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Research Paper

Research on heat resistance of A60 fire-resistant doors used on ships using CFD numerical simulation

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ABSTRACT

Typically, the design of fire doors on ships is mainly to meet thermal requirements, while thermal deformation can also significantly affect the safety performance of the door. When the fire temperature is high, the door tends to warp and deviate from the supporting frame due to uneven temperature distribution, which may lead to the spread of fire and smoke on ships. To evaluate their performance, fire doors must undergo a standardized fire test. Realistic simulation of this fire test can be of great benefit during the design phase in order to reduce the number of prototypes to be manufactured and tested. This article researches the testing process of A60 fire-resistant doors installed on ships. The A60 fire-resistant door consists of two steel plates, each measuring 1600x600x45 mm, with a 42 mm thick layer of mineral wool insulation placed between them. Test samples were heated in a gas-fired furnace for 60 minutes. The findings are given in the form of a temperature-time chart showing that the test samples meet the requirements for fire-resistant doors used for ships. This study holds significant importance for the development of the shipbuilding industry in Vietnam in the near future.

1 Introduction

Vietnam, with a coastline of 3,260 km and an abundant labor force, has a significant advantage in developing the shipbuilding industry [1]. The growing demand for ships makes ensuring passenger safety crucial. Fires can inflict significant damage to people and property. As a result, fire prevention is critical and has become a subject of international agreements governing human lives aboard ships, with stringent rules in shipbuilding standards.

To prevent fires on ships, in addition to using fire extinguishing equipment such as automatic fire extinguishing systems with CO₂ gas, fire-fighting systems with synthetic foam, fire extinguishers or materials and equipment that do not cause fire or explosion, the use of materials and structures that prevent the spread of heat sources that can cause fires is also

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a matter of great concern. Especially for ships, the compartmental structures and room walls are made of metal, so the transmission of heat sources is a factor that can easily cause heat sources to arise in the surrounding areas of areas with high heat sources. Depending on the level of risk of heat generation causing fire and explosion, the regulations will require the structures of compartment walls, rooms, and rooms to meet different fire resistance levels.

Among the elements ensuring fire safety on ships, fire doors play an important role because they serve to both slow down and preventing the spread of fire and smoke between ship compartments and areas simultaneously. Fire doors must perform properly under normal operating conditions and provide safety in the case of a fire.

Fire-resistant structural partitions on ships are classified into six levels by shipbuilding standards: A-0, A-15, A-30, A-60, B-0, and B-15, each with its own set of heat resistance and thermal transmission requirements. The A-60 fire-resistant construction has the highest fire resistance rating. Typically, an A-60 fire-resistant partition consists of two primary components: the base partition and the components mounted atop it. These installed components, commonly windows, are collectively referred to as A-60 fire doors [2].

There are many studies in the world evaluating fire doors on ships. Paolo Boscariol et al. [3] studied the thermomechanical responses of fire doors applied to naval ships. The research team evaluated them through the door fire test process. At the same time, the finite element method was used to analyze the heating process in two states: the instantaneous state and the steady state. Luciano Moro et al. [4] studied and tested fire doors using insulating materials that improved the mechanical response of the door without affecting its insulation properties. This type of door showed a temperature distribution quite similar to the normal case, however the out-of-plane displacement was three times smaller. Giada Kyaw Oo D'Amore et al. [5] used the self-consistent finite element method (FEM) to evaluate fire doors with a new fiberglass-filled foam insulation material that has improved mechanical and acoustic properties compared to traditional insulation materials. The authors have demonstrated that the use of this new insulation material has the advantage of making fire doors 37% thinner and 61% lighter than traditional fire doors. At the same time, it increases the insulation and soundproofing capabilities of the door.

In recent years, the fluctuations of the world economy have greatly affected the shipbuilding industry of Vietnam. With a significant decrease in the demand for transporting goods by sea, it has caused great difficulties for the development of the shipbuilding industry. However, it also shows many limitations in the development of the domestic shipbuilding industry. Especially for the supporting industry for shipbuilding, there are still many weaknesses. The research and manufacture of products for shipbuilding are still underdeveloped, not meeting the development potential of the shipbuilding industry.

A-60 fire doors are widely used in the shipbuilding industry and are required by shipbuilding regulations for A-60 fire partitions [2]. However, currently, domestic shipbuilders mostly rely on importing these items from abroad, which are usually produced in standard sizes by manufacturers. Consequently, adjusting the size to fit the installation space becomes very challenging. Therefore, mastering the technology for manufacturing A-60 fire doors is essential for shipbuilding units to be more proactive in production and business.

This article studies the testing of A-60 fire doors for installation on ships. It also includes CFD simulation experiments of fire door and fire oven temperatures during fire testing. The test results are used to evaluate whether the A-60 fire doors production meets technical requirements as well as fire resistance.

2 Research content

2.1. Theoretical formula

Generalized heat conduction differential equation [6] can be stated as follows

$$\frac{\partial t}{\partial \tau} = a \left(\frac{\partial^2 t}{\partial x^2} \right) \quad (1)$$

where: τ is time, a is temperature conductivity coefficient and t is temperature.

In the fire-test process described in the FTP Code [7] the door was heated from ambient temperature T_μ (in this case 25°C) to 945°C using the time-temperature relationship given by the following equation

$$T_\mu = 345 \log_{10} (8\mu + 1) \quad (2)$$

where: T_μ is the fire temperature and μ is the fire exposure time.

Regarding thermal analysis, radiation coefficients, and convection coefficients, equivalent convection coefficient were determined for the fire-unexposed side of the door using the following equations [5]

$$k_e = \varepsilon \cdot \delta \cdot (T_1^2 + T_0^2) (T_1 + T_0) \quad (3)$$

$$k_c = (Nu \cdot d_0) / H \quad (4)$$

$$K = k_e + k_c \quad (5)$$

where: δ is the Stefan–Boltzmann constant, ε is the emissivity of steel material, T_0 is the fire and ambient temperature, and T_1 is the average temperature between ambient temperature and temperature of the door on the side not exposed to fire, which is calculated without taking into account the effects of radiation and convection,

H is the height of the A60 door,

d_0 is the thermal conductivity of air.

2.2. Door structure and fire testing procedure

In this study, the fire-resistant door being experimented with is a single-leaf, side-hinged A60 fire-resistant door with dimensions of 1600x600x45 mm, D2 steel material inside is fireproof insulation cotton as described in Fig.1. The door dimensions were selected as a standard size commonly used in maritime applications, satisfying regulatory criteria for ship main pathways, basic ceiling heights in interior sections, hallways, and cabin entryways.

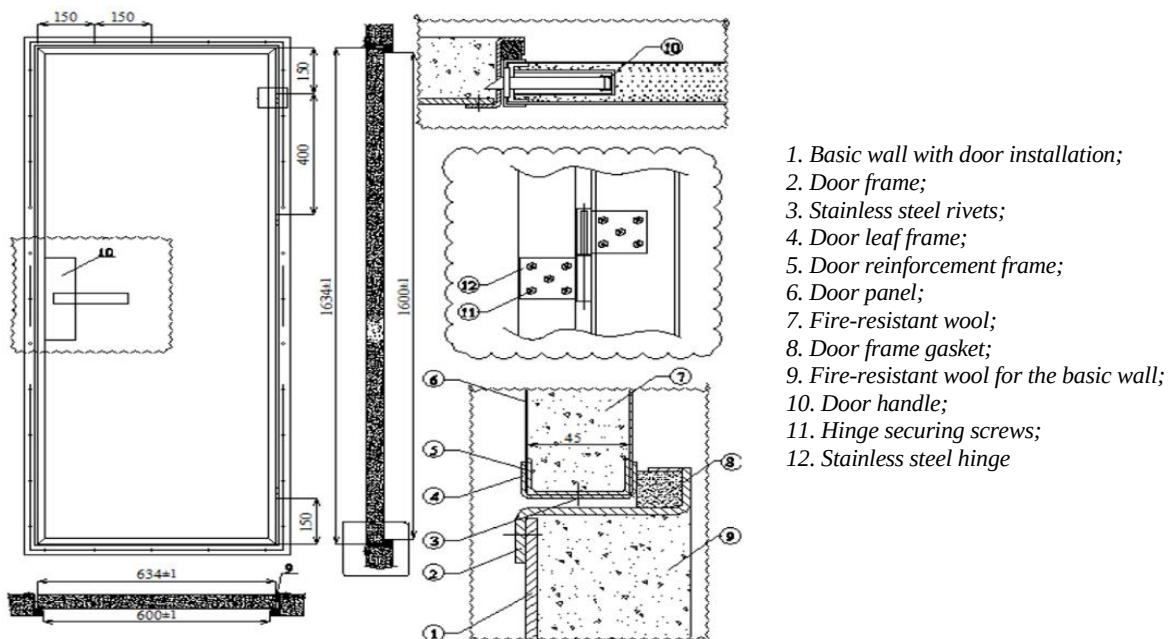


Fig. 1 – A60 Door Structure

Based on the design drawings that are developed (Fig.1), the basic materials are selected to construct the door frame and door leaf. Steel and stainless steel sheets are cut on a CNC cutting machine to create the component blanks. This method quickly achieves the appropriate dimensions for the component blanks without spending much time marking and measuring details. However, it has the drawback that the cut edges must be ground and polished after cutting. To reduce burrs on the cut edges, the blanks are cut using a punch press.

A specialized jig will be fabricated to shape the structure of the basic components: creating a “Z” profile for the door frame, a “U” profile for the door jamb, and reinforcing the door leaf.

Inserting Fire insulation wool Inside the Door Leaf: Inserting thermal insulation wool into the door leaf is a critical step that has a direct impact on the door's surface quality and heat transmission capabilities. Since the thickness of the door cannot be too large—this would impact aesthetics and the installation space—the fireproof wool inside must be tightly compressed without causing the surface of the door leaf to warp (the designed thickness of the door leaf is 45 mm, in compliance with the standard for similar imported doors). To achieve this, before inserting the insulation wool, one face of the door leaf must be securely attached to the reinforcing frame. The insulation is then compressed with a high pressure, and the face is tightly pressed against the reinforcing frame before welding it in place. This ensures that when the weight is removed, the insulation compresses without shrinking or deforming the door surface.



(a) Sensor Arrangement in the Test Furnace



(b) Exterior of the Test Furnace

Fig. 2 – Fire-resistant A60 door testing procedure

Selecting Processing Materials: This is also a fundamental factor that determines the success of manufacturing A-60 fireproof doors. Due to the high requirements for fire resistance and thermal transmission for A-60 fireproof doors used on ships, selecting processing materials is extremely important. Structural steel has no unique heat requirements, but the structure must be carefully constructed and reinforced to guarantee it remains intact under high temperatures. However, certain components, including as door locks, seals between the door and the frame, and insulating wool inside the door leaf, are made of specialist materials. After studying the characteristics of each type of material and consulting samples of similar imported doors, the team has decided to choose:

- **Seal between the Door Frame and Leaf:** The seal is made from ceramic fiber with a cross-section of 20x20 mm. This material is a type of ceramic wool that is commonly used for insulation in high-temperature environments ranging from 1260°C to 1600°C, with excellent stability at high temperatures. It is readily available in domestic supply.
- **A-60 Fireproof Thermal Insulation Wool:** The A-60 fireproof insulation uses mineral wool with a thickness of 50 mm and a density of 120 kg/m³. This thickness is suitable for the door specifications and provides adequate heat resistance corresponding to the A-60 fire rating. It has a low thermal conductivity and is widely used in the shipbuilding industry.
- **Door Lock:** The door lock is a specialized type designed specifically for A-60 fireproof doors.

Fire doors are evaluated for their fire resistance through a standardized test. This test involves using a specialized furnace to heat the sample at the fire prevention laboratory LAS-XD 416, in accordance with a specified temperature-time standard (see Fig. 2). The supporting structure including the frame and furnace walls are constructed according to the specified instructions. The fire-resistant A60 door is part of the supporting frame, then sealed into the furnace. In this study, A-60 class doors are tested, and the procedure involves heating the sample to 945°C over 60 minutes, following the International Maritime Organization's fire-test procedure (FTP) code [8]. The door must meet certain criteria: the average temperature on the unexposed side should not surpass a specified limit, and only minimal gaps between the door and the door frame are acceptable to ensure no flames or smoke escape throughout the door. To measure the temperature of the heat zone inside the furnace and the area outside the door not exposed to fire, a temperature sensor system connected to the control and monitoring system is used. The test is considered successful if these criteria are met.

2.3. Construction of references

Results from a numerical model and a common fire endurance test are compared in this study using software ANSYS 19.2 [6], applied to steel fire doors. The simulation of the fire testing process for the A60 door examines the door's mechanical and thermal characteristics. The authors used two gas burners to directly supply heat to the test furnace. By using simulation, we can experiment on many different boundary conditions: increasing the speed of the heat source, the heat-generating agent, the test temperature, the door material, the door structure, etc. From here, the heat resistance limit of the door as well as the direction of the heat source can be calculated. The input parameters are as follows:

Table 1 – Input parameters

Testing Duration	60 minutes	
Materials	D2 steel plates and insulating wool	
Simulation Type	Energy simulation	
Mode	Steady-state	
Heating Source	Gas combustion	
Temperature	Outer surface of the door	300°C
	Core of the door	94°C
	Inside the furnace	945°C
Boundary	Boundary conditions	Velocity: 2 m/s, Temperature : 1000°C
	Furnace interior	Pressure: 100 Pa, Temperature : 945°C

3. Illustrations

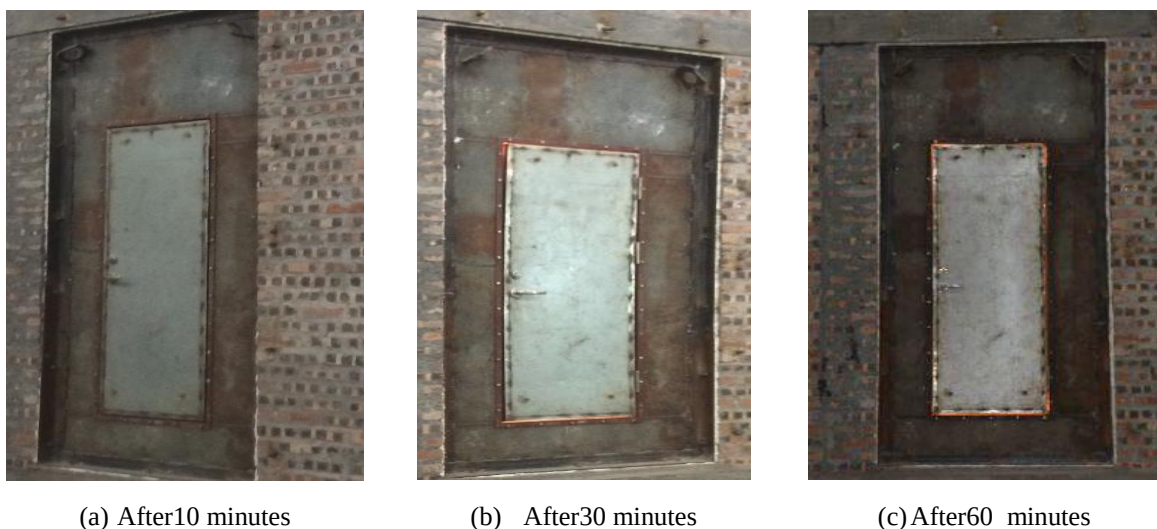
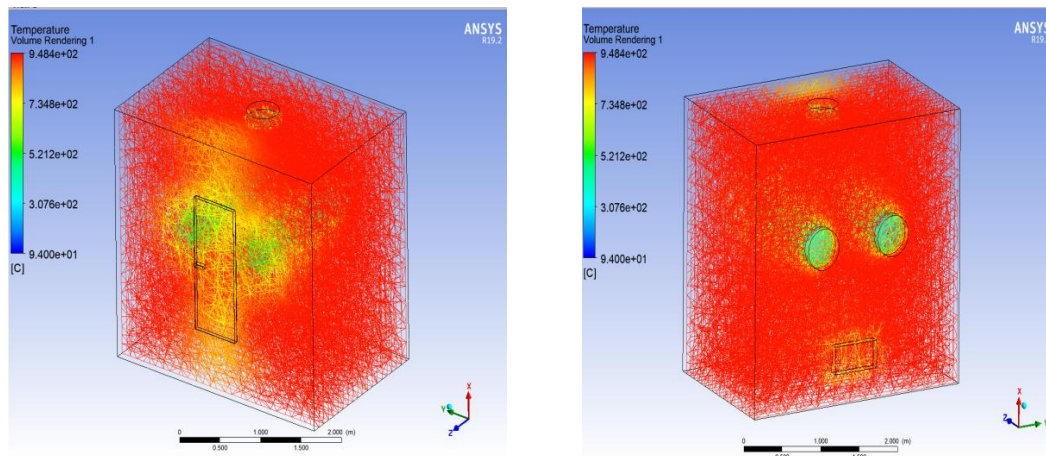


Fig. 3 – The exterior surface of the A60 door that was not exposed to the fire after the fire test

Fig. 3 illustrates how the non-exposed surface of the A60 door changes over the duration of the fire test. As the fire test progresses, the color of the door surface becomes darker. The image shows the color of the A60 door changes after 10 minutes, 30 minutes, and 60 minutes of fire test. The A60 door sample used for the test did not collapse during the process. The assessment concludes that the test samples maintained its integrity throughout the 60-minute test.

- The test samples system is A60 door that does not collapse during the fire test.
- The components of the test samples, such as hinges, door handle, and lock, remained in their original positions.
- The gap between the test door panel and the frame did not exceed the allowable limits specified by the standards.



(a) The Furnace's Temperature Distribution

(b) Temperature Distribution on the Furnace Front

Fig. 4 – Simulation Image of the Furnace Temperature Distribution

The simulation image shown in Fig.4 demonstrates that the furnace temperature is evenly distributed within the test chamber. Different temperatures are simulated by different colors. Blue represents low temperature, red represents high temperature. It can be seen that the temperature of the furnace is very high and evenly distributed, which proves that the heat source is properly and accurately adjusted.

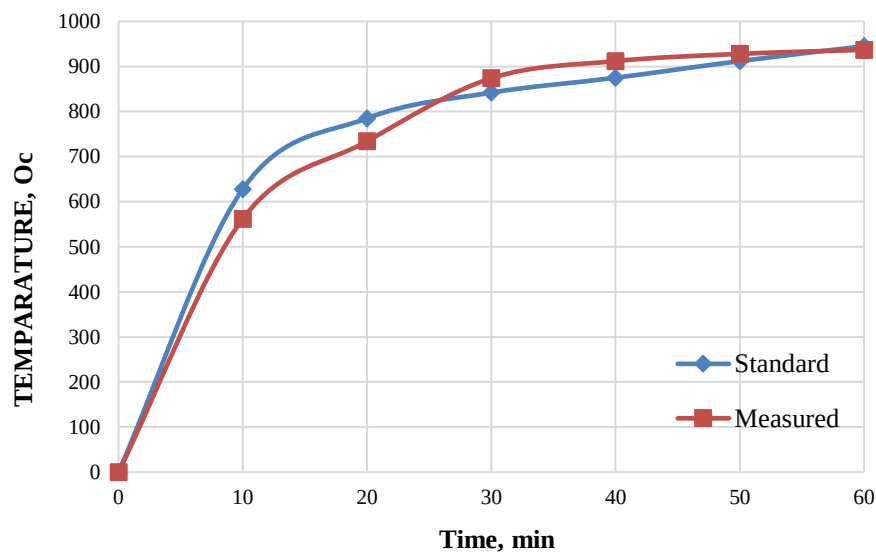


Fig. 5 – Average Temperature Inside the Fire Test Furnace

Temperature inside the furnace is measured by temperature sensors, which record and convert temperature variations into electrical signals. These signals are subsequently transferred to reading and processing equipment, which display and save temperature data (see Fig. 5). The blue curve in the graph represents the standard average furnace temperature following the International Maritime Organization's fire-test procedure (FTP) code. The red curve in the graph represents the actual average furnace temperature measured by the research team. The average temperature measurements inside the furnace show minimal deviation from the standard temperature curve, indicating good calibration of the furnace burners. The furnace's average temperature during the fire test rises rapidly within the first 10 minutes. At the completion of the 60-minute burning test, the temperature on average inside the furnace is 937°C, which is within the standard limits.

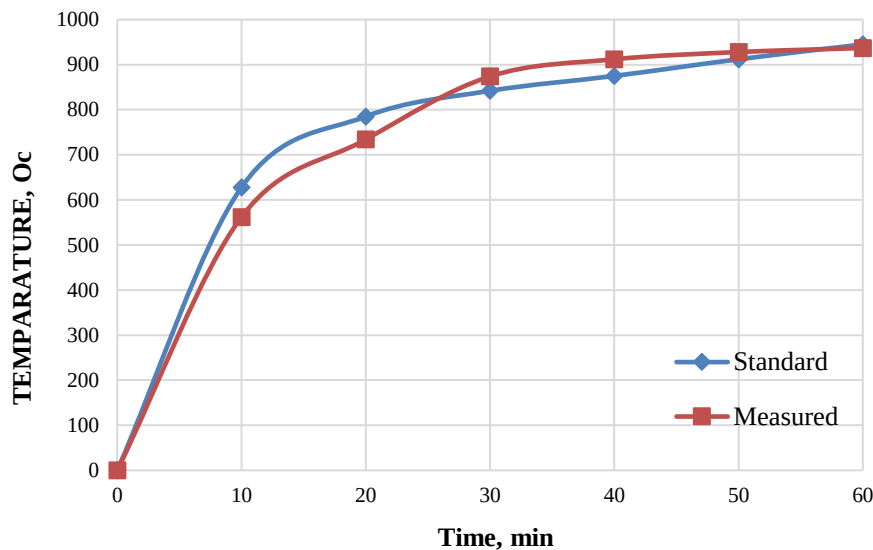
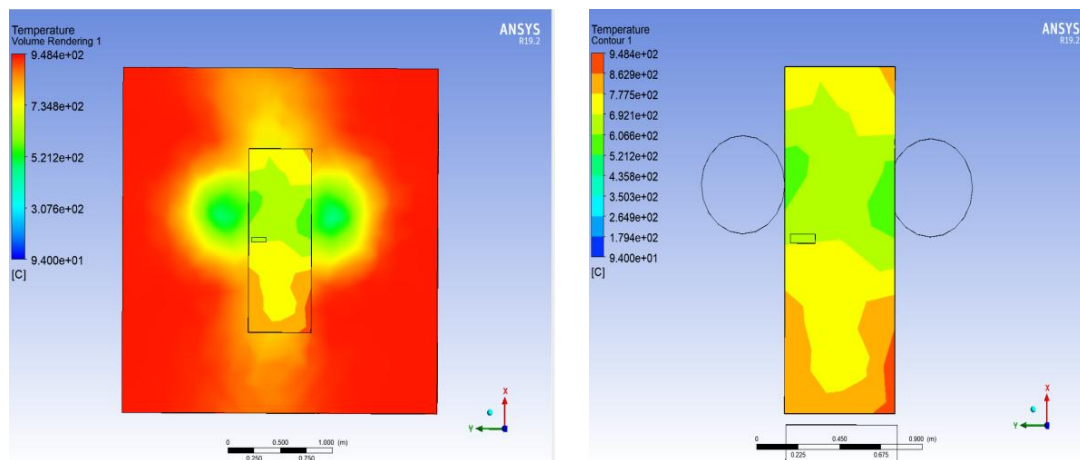


Fig. 5 – Average Temperature Inside the Fire Test Furnace

Additionally, this study uses temperature sensors to assess the temperature of the non-exposed exterior surface of the A60 door (Fig. 6). Figure 6 shows the simulation of the temperature distribution outside the furnace wall (a) and the temperature distribution of the A60 door (b). The furnace walls maintain a high temperature, as indicated by the deep red color. Looking at the image, it can be seen that the entire furnace wall is subjected to very high temperatures. The area surrounding the fire door is shown in yellow, where the temperature is lower.



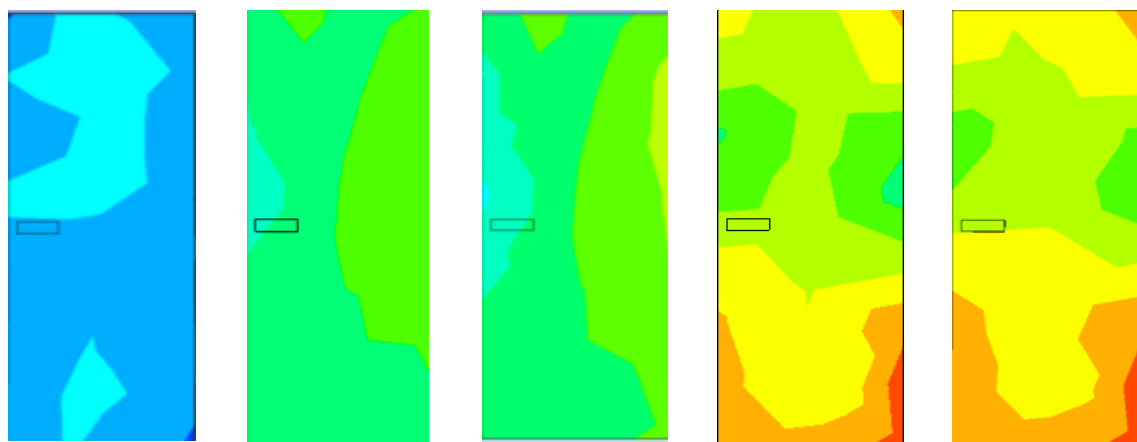
(a) Temperature Distribution of the Furnace Walls

(b) Temperature Distribution of the A60 Door

Fig. 6 – Simulation Image of the distribution of temperatures outside the A60 door and on the Furnace wall

The temperature of the front surface of the A60 fire-resistant door after 60 minutes of baking is unevenly distributed. The temperature is divided into many different zones represented by many colors such as green, yellow, orange, red. This shows that the surface temperature of the door is much lower than the temperature in the furnace. The simulation results are consistent with the prediction due to the 45 mm thick insulation layer in the A60 door. The A60 door is designed with an insulation layer in the middle, which has the effect of preventing the temperature from passing through it.

To see more clearly the temperature change of the A60 door over time, we observe Fig. 7. below simulates the image of the A60 door when tested for fire after 5 minutes, after 10 minutes, after 15 minutes, after 30 minutes, and after 60 minutes. We can clearly see the temperature of the door increasing through the colour of the door. The average temperature range of the door during the fire test is shown by many colors: blue represents the lowest temperature, green, yellow, orange, red. As the door heating time increases, the average temperature of the door also increases. However, the temperature of the red area is very small and insignificant, mainly around the edge of the door. After 60 minutes of the fire test, the colour that occupies the majority of the door area is still green and yellow; the average temperature of the door is not too high.



(a) After 5 minutes b) After 10 minutes c) After 15 minutes d) After 30 minutes e) After 60 minutes

Fig. 7 – Simulated image of temperature distribution of door A60 depending on time

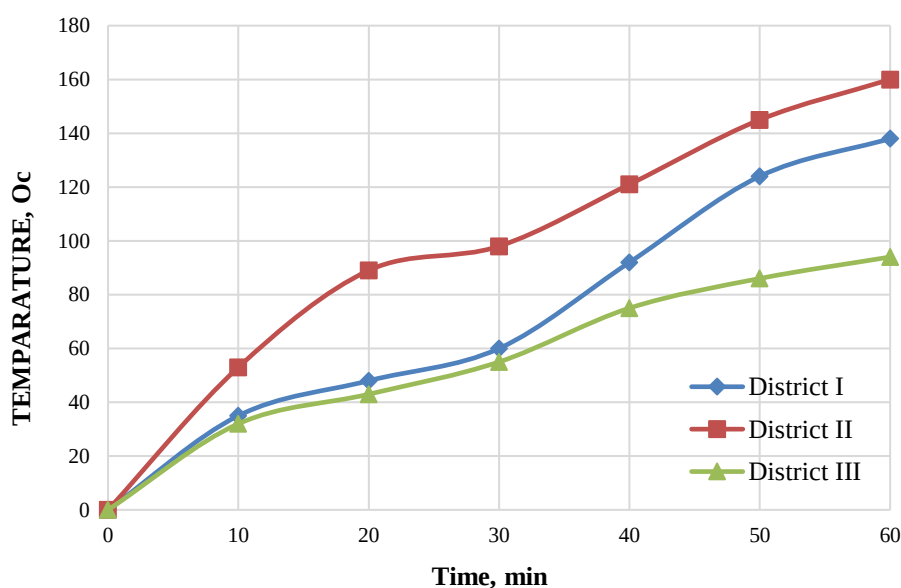


Fig. 8 – Temperature of the outer surface of A60 door during the fire test

The temperature sensors measure the temperature of the non-exposed outer surface of the A60 door, which is separated into three zones as illustrated in Fig. 8: Zone I is the area around the lock handle, 100 mm away; Zone II is the area around the door's edge and hinge frame; Zone III is the central region of the door. The blue curve in the graph shows the average temperature of zone I, the red curve in the graph shows the average temperature of zone II, and the green curve shows the average temperature of zone III. Temperatures in all zones increase over time. Looking at the graph, we can see that the average temperature of zone II is the highest, followed by the average temperature of zone I, and the average temperature of zone III is the lowest. After 60 minutes of the fire test, the average temperature for Zone I is 138°C, for Zone II is 160°C, and for Zone III is 94°C, all of which are below the permissible temperature limit of 180°C. The quality of the materials used in the A60 fire-resistant frame ensures the measured and simulated results, where Zone II, with its orange and red temperatures, is the highest temperature zone.

4. Conclusion

Fire-resistant doors are an important element in the fire safety design of ships. The design of these doors focuses on the requirements of ensuring fire resistance according to standards, ensuring smoke protection, and ensuring durability.

The A60 fire-resistant door is researched, designed and manufactured with dimensions of 1600x600x45 mm made of D2 steel plate, with a layer of insulation cotton in the middle. The door is tested for fire according to FTP Code conditions. The temperature on average on the outer surface of the door not exposed to the highest heat source is 160°C, ensuring that the prescribed standard does not exceed 180°C. However, there is still a difference between the measured results and the simulation results but not significantly (0.63%). In conclusion, the A60 fire-resistant door sample ensures integrity after 60 minutes of testing, meeting the requirements of use: the components of the test samples, such as hinges, door handle, and lock, remained in their original positions; the gap between the door panel and the frame did not exceed the allowable limits specified by the standards. Therefore, this is an important premise in the processing and manufacturing of fireproof doors used in the construction and repair of ships.

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