the resolution required for accurate simulation results. The characteristic fire diameter (D^*) depends on factors such as the heat release rate ($\dot{Q}$) and ambient conditions according to equation 6 as below:

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

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 calculations, a cubic mesh is used with 0.5m dimension [30].

In conclusion, main parameters of fire dynamics simulation are given and summarize in Table 2 and geometry of

J Ther Eng, Vol. 11, No. 2, pp. 434−447, March, 2025

Table 2. Main parameters of the fire simulation

Initial temperature	20 °C
Initial pressure	1013 hPa
Initial humidity	40%
Fire reaction	Propane
Turbulence model	Very-Large Eddy Simulation (V-LES)
Maximum heat release rate	7000 kW per EV
Fire source dimensions	4m*3m*2m
Control volume	145m*23m*5m
Mesh size	0.5m

the EV space in the RoPax ship is shown in Figure 4. In this control volume, boundary conditions for the case of fire dynamics simulation are depicted in Figure 5.

FIRE DYNAMICS SIMULATION RESULTS

In this study, mainly heat release rate and pressure in the control volume are analyzed for the initial results of the simulation. Figures 6 and 7 present the heat release rate and pressure changes in the control volume along the time respectively. In Figure 6, heat release rates reach to almost 240 MW value at the early phase of the fire. After

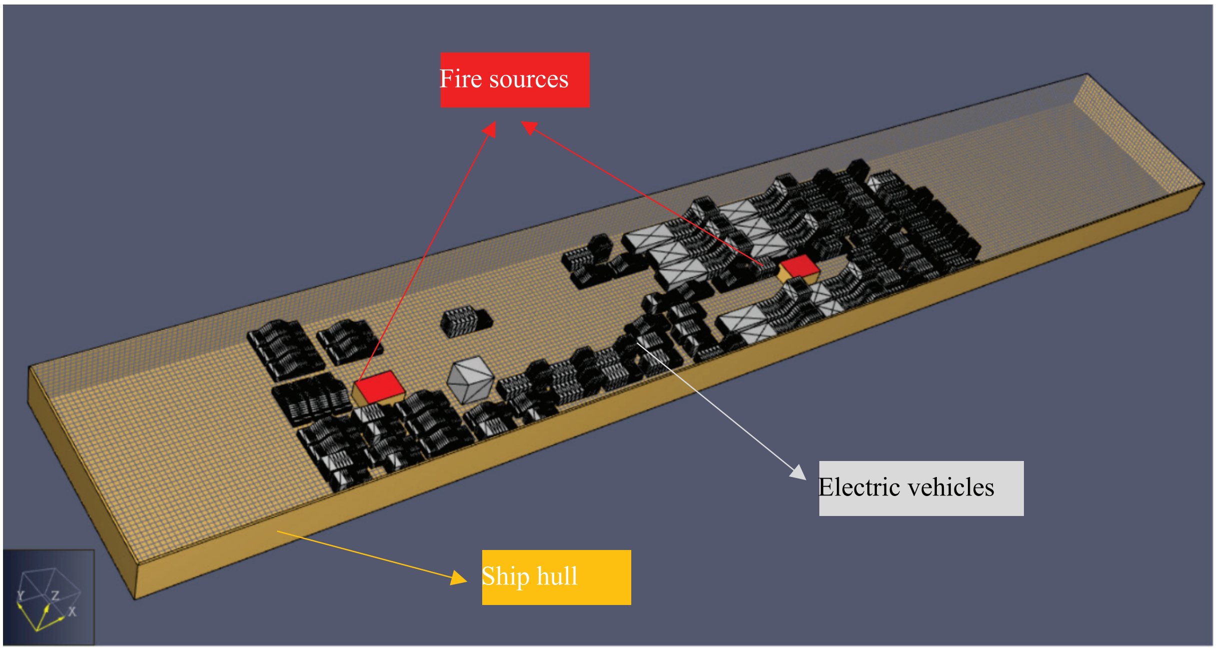

Figure 4. Geometry of the fire simulation space in the ROPAX.

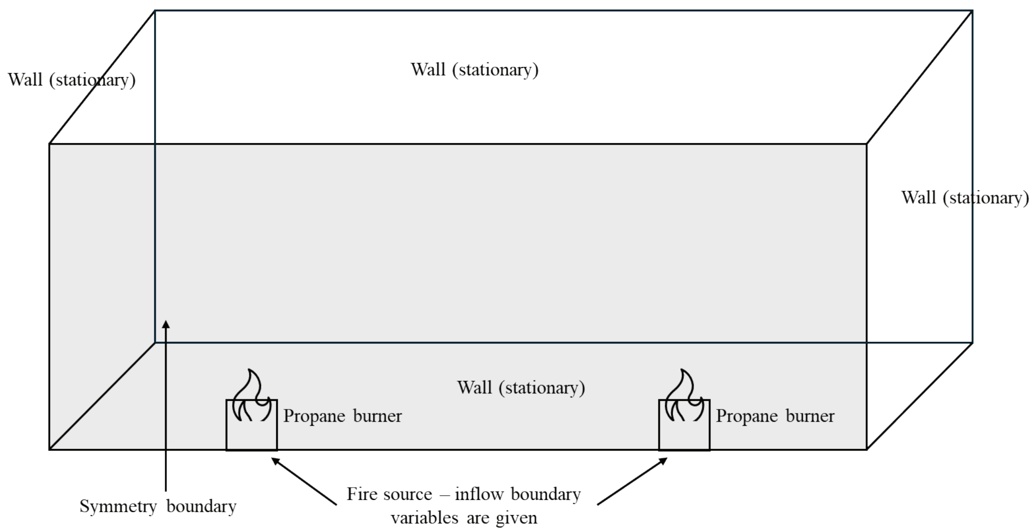

Figure 5. Boundary conditions for the case of fire simulation.

the fluctuation around 160 MW that is calculated as a maximum heat release rate while designing simulation, heat release rate stabilizes to zero around 150s. Figure 7 demonstrates the pressure changes at time steps and almost 40 kPa pressure in the control volume are calculated. To sum up, in the compartment fires, due to the lack of combustible materials, fire burns itself out. After approximately 300s, all these critical parameters are stabilized.

Temperature distributions along the control space are significant to evaluate the severity of the fire incident. Due to that, plates in x-direction (10 m), in y-direction (11.5 m) and in z-direction (4.5 m) are specified aligning with center of fire sources to track the temperature distribution. Figure 8 indicates the temperature distribution in x-direction (lengthwise in the compartment) at time steps as 50s, 100s, 150s and 200s. At the early stage of the EV space, temperature dramatically increases to almost 1000°C. Structural elements of the vessel, EVs and equipment in the space can be ignited and lose of their functions by this temperature level organically. Due to the fact that, this temperature level

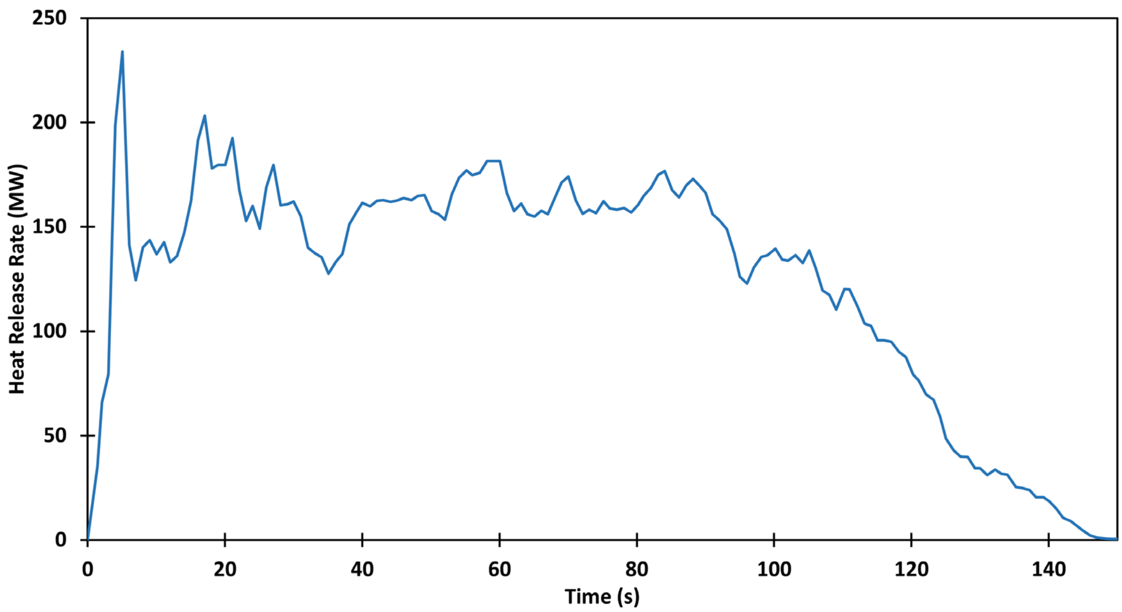

Figure 6. Heat release rate (MW) vs. time (s) graph of the simulation.

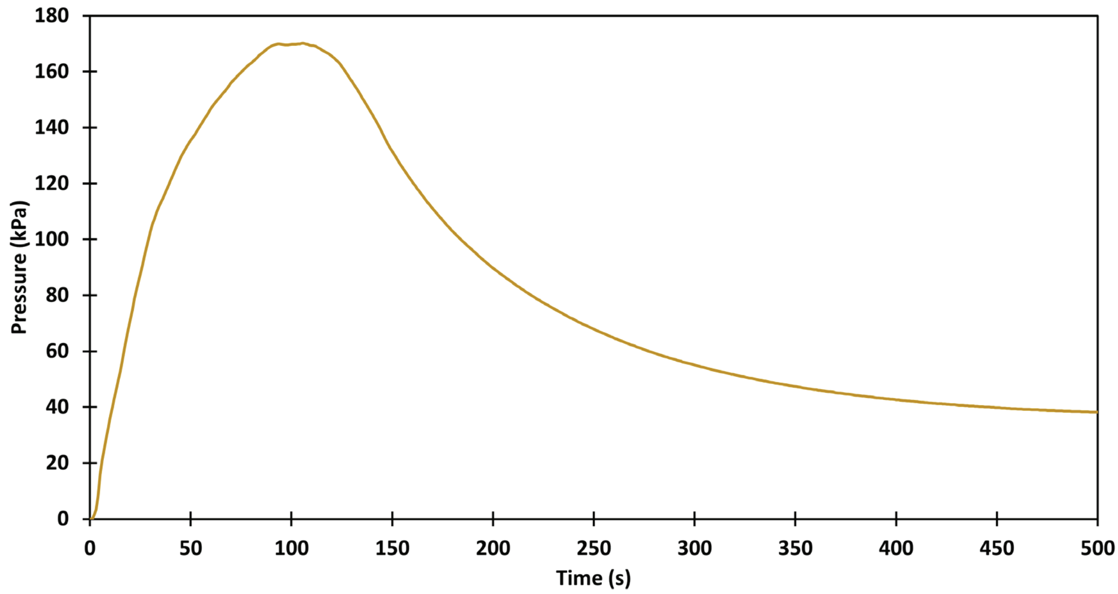

Figure 7. Pressure (kPa) vs. time (s) graph of the simulation.

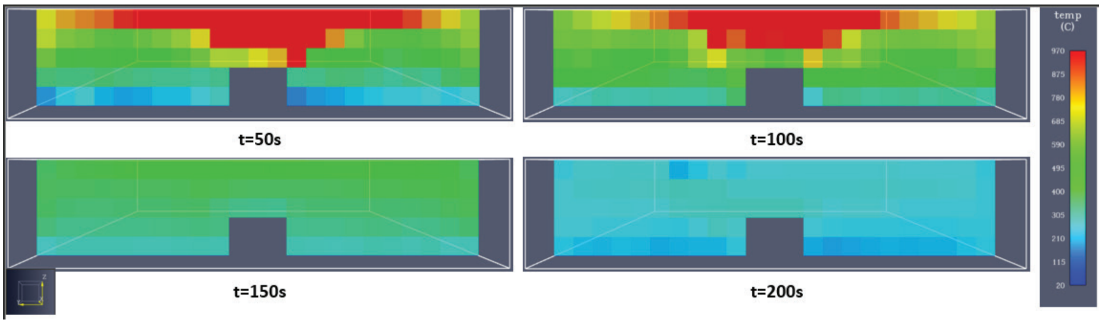

Figure 8. Temperature distribution on x=10m at time 50s, 100s, 150s and 200s.

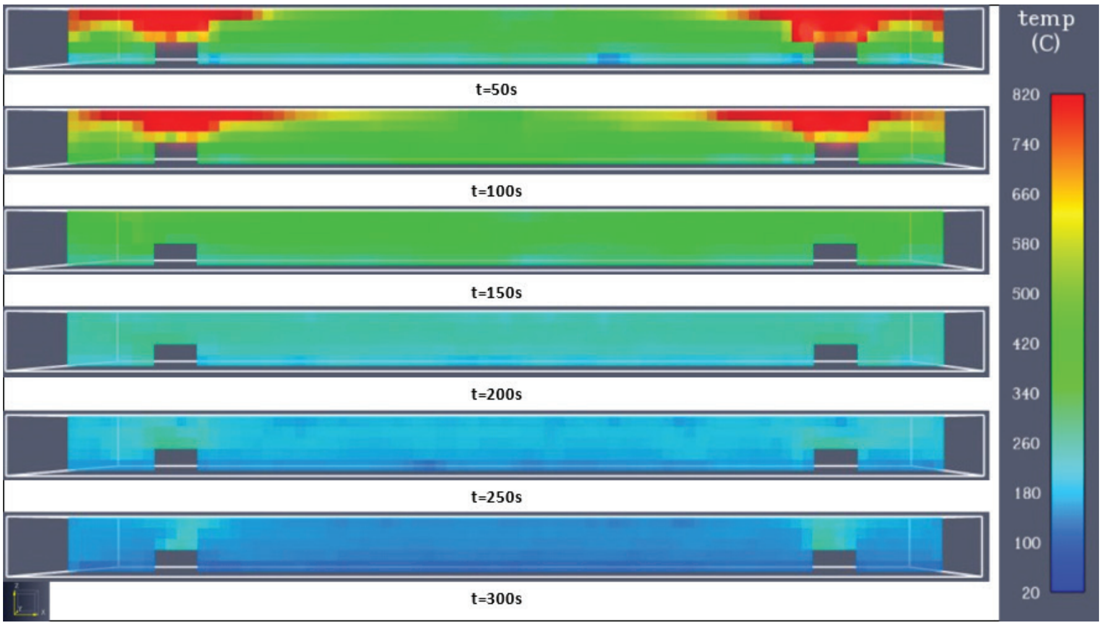

Figure 9. Temperature distribution on y=11.5m at time 50s, 100s, 150s, 200s, 250s and 300s.

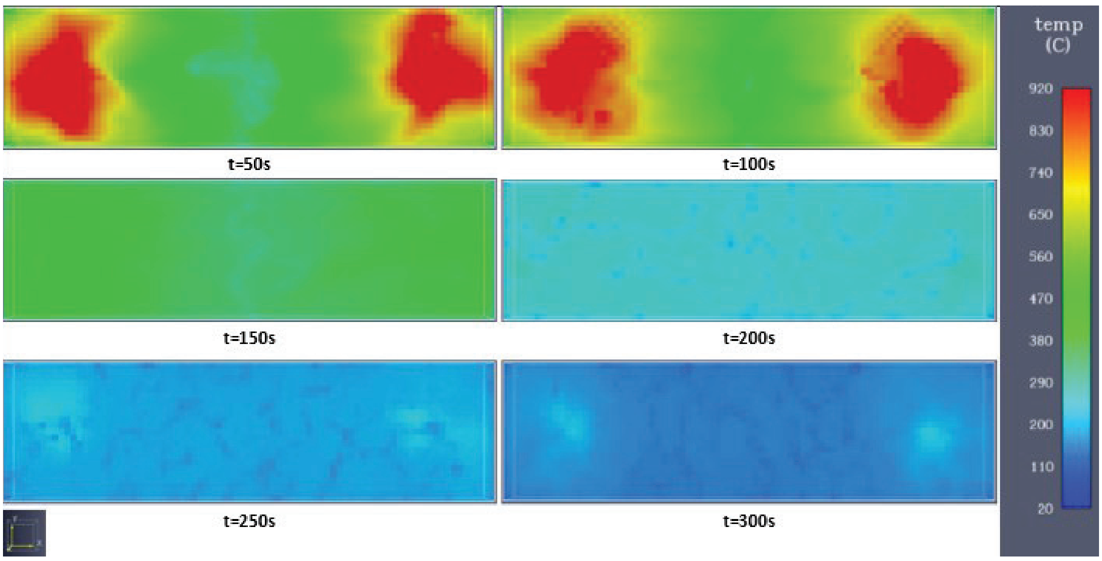

Figure 10. Temperature distribution on z=4.5m at time 50s, 100s, 150s, 200s, 250s and 300s.

onboard ferries, the spaces or compartments of EV transportation in the ferries have to be designed with structurally resistance materials to the fire. In this study, the ignition and explosibility are ignored due to decrease complexity of the case study.

Temperature distribution on y=11.5m and z=4.5m at six different time steps such as 50s, 100s, 150s, 200s, 250s and 300s are depicted in Figure 9 and 10 respectively. In these figures, interaction between two fire sources starts after 100s and this is harmonized at following time steps. Same as the Figure 8, the planes exceed the critical temperature level for the space quickly. In the first 50s, temperature distribution shows that the EV fires have a significant impact on the surrounding elements such as structural steels, other vehicles, machineries, equipment etc. Therefore, Figure 11 presents the 3D perspective view of the thermal distribution in the control volume at the time of 75s, 125s, 175s and 225s. This perspective views.

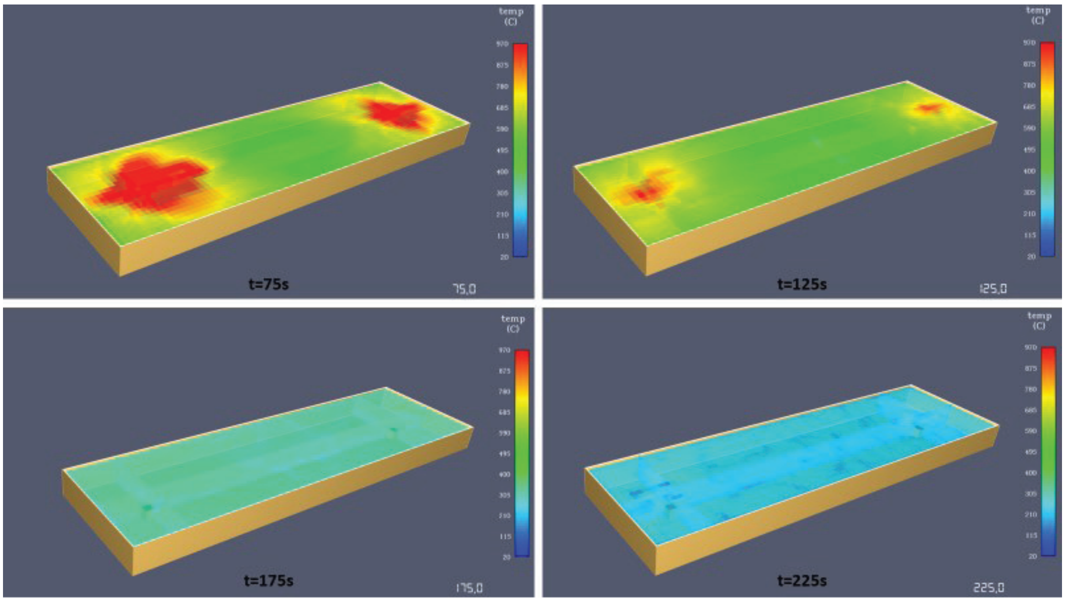

Figure 11. Temperature distribution on 3D perspective view at time 75s, 125s, 175s and 225s.

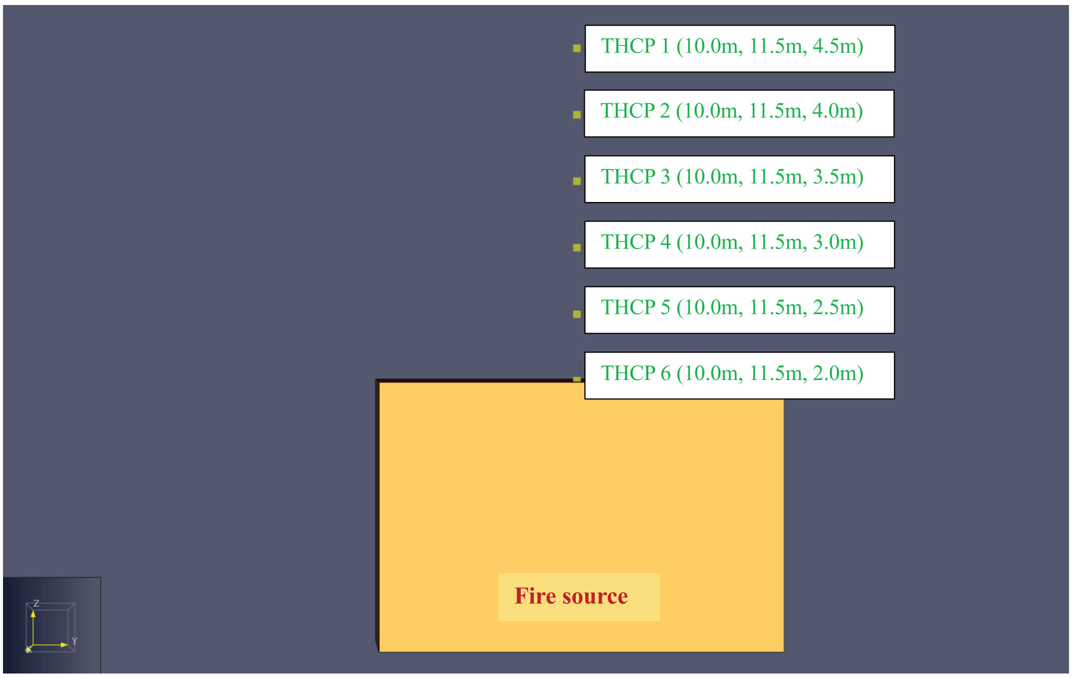

Figure 12. Arrangement of thermocouples.

In addition to the figures related to the temperature distribution, thermocouples are placed on the different locations as a center of fire source, y, and z planes. There are 6 thermocouples on the fixed directions of x=10m and y=11.5m and derived by the z direction. From top to bottom direction, thermocouple 1 is placed on z=4.5m that is the top of the EVs space deck and other ones are arranged by 0.5m dimension successively. Figure 12 is depicted the location of the thermocouples in the EVs space.

Temperatures on the thermocouples are given in Table 3. As reviewing the temperatures on the selected thermocouples, extremely increase in the initial time steps are realized. For each thermocouple reaches to the maximum temperature levels on the time between 30s and 40s and after 50s the temperatures are decreasing step by step. Even though, the value of the temperature is deriving from the location to location, the characteristic of graph is mainly similar to all thermocouples. Also, the maximum temperatures

Table 3. Temperatures on the thermocouples

Time (s)	Temperature (°C)					
	THCP1	THCP2	THCP3	THCP4	THCP5	THCP6
0.0	20.00	20.00	20.00	20.00	20.00	20.00
2.5	55.50	124.56	248.53	371.33	448.35	428.81
5.0	827.38	951.40	988.54	986.84	931.92	814.62
10.0	989.19	1026.85	1031.24	1020.27	936.27	823.27
20.0	1083.84	1083.67	1046.55	986.97	904.71	819.17
30.0	1126.80	1155.26	1148.79	1113.64	1053.46	963.59
40.0	1131.28	1182.13	1191.42	1169.16	1082.68	939.76
50.0	1086.06	1148.32	1180.33	1164.19	1094.51	973.85
100.0	917.61	943.53	940.91	914.16	846.28	767.28
150.0	903.83	856.74	835.24	797.39	645.97	408.01
200.0	794.06	687.63	598.86	461.81	392.11	345.73
250.0	287.22	292.13	295.30	297.19	295.84	300.27
300.0	216.61	226.27	230.74	234.73	243.66	283.96
Tmax	1186.72	1233.68	1217.59	1184.57	1098.82	998.97
Tmean	743.08	745.66	731.08	685.24	608.15	539.08

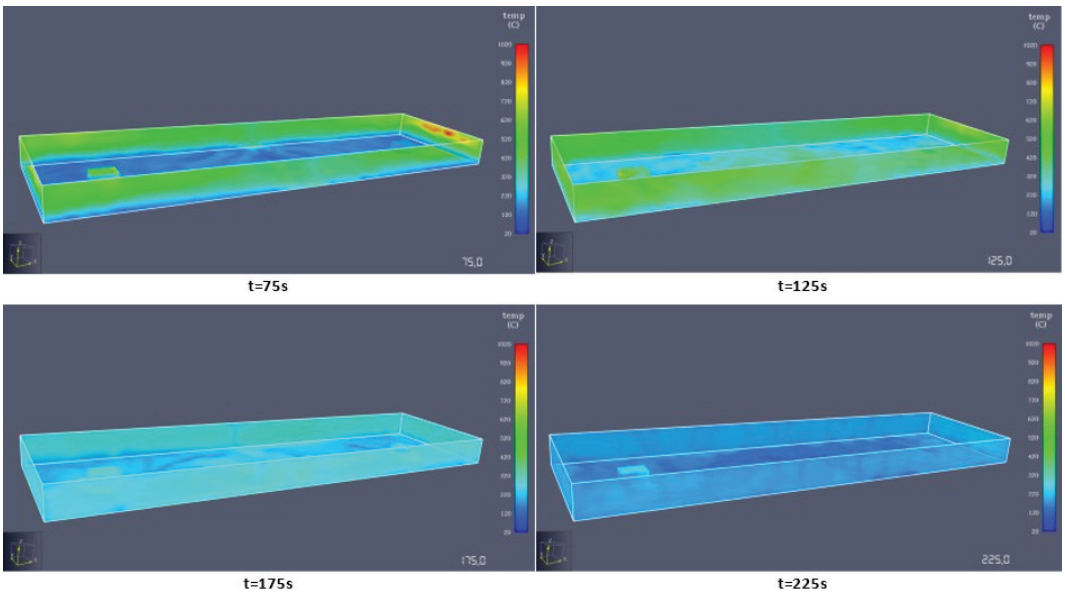

Figure 13. Gas temperature distribution on 3D perspective view at time 75s, 125s, 175s and 225s.

and the average values reach to around 1200°C and 700°C respectively.

Temperature of gas in the control volume is another crucial parameter to investigate fire scenario for the EV spaces onboard ferries. The combustible material such as propane burner in this study is directly affected to the gas distribution and the temperature of it. Gas temperature distribution 3D view at different time steps such as 75s, 125s, 175s and 225s are depicted in Figure 13. Same as the temperature distribution, gas temperature also reaches to 1200°C at early times. Then, the gas temperature decreases in each time step to approximately 500°C, 300°C and 100°C respectively in Figure 13. In summary, by understanding the dynamics of gas temperature, maritime engineers can develop effective fire safety measures to mitigate risks and ensure the safety of passengers, crew, and cargo in maritime environments.

CONCLUSION AND RECOMMENDATIONS

In this study, fire safety analysis of EV spaces onboard ships is examined using a fire dynamics simulation method known as the field model. By using performance-based design and fire dynamics simulation tools to predict the temperature level of the incident, this study brings novelty to the fire safety analysis of EV transport onboard RoPax ship. Due to the fact that, sales volume of EV is increasing significantly, transportation of the EV is trend topic in terms of marine safety. Also, serious, and very serious fire incidents' rate among ships cannot be ignorable according to historical data. Crucial parameters in fire safety such as temperature, pressure, heat release rate and total energy are examined to reveal severity of the EV spaces onboard ships. Extra high temperature levels around 1200°C especially in the early stage of the EV fire incidents are the main output of this study. This temperatures in the transportation, accommodation or technical spaces inside the vessel cause severe results in terms of life and asset safety. Additionally, structural stability of vessel is mainly affected from the high temperature and structural and insulation products have to be resistant to the temperature level. Lastly, extinguishing, detection and evacuation topics should be designed depending on crucial temperature increase in the initial stage of fire incident. Fire dynamics simulations indicate that temperature reaches to the peak level in approximately 40s.

The rapid growth of the EV market in the world brings with the risk of major fire accidents during the transport of EVs by ships. In recent years, several ships have suffered major accidents as a result of fires during EV transport, most of them were total losses. Transportation of EV onboard ships need extra precautions in terms of fire unlike internal combustion engine-powered vehicle. As known, EV battery fires ignite quickly and intensively in the initial phase of fires. For this reason, it is necessary to prevent and intervene very strictly while the fire is still at the beginning. Finally, from the perspective of insurance companies, regulations should be specified for EV transported onboard ships in order to mitigate fire safety risks.

Incorporating these recommendations into this study efforts can contribute to the development of more robust fire safety measures for EV transportation onboard ships. By addressing these key areas, stakeholders well mitigate fire safety risks and ensure the safety of passengers, crew, and assets in maritime environments. Additionally, implementing regulations specific to EV transportation onboard ships can further enhance safety standards and minimize the occurrence of fire incidents.

For future research endeavors, it is recommended to consider the further topics. From the perspective of performance-based design, fire safety systems such as structural, fire extinguishing and detection systems can be added to the fire dynamics simulations and integrate these systems together. Additionally, different fire incidents at the same time in the EVs spaces onboard ship are taken into consideration while simulating. In addition to the above recommendations, human factor analysis can be added to the study for the future research. Evacuation models are affected directly by human factors. For the evacuation modelling, simulation tool dedicated to the fire safety industry called as PathFinder is advised to integrate. Also, performance-based fire safety analysis onboard passenger ship is a developing research area and fire dynamics simulations can be applied to the various ship compartments such as machinery room, atriums, galleries and accommodations.

ACKNOWLEDGEMENTS

This work is a part of the first author's PhD study in Istanbul Technical University, Department of Naval Architecture and Marine Engineering. We would like to express our deepest appreciation to Thunder Engineering for the academic usage of Pyrosim software.

AUTHORSHIP CONTRIBUTIONS

The authors confirm contribution to the paper as follows:

- study conception and design: T. Ayci, B. Barlas, A.I. Olcer
- data collection: T. Ayci, B. Barlas, A.I. Olcer
- fire dynamics simulations: T. Ayci
- analysis and interpretation of results: T. Ayci, B. Barlas, A.I. Olcer
- draft manuscript preparation: T. Ayci, B. Barlas.

All authors reviewed the results and approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Barlas B, Ozsoysal R, Bayraktarkatal E, Ozsoysal OA. A study on the identification of fire hazards on board: a case study. Brodogradnja 2017;68:71–87. [CrossRef]

[2] GISIS. Maritime Casualty and Incidents, Global Integrated Shipping Information System. Available at: http://gisis.imo.org. Accessed Jan 01, 2023.

[3] IEA. Electric car sales, 2016-2023, IEA, Paris. Available at: https://www.iea.org/data-and-statistics/charts/electric-car-sales-2016-2023. Accessed Mar 06, 2025.

[4] Statista Research Department. Annual car sales worldwide 2010-2023, with a forecast for 2024, https://www.statista.com/statistics/200002/international-car-sales-since-1990/. Accessed Mar 06, 2025.

[5] Zhang DL, Xiao LY, Wang Y, Huang GZ. 2019. Study on vehicle fire safety: statistic, investigation methods and experimental analysis. Safety Sci 2019;117:194–204. [CrossRef]

[6] BBC news. Ameland rescue: Crew jump off ship ablaze with cargo of 3,000 cars. Available at: https://www.bbc.com/news/world-europe-66310280. Accessed Mar 06, 2025.

[7] SOLAS. The International Convention for the Safety of Life at Sea (SOLAS), International Maritime Organization (IMO) Chapter II-2.

[8] Cowley J. Fire Safety at Sea. Institute of Marine Engineering, Science and Technology; 2002.

[9] UK Government, Maritime & Coastguard Agency. Electric Vehicles Onboard Passenger Ro-Ro Ferries. Available at: https://www.gov.uk/government/publications/mgn-653-m-amendment-1-electric-vehicles-onboard-passenger-roll-onroll-off-ro-ro-ferries. Accessed Mar 06, 2025.

[10] Nippon Kaiji Kyokai. Guidelines for the Safe Transportation of Electric Vehicles. Available at: https://www.classnk.or.jp/hp/pdf/activities/statutory/ev_carriage_safety/gl_ev_carriage_safety_e202308.pdf. Accessed Mar 06, 2025.

[11] Salem A. Fire engineering tools used in consequence analysis. Ship Offshore Struct 2010;5:155–187. [CrossRef]

[12] Drysdale D. An Introduction to Fire Dynamics. 2nd ed. Hoboken: Wiley; 1999.

[13] Wang L, Su S. Simulation of smoke motion in fire of the ship engine room with multilayer structure. Brodogradnja 2011;62:366–372.

[14] Autian J. Toxicologic aspects of flammability and combustion of polymeric materials. J Fire Flamm 1970;1.

[15] Rasbash DJ, Ramachandran G, Kandola B, Watts JM, Law M. Evaluation of Fire. England: John Wiley & Sons; 2004. [CrossRef]

[16] Novozhilov V. Computational fluid dynamics modelling of compartment fires. Prog Energy Combust Sci 2001;27:611–666. [CrossRef]

[17] Hurley MJ. SFPE Handbook of Fire Protection Engineering. 5th ed. New York: Springer; 2016.

[18] Thomas PH. Design guide: Structure fire safety cib w14 workshop report. Fire Safety J 1986;10:77–137. [CrossRef]

[19] Jiao Y, Wang JH, Xiao MJ, Xu T, Chen WJ. Development of field-zone-net model for fire smoke propagation simulation in ships. Proceedings - 7th International Conference on Intelligent Computation Technology and Automation, Changsha, China, 25-26 October 2014. pp. 190–193. [CrossRef]

[20] Li J, Pu J, Ren K, Zhang K, Ding L. Fire smoke characteristics in closed ship cabin: A fire model study. Int J Syst Assur Eng Manage 2016;7:257–261. [CrossRef]

[21] Zhu X, Chenhua Z, Zhiqing Y. Research of temperature prediction in steel cabin fire with large eddy simulation and experiment. Proceedings - 2011 International Conference on Computational and Information Sciences, Sichuan Chengdu, 21-23 Oct 2011. pp. 889–892. [CrossRef]

[22] Kang HJ, Jin C, Dongkon L, Beom JP. A framework for using computational fire simulations in the early phases of ship design. Ocean Eng 2017;129:335–342. [CrossRef]

[23] Lee EJ, Ruy WS, Seo J. Application of reinforcement learning to fire suppression system of an autonomous ship in irregular waves. Int J Naval Arch Ocean Eng 2020;12:910–917. [CrossRef]

[24] Omidvar A, Mahdavi A, Mehryar R. A simulated study on the effect of water temperature on cooling efficiency of water mist fire extinguishers. J Therm Eng 2020;6:460–473. [CrossRef]

[25] Koromila IA, Spyrou KJ. Design fire methodology for vehicle spaces onboard ships. Fire Technol 2023;59:1725–1759. [CrossRef]

[26] Sun P, Bisschop R, Niu H. Huang X. A review of battery fires in electric vehicles. Fire Technol 2020;56:1361–1410. [CrossRef]

[27] Labois M, Djamel L. Very-large eddy simulation (V-LES) of the flow across a tube bundle. Nuc Eng Des 2011;241:2075–2085. [CrossRef]

[28] Tiwari P, Xia Z, Han X. Comparison of VLES and LES turbulence modeling for swirling turbulent flow. J Appl Fluid Mech 2020;13:1107−1116. [CrossRef]
[29] Brzezinska D, Bryant P. Performance-based analysis in evaluation of safety in car parks under electric vehicle fire conditions. Energies 2022;15:649. [CrossRef]
[30] McGrattan K, Hostikka S, McDermott R, Floyd J, Weinschenk C, Overholt K. Fire Dynamics Simulator, User's Guide. 6th ed. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland; 2013.