Journal of
Marine Science and Engineering

MDPI

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Experimental Study on the Hot Surface Ignition Characteristics and a Predictive Model of Marine Diesel in a Ship Engine Room

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Abstract: To ensure the safe protection of marine engine systems, it is necessary to explore the hot surface ignition (HSI) characteristics of marine diesel in ship environments. However, an accurate model describing these complex characteristics is still not available. In this work, a new experimental method is proposed in order to enhance prediction performance by integrating testing data of the characteristics of HSI of marine diesel. The sensitivity of HSI is determined by various factors such as surface parameters, flow state, and the ship's environment. According to variations in the HSI status of marine diesel in an engine room, the HSI probability is distributed in three phases. It is essential to determine whether the presence of marine diesel or surrounding items can intensify the risk of an initial fire beginning in the engine room. A vapor plume model was developed to describe the relationship between HSI height and initial specific buoyancy flux in vertical space. Further, field distribution revealed significant variation in the increase in temperature between 200 and 300 mm of vertical height, indicating a region of initial HSI. In addition, increasing surface temperature did not result in a significant change in ignition delay time. After reaching a temperature of 773 K, the ignition delay time remained around 0.48 s, regardless of how much the hot surface temperature increased. This study reveals the HSI evolution of marine diesel in a ship engine room and develops data-based predictive models for evaluating the safety of HSI parameters during initial accident assessments. The results show that the goodness of fit of the predictive models reached above 0.964. On the basis of the predicted results, the HSI characteristics of marine diesel in engine rooms could be gleaned by actively determining the parameters of risk.

Keywords: ship engine room; marine diesel; ignition characteristics; surface temperature; predictive model

Citation: Wang, K.; Qiu, R.; Ming, Y.; Xu, H. Experimental Study on the Hot Surface Ignition Characteristics and a Predictive Model of Marine Diesel in a Ship Engine Room. *J. Mar. Sci. Eng.* **2024**, *12*, 798. https://doi.org/10.3390/jmse12050798

Received: 15 April 2024
Revised: 2 May 2024
Accepted: 7 May 2024
Published: 10 May 2024

1. Introduction

When a ship is sailing or working near a port, a failure in the marine fuel container or oil supply pipeline of an engine system can cause combustible liquid leaks and flows. Marine fuel can leak and make contact with typical high-temperature machinery surfaces and then easily trigger hot surface ignition (HSI). Ship fires are a serious and dangerous type of maritime accident that can result in injuries and fatalities. According to statistical data from 2017–2022 by Det Norske Veritas, approximately 63% of fires and explosions originate in the engine room. The leakage and dispersion of operating fuels onto hot surfaces are a common cause of accidental fires. The piping system, piping connections, and associated components such as O-rings pose a higher risk of fire in some cases. For instance, marine diesel can leak when the piping components are not tightened to the required torque. Sometimes, piping connections may loosen due to vibrations caused by the ship's motion on the sea. The oil filter covers of marine diesel may also come loose, and the rotary spindle may become displaced from the top cover for various reasons. These issues can result in minor leaks in the engine room, which can cause oil to soak into the surrounding area over time. Rubber hoses can be vulnerable to rupture due to thermal damage from the ship's mechanical equipment. In addition, bolts for flanges or filters may break due to fatigue caused by overtightening over time, and securing bolts may be found loose or missing altogether. Other potential causes of failure include incorrect assembly after maintenance in the ship engine room. However, the aforementioned common causes of marine diesel leakage and dispersion often result in fires. These incidents are primarily caused by energy system failures, most commonly in low-pressure marine diesel piping, which allows for the leakage of diesel, allowing it to come into contact with an unprotected hot surface. The current study highlights three main aspects: the diesel's properties, the high-temperature ignition source, and a reasonable guide for preventing highly flammable marine diesel from contacting a high-temperature ignition source.

The incidence of accidents caused by engine room fires is much higher than that in passenger cabins, cargo storage, and other ship areas. Some researchers have analyzed ship engine system fires and the damage they cause [1–3]. The Le Boreal incident [4] demonstrated that safer alternative arrangements for the ship engine room were not considered, and the fire scenario was deemed too unlikely for cost-effective safety measures. Spyrou et al. [5] discovered that ignition probabilities can be calculated using the present empirical formula. However, larger ships may have lower probabilities of fire occurring in the engine room. The engine system contains many combustible materials, such as fuels or chemicals, which can potentially be ignited. Any thermal source that ignites these materials can cause fire accidents [6–8]. Shao et al. [9] identified hazard identification as an essential stage in the unique development of a ship. It was found that the most significant risk factors in the engine system were fire accidents caused by fuel leakage from connecting valves or flanges. These accidents occur when combustible materials reach their ignition temperature and enter into a chemical reaction with an oxidizer. The ignition of leaked fuel continued in the engine room due to the presence of an ignition source and combustible materials [10].

Numerous studies have been conducted on fireproofing and fire evaluation using numerical tools. Numerical simulations of some cases indicate that in both the engine room and the vicinity of the exit, the position of the fire exerts the greatest influence on the distribution of temperature [11]. Ship fire accidents in engine rooms with different types of low-pressure fuel gas supply systems have been compared, and the potential risk of a high concentration of leaked fuel vapor has been identified [12,13]. The simulation database is crucial in developing a ship fire safety plan that enhances safety management in the early design stage [14]. Additionally, fatality estimation is beneficial for improving design safety and ensuring an effective response to ship engine room fires [15,16]. Lan produced a full-scale model of the engine room and found that ventilation conditions had a significant effect on combustion behavior [17]. While numerical methods have certain advantages [18], it is important to constantly improve results and models by comparing them with real experimental data. In their study, Wang et al. conducted experiments in an engine room to investigate the vertical temperature distribution profile during a fire [19]. They found that the development of the fire was primarily influenced by the concentration of oxygen. Additionally, the mass loss rate of marine fuel was identified as an important parameter that characterizes the combustion process in engine room fires [20]. Marine diesel is a commonly used fuel in ship engine systems. Ignition can be triggered by equipment failure or thermal sources. Liu et al. [21] conducted an experiment using a rectangular pool to study the ignition zone and flame behavior after initial fire growth. The ventilation structure and mode of the engine room were different from those in other cabin rooms. The mass loss rates of leaked fuel increased as the ventilation velocities increased in the ship engine room [22]. During the initial stage of the fire, air entrainment was greatly limited [23], resulting in the formation of a broken fire merge above the obstacle in the ship engine room. It was found that the overall heat loss factor was the critical variable that significantly determined the increase in pressure and smoke filling [24]. Additionally, the ignition sources during the initial stage of an engine room fire were affected by various factors, including the properties of the fuel, geometry of the ignition source, and environmental boundaries. A significant heat transfer mechanism was observed with a continuous fuel dispersion process and ignition [25]. In ship engine rooms, the conductive heat transfer term is not applicable, and heat loss to the substrate cannot be ignored in thin layers of marine fuel. One study suggested that fire prevention measures could be improved by detecting proximate events that occur immediately before the HSI [26].

Many engine room fires are caused by failures in marine oil systems, which allow leaked fuel to come into contact with unprotected hot surfaces. Recent research has been conducted to clarify the relevance of the evaporation process and ignition mechanism. Mizomoto et al. focused on measuring the mass of n-cetane evaporated a short time after the droplet's contact with a hot surface [27]. They found that ignition occurred when the stoichiometric n-cetane/air mixture reached a droplet diameter of approximately 4 mm to 5 mm. Bennett et al. proposed a one-dimensional model for the airborne HSI event, which revealed that diffused fuel vapor buoyancy and surrounding entrained air limited ignition over a wider elevation range [28]. Statistical measurements could provide the critical temperature at which the ignition probability was 50% [29]. The materials of the hot surface affected the fuel ignition process. It was found that the ignition temperature on a hot surface made from a stainless steel heat shield was generally lower than the temperature of one made from 409 stainless steel [30]. One study utilizing high-speed video data records revealed that the temperature of the combustible fuel was higher during the initial stage, resulting in a lower ignition delay time [31]. The ignition was affected by the flammable liquid's properties, the hot surface temperature, hot surface type, and environmental parameters [32]. However, there is currently no widely applicable model for HSI, so individual experiments must be carried out for different liquids in ship engine rooms.

This study focuses on experimentally investigating the ignition characteristics of leaked marine diesel on a hot surface in a ship engine room. The purpose of determining the phase transition, initial ignition, and flame propagation of marine diesel after leakage onto a high-temperature surface is to predict the characteristics and parameters of the HSI process. To achieve this, HSI equipment was set up in ship laboratory to test the HSI parameters of marine diesel. This study analyzes high-speed camera images to determine the spatial locations of the hot surface-driven initial ignition behavior of marine diesel. A predictive model for ignition height is proposed by combining experimental data with heat transfer mechanisms. The temperature field's distribution and radiant heat transfer mode from diesel contacting a hot surface until ignition are investigated using data collected by ten thermocouples. A predictive model of the HSI delay time of marine diesel and surface temperature is developed, taking into account a hot surface characterization system (e.g., temperature field, ignition occurrence, hot surface temperature, etc.) that covers key factors in flow field and combustion. This study expands the existing limitations of assessing ignition sources with predictive models, aiming to provide more support for controlling and evaluating marine diesel leakage in ship engine rooms.

2. Materials and Methods

2.1. Experimental Method

The purpose of this study is to investigate the initial ignition and combustion process of marine fuel on hot surfaces. To achieve this, an effective experimental platform and data acquisition system must be constructed. The ship utilized in the current study is a deep sea double-deck trawler, a type of fishing vessel that is primarily employed for single-bottom trawling in the West African sea. The length of pelagic trawl is 33.2 m, with a design draft and a displacement of 3.5 m and 510.81 t, respectively. The main engine is a model of a diesel engine, with a rated power of 551 kW. Figure 1 shows a schematic diagram of the complete experimental test system located in the ship's engine room. Additionally, a hot surface simulation device featuring temperature regulation was designed for this experiment. The hot surface device can accurately adjust the increase in temperature to within 1.0 K, with a maximum temperature of 1100.0 K. To accommodate its high power usage, the device's power cord is connected to the outside through an opening on the side of the ship engine room. It is capable of simulating local high-temperature areas generated by equipment or pipe housings in the ship engine room. The hot surface device has an effective surface size of 0.4 m × 0.4 m, and its structure can be modified by adding an edge structure. The device is controlled by an external controller located outside the ship engine room, connected through an extension cord, and set by researchers for each group of experimental tests. An electronic balance with high measurement precision of up to 0.01 g is placed underneath the hot surface. The mass loss rate of the marine diesel leaking onto the hot surface can therefore be obtained. The hot surface device is placed on a three-degrees-of-freedom sloshing simulator to produce effective simulations of hull tilt and movement for study in the stationary ship engine room. A device for controlling marine diesel leakage is positioned above the hot surface and connected to a peristaltic pump. This device ensures that marine diesel consumption during each experiment remains within the range of 5 mL to 20 mL, which is similar to the ignition of fuel droplets on a hot surface. Following a brief interval, a marine diesel droplet comes into contact with the hot surface device. According to the height set by the nozzle of the flow controller in this experiment, the distance between the droplet touching the hot surface after flowing out of flow controller is approximately 0.045 m. Once the fuel vapor concentration in the vicinity of the droplet reaches a specific threshold and the temperature is sufficiently elevated, the ignition process is initiated.

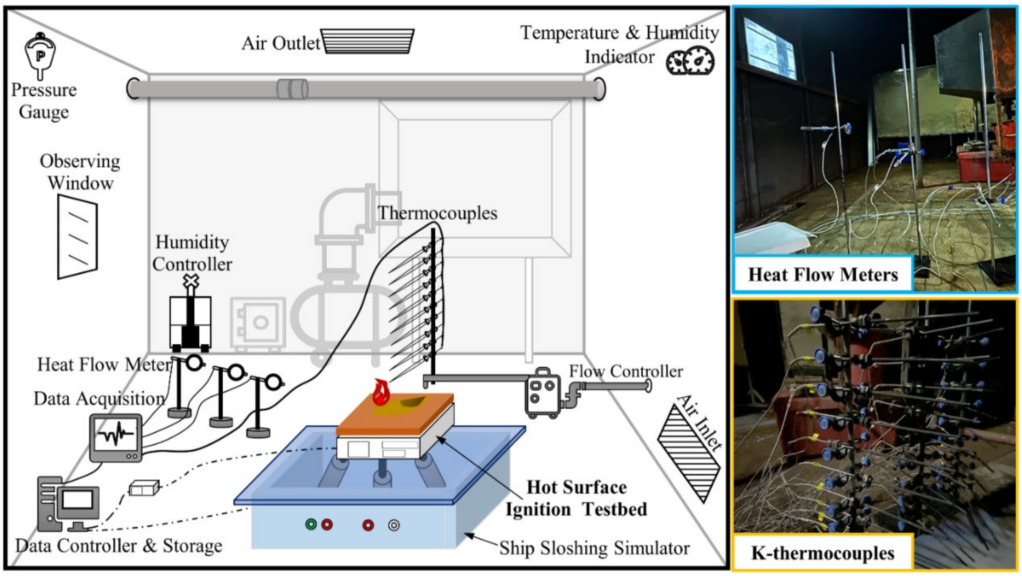


Figure 1. Configuration of experimental apparatus and system utilized in HSI tests.

The temperature data are collected during the ignition of marine diesel using K-type thermocouples to determine the distribution of the air temperature field. K-type thermocouples typically consist of temperature-sensing elements, mounting fixtures, and junction boxes. For this study, a bundle of thermocouple test rods are formed by installing ten K-type thermocouples on a unified test rod. The thermocouple test rod is positioned above the hot surface, with the thermocouples arranged in sequence and labeled T1 to T10. The spacing between the first and second thermocouples and the hot surface is 20 mm, while the distance between the third and fourth thermocouples and the previous thermocouple reaches 30 mm. The spacing between the fifth and tenth thermocouples is 50 mm. The real-time data obtained from thermocouple acquisition are connected to and stored in the TP-700 data acquisition device via a connection cable. In this experiment, two high-speed cameras are positioned at the observation port and inside the ship engine room to capture the initial moment of ignition of the marine fuel on the hot surface. A SONY AX700 high-speed camera (Sony, Tokyo, Japan) is used, which is capable of capturing images up to 1000 fps/s. The laboratory is equipped with humidity controllers to simulate the humidity conditions in the ship engine room during offshore operations. The laboratory's humidity is regulated and maintained between 70% and 90%, based on monitoring data from the ship nacelle. The temperature and humidity monitoring instruments are installed on the opposite side of the wall to ensure consistency between the experimental scenario and the real operating environment of the ship engine room. It is important to adjust the temperature and humidity accordingly.

2.2. Experimental Materials

According to accident cases, this experiment identifies three types of marine fuel as experimental tests and determines the physical and chemical properties of experimental materials, as shown in Table 1. The marine diesel used in this experiment consists of various components, including alkanes, cycloalkanes, alkenes, cycloalkenes, and aromatic hydrocarbons. The heavy molecular combustion of marine diesel is based on the hydrocarbon composition characteristics of typical blended raw materials. Among them, the asphaltene molecule has an average molecular structure of asphaltene in crude oil, whose average molecular formula is $C_{47}H_{41}NOS_2$ and whose relative molecular mass is 699. The main raw materials of marine diesel are light cycle oil (LCO), and the saturated hydrocarbon components in LCO are mainly alkanes. The origin of marine diesel used by the main engine of multifarious ships displays differences, which leads to differences in marine diesel components. Using the numerical method, it is difficult to directly present the ignition characteristics of actual marine diesel. Therefore, the ignition characteristics of marine diesel are usually represented by n-heptane, whose cetane number is close to that of marine diesel. According to the experimental tests in the current study, the experimental amount of marine fuel ranges from 5 mL to 20 mL. Table 1 presents the marine diesel fuels selected for this experimental test of ignition on heated surfaces. A total of 30 tests in different conditions are performed to determine the ignition and combustion characteristics of marine fuels on hot surfaces.

Table 1. Physical properties of marine diesel in the current experimental work.

Items	Density at 288.15 K (kg/m^3)	Viscosity at 313.15 K (mm^2/s)	Flash Point (K)	Pour Point (K)	Total Base Number (mg KOH/g)
Marine diesel	864.0	4.52	375	264	13.5

3. Results and Discussion

3.1. Initial Position of HSI Occurrence with an Elevated Hot Surface Temperature

The fuel leaked in the ship engine room evaporates through heating on a hot surface, forms combustible vapor above the hot surface, and mixes with the surrounding air. The combustible vapor mixture ignites over the hot surface. In the process of heat evaporation, the leaking marine fuel also causes heat loss to air and the surface housing the equipment due to the action of the heat source. In the process of fuel his, the leaking fuel is affected by air flow organization, environmental humidity, and wall thermal feedback. As a result, the leaking marine fuel's HSI characteristics, ignition time and ignition probability are changed. The heat loss of combustible liquid and the effect of environmental thermal feedback are affected by the specific design of the top opening in the engine room and changes in humidity in the operating environment. NFPA 921 suggests that ventilation can influence ignition. If too much air blows across a hot surface, it can hinder the ability of the combustible liquid to volatilize quickly enough to allow ignition. Conversely, if too little air blows across the hot surface, the atmosphere can become too rich. According to Equation (1) [33], the heat received by the surface of marine fuel may be the sum of heat conducted by the hot surface, heat transferred to the liquid surface by thermal convection, and heat transferred to the liquid surface by thermal radiation.

$$Q_{ex} = Q_{cond} + Q_{conv} + Q_{rad} \quad (1)$$

where Q_{conv} is the heat generated by thermal convection, kW/m^2; Q_{rad} is heat transferred by thermal radiation, kW/m^2; Q_{ex} is heating rate of external heat source per unit area of liquid surface, kW/m^2; and Q_{loss} is heat loss rate per unit area of combustible liquid, kW/m^2.

According to the experimental tests in the previous section, the process of the ignition of leaking marine diesel above a hot surface is accompanied by significant and complex evaporation behavior. In this study, the evaporation and ignition characteristics of marine diesel in the vertical space of a hot surface are analyzed. The data are collected by a high-speed camera, and each image is processed according to a time axis. The experimental amount of marine diesel is 10 mL and the hot surface temperature is set at 748 K as an example. Figure 2 presents the process of diesel leaking onto a high-temperature surface, causing evaporation and initial ignition. When marine diesel leaks onto a hot surface in the initial stage, the rapid phase transition of marine diesel can be clearly observed. Due to the high temperature of the hot surface, marine diesel is almost always in a state of film boiling. This creates a gaseous layer between the diesel and high-temperature surface, which changes the mode of heat transfer from the high-temperature surface to liquid. At 3.675 s, a significant amount of white vapor mixture is produced when marine diesel comes into contact with a hot surface. The marine diesel produces a wider range of combustible vapor mixtures above hot surfaces when compared to marine lubricant. This is due to the flow characteristics of marine diesel. The evaporation product of diesel on the high-temperature surface mixes fully with fresh air, forming a combustible mixture in the vertical space. The heat continually transfers from the high-temperature surface to the liquid surface and, coupled with thermal feedback, causes the initial ignition behavior of the high-temperature surface; ignition therefore occurs instantaneously when diesel leaks at 3.725 s. Once the initial ignition forms a core in the air, it gradually grows and generates flame propagation, as depicted at 3.733 s. This reveals that the initial ignition takes place at a higher position above the high-temperature surface.

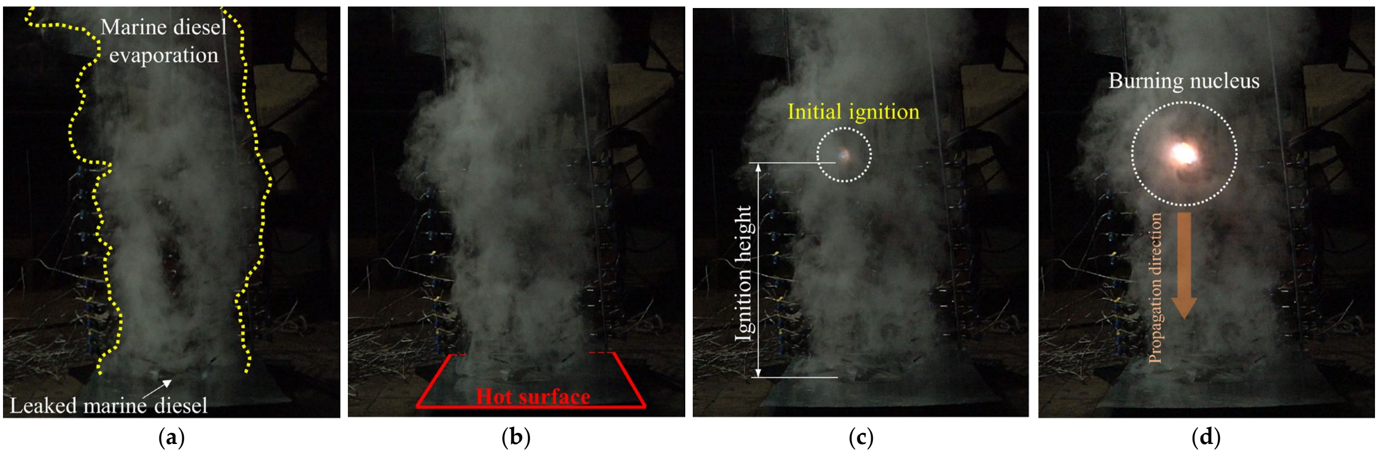


Figure 2. The initial ignition of marine diesel leaking onto the hot surface of a ship engine system. (**a**) t = 3.108 s; (**b**) t = 3.675 s; (**c**) t = 3.725 s; (**d**) t = 3.733 s.

The interface between the leaked fuel and high-temperature hot surface is a solid–liquid-state heat transfer interface. At this interface, the high-temperature surface of the ship engine system transfers heat to leaking oil by means of heat conduction. The hybrid scenario shows faster movement of liquid marine fuel due to the formation of vapor underneath and the curvature of the leading edge of leaked marine fuel caused by surface tension. If the high-temperature surface is significantly elevated, the marine fuel will boil violently on the high-temperature surface, and a film of vapor will form on the surface of the liquid fuel. The film's boiling mode can cause the pool of marine fuel to break up into smaller globules due to surface tension. When film boiling occurs in the marine fuel above the hot surface, combustible vapor is generated at different distances from the marine fuel's surface. The film boiling regime of leaked marine fuel starts at a specific value of excess T_s over T_{sat} and can be given by Equation (2) [34].

$$T_s\text{-}T_{sat} = \frac{0.127\sqrt[3]{g}h_v\rho_v}{\lambda_v}\sqrt{\frac{\sigma}{\rho_l}}\sqrt[3]{\frac{\mu_v}{\rho_l}} \tag{2}$$

where ρ_v is the density of fuel released into ambient air from the hot surface, kg/m^3; ρ_l is the density of marine fuel, kg/m^3; λ_v is the thermal conductivity of vapor in the film between the marine fuel and hot surface, W/(m·K); h_v is the latent heat of vaporization, kJ/g; σ is the surface tension of marine fuel; and N/m; μ_v is the viscosity of the vapor in the film between the surface and fuel, mm^2/s.

When marine fuel on a high-temperature surface is in a film boiling state, h_f can be presented [35] as follows.

$$h_f = 0.425\sqrt[4]{\frac{\lambda_v^3 h_v \rho_l \rho_v g}{(T_s\text{-}T_{sat})\mu_v\left(\frac{\sigma}{\rho_l}\right)^{\frac{1}{2}}}} \tag{3}$$

where h_f is the heat transfer coefficient of film boiling, W/m^2·K.

In the film boiling state, the evaporation rate of fuel on a high-temperature surface can be obtained by Equation (4) [36], as shown:

$$m_f = \left(\frac{h_f S}{c_p}\right)\ln(B+1) \tag{4}$$

where m_f is the evaporation rate of leaked marine fuel within unit area, g/s; S is the surface cross-sectional area from leaking marine fuel on the hot surface, m^2; and B is the mass transfer number.

The mass transfer number is also called the D. B. Spalding number, which represents the ratio of chemical energy to the evaporation energy of fuel. B can be found using Equation (5) [37]:

$$B = \frac{c_p(T_s\text{-}T_b)}{h_v} \tag{5}$$

where T_b is the boiling temperature, K, and c_p is the specific heat, J/(kg·K).

Figure 2 illustrates that when the marine diesel leaks and is ignited above a hot surface, the initial flame entrains air in the engine system. The experimental phenomenon demonstrates that without mechanical ventilation, ignition always occurs vertically upward from the center line of the high-temperature surface. Marine diesel HSI typically occurs between the heated surface and the ceiling of the ship engine system. The initial flame appears on the hot surface and further spreads. This shows that the accumulation of marine diesel vapor above the heating surface, combined with the hot surface temperature, affects the entrainment of the vapor/air mixture. Equation (6) shows the relationship between the entrainment velocity of the high-temperature surface ignition flame and the rising velocity of the gaseous mixture in the initial fire core [38].

$$u_e = \eta u_b \tag{6}$$

where u_e is flame velocity at which the vapor/air mixture is entrained in the horizontal direction, m/s; u_b is the rising velocity, which is attributed to vapor and buoyancy effect, m/s; and η is the correction coefficient.

Equation (7) expresses that the rising velocity decreases as the distance from the high-temperature surface increases in the vertical space in which a gaseous mixture is formed by the marine diesel vapor and air existing in the engine room [39].

$$u_\mathrm{b} = \left(\frac{7.3q_\mathrm{s}\mathrm{g}H}{c_\mathrm{p}T_\mathrm{a}\rho_0}\right)^{\frac{1}{3}} \tag{7}$$

where q_s is the heat flux density of the solid–liquid surface, $\mathrm{W/m^2}$; g is the gravitational acceleration, $\mathrm{m/s^2}$; H is the marine diesel ignition height, m; ρ_0 is the ambient air density, $\mathrm{kg/m^3}$; T_a is the initial temperature of ambient air, K; and c_p is specific heat, J/(kg·K).

As a result, by obtaining the correction coefficient, we can further determine the expression of the entrainment velocity at which the initial ignition flame is on the hot surface. Figure 3 presents the difference between the initial ignition height of marine diesel and the heated surface's temperature. The ignition height of marine diesel exhibits a declining trend with an increase in heated surface temperature. However, this downward trend does not follow a simple linear relationship, as can be seen in the experimental results when the probability of HSI is 50%, for instance. When the heated surface temperature is close to 748 K, the ignition height of marine diesel above the hot surface is about 0.51 m. If the surface is heated and reaches a temperature of 758 K, the ignition height drops to approximately 0.42 m, with a change amplitude of 0.009 m/K. If the surface reaches a temperature of 778 K, the diesel will be ignited on the hot surface with 100% probability. At this high surface temperature, the height of the HSI for marine diesel is 0.22 m. The increase in surface temperature causes the marine diesel that leaks onto the hot surface to evaporate rapidly, forming combustible vapor that mixes with the fresh air. The high-temperature surface has a great thermal effect in a short time, leading to HSI behavior in the area near the high-temperature surface. As the heated surface's temperature goes up, the ignition height remains around 0.18 m above the hot surface instead of fluctuating greatly. In a previous work [40], a vapor plume model was developed. This model is presented in Equation (8) and can be used to describe the relationship between the ignition height of marine diesel and the initial specific buoyancy flux [41] in a certain vertical space.

$$\frac{(\rho_0\text{-}\rho_\mathrm{v})}{\rho_0^2} = H^{-\frac{5}{3}}\left(\frac{5B_\mathrm{i}}{6a\pi g}\right)\left(\frac{9B_\mathrm{i}a}{10\pi}\right)^{-\frac{1}{3}} \tag{8}$$

$$B_\mathrm{i} = \frac{Q_\mathrm{v}g(\rho_0\text{-}\rho_\mathrm{v})}{\rho_\mathrm{v}} \tag{9}$$

where ρ_0 is the density of ambient air, $\mathrm{kg/m^3}$; ρ_v is the density of marine diesel released into the ambient air from the hot surface, $\mathrm{kg/m^3}$; H is the ignition height of marine diesel, m; B_i is the initial specific buoyancy flux, $\mathrm{m^4/s^3}$; a is the correction coefficient, dimensionless; and Q_v is the volumetric flow rate of marine diesel, $\mathrm{m^3/s}$.

Using the experimental data, a relationship between initial ignition height and hot surface temperature is developed in the current study, as proposed in Equation (10). This model is expected to predict the initial location of ignition given various heated surface temperatures when marine diesel leaks into a ship's engine room.

$$H = H_0 + 0.401exp\left(\text{-}\frac{T_\mathrm{s}\text{-}T_\mathrm{sat}}{\pi g T_0}\right) \tag{10}$$

where H is height at which the ignition of marine diesel initially occurs, m; H_0 is the surface height of marine diesel, m; T_s is the hot surface temperature, K; and T_0 is the initial temperature of marine diesel, K.

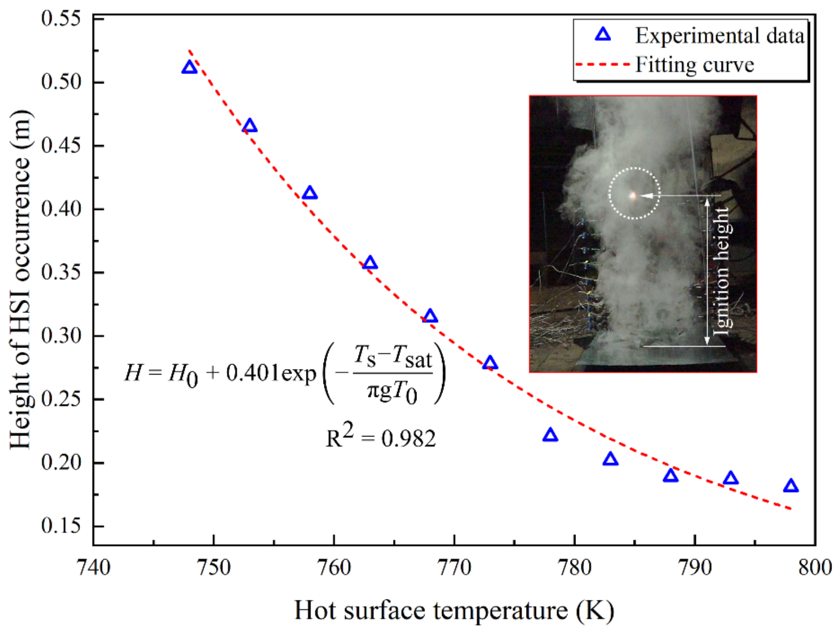


Figure 3. Heights at which marine diesel ignites with various heated surface temperatures.

To alleviate the issue of increasing hot surface-driven initial ignition height, the following steps can be taken:

(a) The on-site safety manager can regularly inspect the vicinity of pipelines, paying special attention to thermal insulation measures to protect the hot surfaces of equipment and thus preventing the ignition of accidentally leaked marine diesel by a hot surface;
(b) An existing monitoring gauge in ship engine room may be used. The research results of this section suggest installing an area covering the vertical space of the high-temperature surface of the equipment in the ship engine room in order to monitor the possible initial ignition of a fire core in different positions.

3.2. Temperature Field Distribution according to HSI-Driven Flame Propagation

After the marine diesel is ignited on a high-temperature surface, the size of the fire core rapidly increases, and flame propagation forms. According to the relationship between the initial temperature of combustible fuel and its flash point, flame propagation on the liquid surface can be classified into liquid-phase controlled fire spreading and gas-phase controlled fire spreading. If ignition occurs on a hot surface, the flame propagates rapidly through premixed combustion. The size of the marine diesel leakage area on the high-temperature surface has a small influence on the flame propagation. Figure 4 shows the transmission of combustion flames after the marine diesel is ignited above the hot surface. When marine diesel leakage occurs at 3.741 s, the fire nucleus generated in the air begins to grow larger. Because the flame consumes more combustible vapor mixture, it needs more fuel. The flame gradually begins to propagate in the direction of the hot surface. This reflects the energy transfer from the flame in the chemical reaction zone to the unburned gas mixture in the preheating zone. The flame trajectory of the marine diesel vapor in the vertical space can be observed in Figure 4. When the flame is transmitted, it is not in the form of a small core but instead in the form of a larger fireball. The color of the HSI-driven flame as it passes is a bright red–yellow, which is different from the blue core produced during initial ignition. The HIS-driven flame surface is accompanied by the consumption of components of marine diesel vapor and the generation of combustion products and heat. As the flame passes to the hot surface, the remaining marine diesel is further ignited.

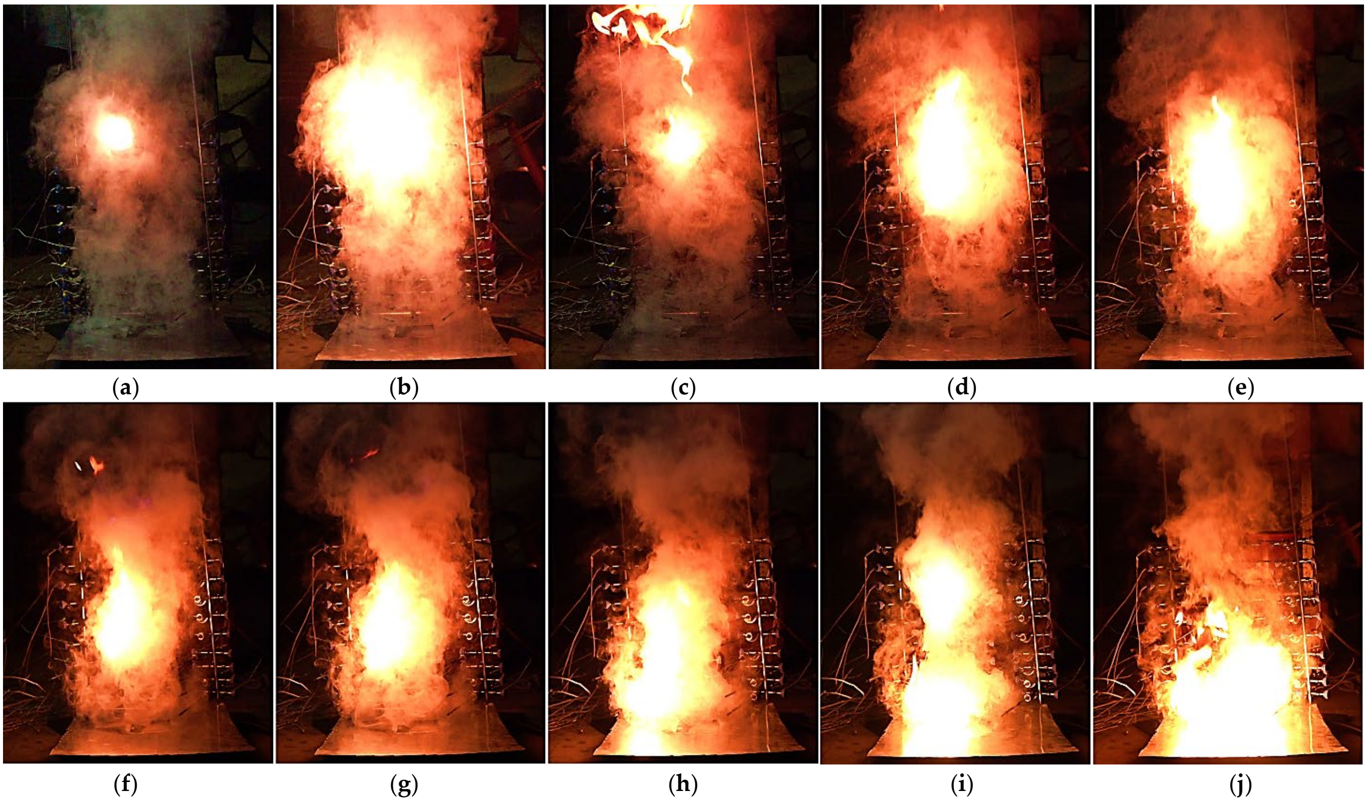
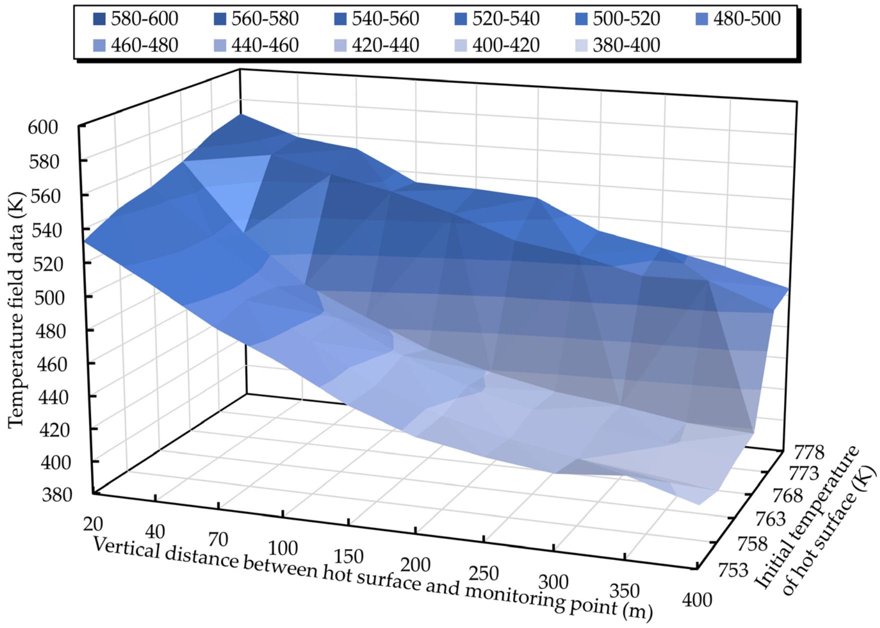


Figure 4. Flame propagation from ignition position to the hot surface. (**a**) t = 3.741 s; (**b**) t = 3.758 s; (**c**) t = 3.933 s; (**d**) t = 4.091 s; (**e**) t = 4.174 s; (**f**) t = 4.299 s; (**g**) t = 4.333 s; (**h**) t = 4.424 s; (**i**) t = 4.541 s; (**j**) t = 4.673 s.

During the thermal oxygen degradation process, it can be observed that the lightweight components—such as water, trace lipids, and ethers—evaporate first as the hot surface temperature increases. Figure 5 presents temperature field variation during marine diesel HSI as the temperature of the surface continues to increase. The specified marine diesel has 10 mL leakage, and the heated surface temperature ranges from 753 K to 778 K. The thermocouples are positioned above the center of the high-temperature surface to measure temperatures at different heights ranging from 20 mm to 400 mm above the hot surface. Figure 5 shows that as the heated surface temperature increases, the temperature field distribution in the vertical space increases accordingly. The temperature field distribution mainly changes between 3.011 s and 9.036 s after the marine diesel contacts the hot surface, as indicated by the temperatures obtained at different times.



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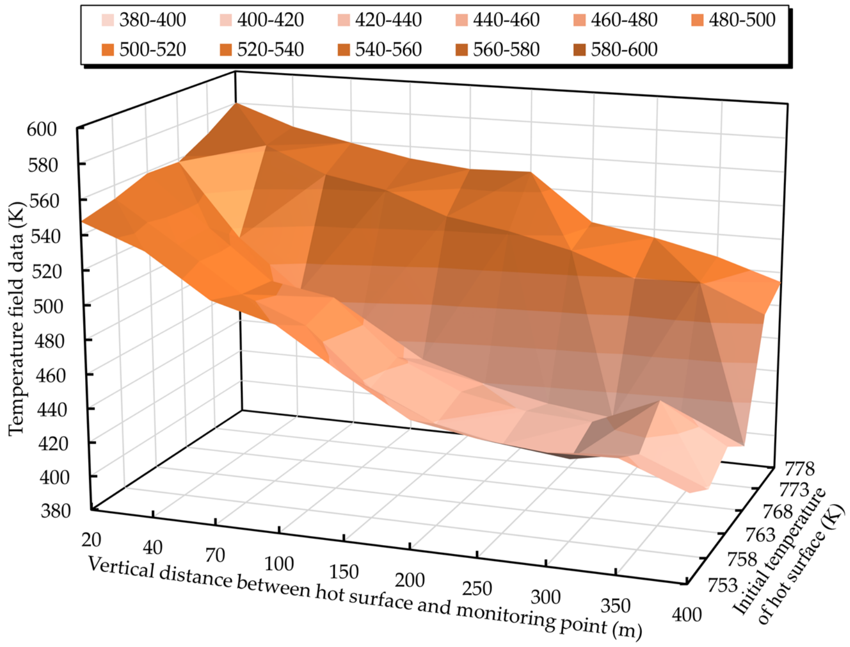
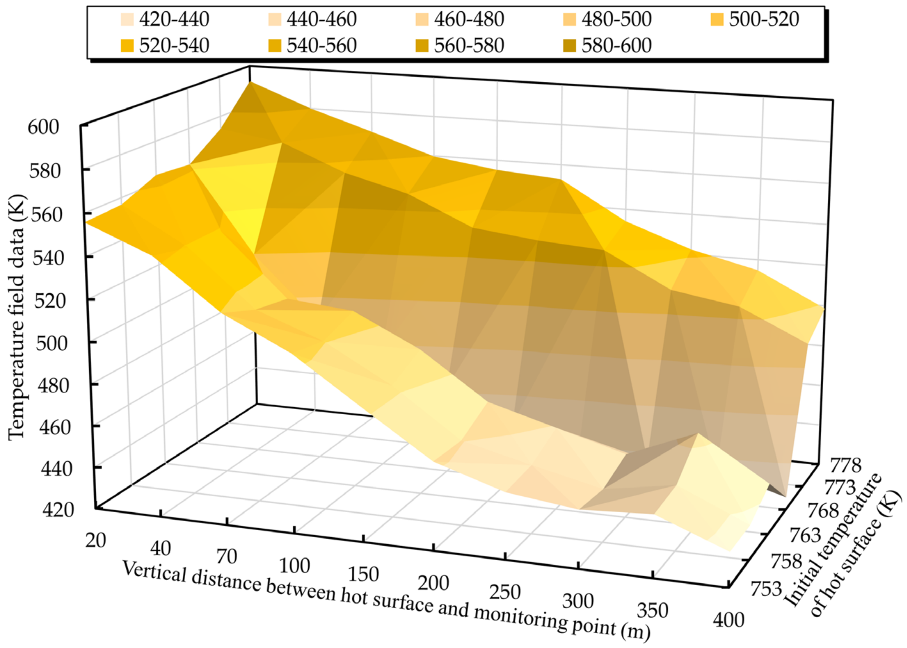
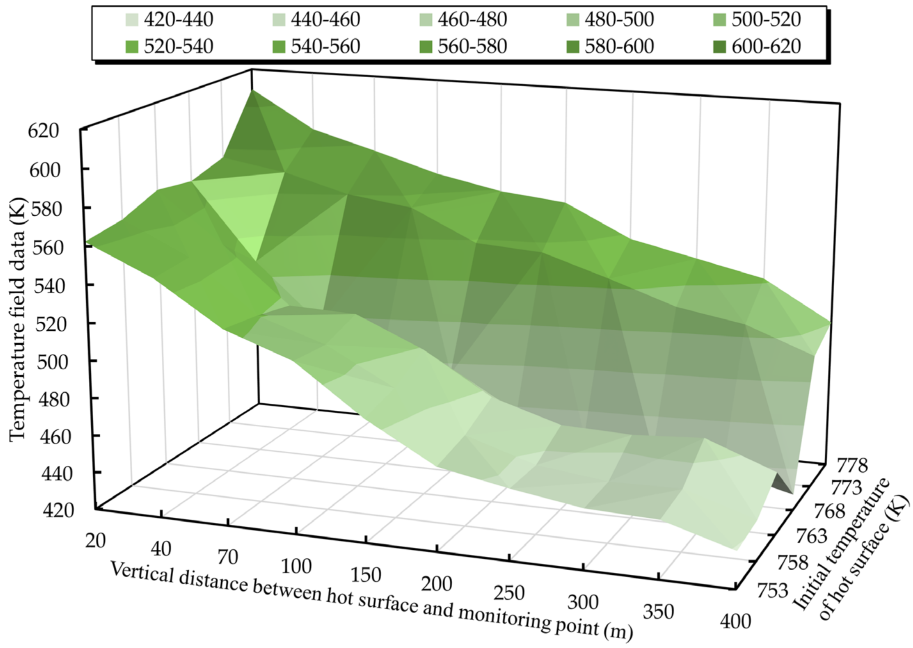


(**b**)

Figure 5. *Cont.*



(**c**)



(**d**)

Figure 5. Temperature field distribution induced by marine diesel HSI. (**a**) t = 3.011 s; (**b**) t = 5.132 s; (**c**) t = 7.312 s; (**d**) t = 9.036 s.

Figure 5a indicates the temperature field changes in the vertical space as ignition occurs at 3.011 s. The thermocouple located 20 mm above the high-temperature surface exhibits the fastest response to the temperature increase. As the surface is heated to temperatures from 753 K to 778 K, the air temperature at 20 mm changes from 532.81 K to 570.89 K. This indicates that the increase in air temperature is not the highest closest to the hot surface. When the leaked marine diesel is evaporated by the hot surface, it diffuses to the top of the hot surface to form a certain distribution of concentrated liquid and gas. Meanwhile, due to the temperature transfer generated by thermal diffusion and thermal conduction of high-temperature marine diesel and gas, a certain spatial temperature field is formed. It can be seen from Figure 5a that because marine diesel is a large-mass molecule, the heat transfer rate is greater than the mass transfer rate in the process of marine diesel evaporation when the leakage is from 5 mL to 20 mL. As a result, the temperature in the vertical space of the hot surface rises very fast. At a vertical height of 200 mm, the temperature goes up from an initial 437.07 K on the hot surface to 529.41 K at the maximum temperature, resulting in a temperature increase of 21.14%. Based on the data from the thermocouple farthest from the hot surface, the temperature varies from an initial temperature of 416.39 K to a maximum of 484.46 K, presenting a range of over 16.34%. In conditions in which the hot surface temperature is below 750 K, the temperature field's distribution is mainly caused by the joint action of fuel vapor and hot surface heat transfer, as there is no hot surface ignition behavior at 3.011 s. However, when the surface is heated to a temperature over 751 K, the HSI behavior occurs within 3.0 s. Combustion cores and flame transfer phenomena are observed in the vertical space. During flame transfer over a hot surface, the flame continuously heats the combustible gaseous mixture on the surface, maintaining the combustion process in the vertical space. Additionally, the remaining liquid diesel on the hot surface is vaporized by the heat transmitted by the flame. As a result, the temperature of the remaining diesel goes up, causing it to change from a liquid to a gaseous fuel vapor. The vapor that becomes volatile accumulates above the hot surface, leading to incomplete combustion with air due to the consumption of auxiliary gas in the early combustion process. Once the flame spreads to the hot surface, a fuel-rich core with a higher concentration and relatively lower temperature forms at the bottom of the flame. The temperature field distribution shows significant variation in the temperature increase between 200 mm and 300 mm in vertical height, indicating the region of initial HSI. When marine diesel in only a small amount drops on a hot surface, the liquid is decomposed by the action of heat generated by the hot surface to produce reactive free radicals. Under the action of a pressure gradient and buoyance, steam containing free radicals rises and mixes with air to form high-temperature combustible mixed gas. Meanwhile, the concentration of combustible premixed gas gradually accumulates until it reaches the limit of the concentration range of combustion. As the equipment surface is heated to an elevated temperature, droplet evaporation continues. At a vertical height of 200 mm to 300 mm, when the hot surface's temperature is lower than the critical temperature or premixed gas does not meet the combustion limit, the ignition phenomenon will not occur. Due to the action of air entrainment, the temperature at this height exhibits a declining trend. However, marine diesel continues to evaporate and accumulate, leaving the fire hazard. Once the minimum ignition temperature of the hot surface is reached, the HSI phenomenon may occur. The change in the temperature field over time reveals higher temperatures in the vertical space between 20 mm and 150 mm, leading the direction and path of flame propagation.

3.3. Heat Flux Intensity of the Marine Diesel HSI Process

The marine fuel surface radiant heat flux meter provides data on the thermal feedback of the flame to the fuel surface during flame propagation. The experimental data quantifies the total thermal feedback received by the marine fuels. Figure 6 shows the data collected by the heat flux meter located in different areas during the HSI of marine fuels. In this experiment, the heat flux meter is arranged sequentially, with the hot surface at the center. The heat flux meter closest to the hot surface is set at a height of 0.3 m, and the horizontal distance from the hot surface center is 0.4 m. The settings of the other heat flux meters are shown in Figure 6, which illustrates the variation of heat flux intensity with time during the marine diesel HSI. This study analyzes the condition of 15 mL of marine diesel leaked onto a surface with a temperature of 753 K. Figure 6 shows that as the contact time between the marine diesel and the heated surface rises, the heat flux intensity shows a sudden increase within a certain period; this is followed by decay in different forms. Heat flux intensity begins to increase at 2.198 s in the area closest to the hot surface. During this period, the region distant from the hot surface does not receive heat from the gas-phase medium due to the rapid phase transformation of the fuel on the hot surface. Between 2.6 s and 2.8 s, the heat flux intensity near the hot surface reaches a maximum of approximately 8.42 kW/m^2.

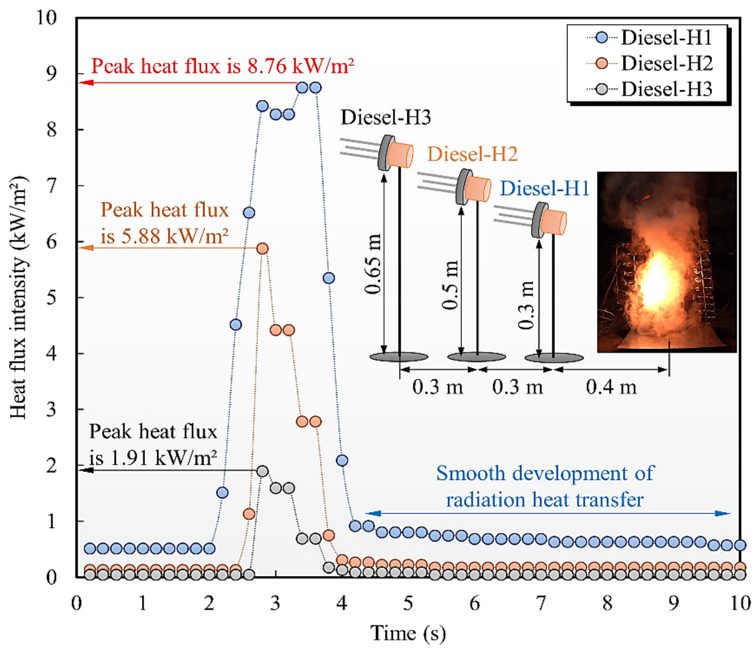


Figure 6. Heat flux intensities of marine diesel HSI changes with distance from the hot surface.

Compared with the initial state, the rate of change in heat flux intensity is significant. Based on observations, HSI of marine diesel occurs within the aforementioned time range, leading to the formation of an initial fire nucleus. During flame propagation, the surrounding area receives radiant heat from the flame. At a distance of 0.7 m and 1.0 m from the center of the hot surface, the heat flux intensities are 5.88 kW/m^2 and 1.91 kW/m^2, respectively. When the flame spreads to the high-temperature surface, it continues to transfer heat flux to the surrounding space, resulting in stable heat flux intensity for a period of time. As the flame spreads to the hot surface and burns the remaining marine diesel, the heat flux intensity begins to decay. The position farthest from the center of heated surface presents the most significant attenuation of heat flux intensity, dropping to 0.172 kW/m^2 at 3.811 s. The results indicate that the heat flux intensity during fuel HSI is transferred to surrounding area. The area in close proximity to the hot surface may receive intense radiant heat, which increases the risk of reigniting leaked fuel in adjacent areas. Due to the properties of marine diesel, the peak value of heat flux intensity is not sustained for a long time during the HSI process. The heat flux intensity begins to decay after the flame propagates to heated surface of the equipment. Observing the thermal performance of HSI-driven flame propagation, the following conclusions can be drawn:

(a) It is essential to pay attention to temperature change in the vertical space of equipment surfaces (in which it is easy for a heated surface to form) in order to prevent the accidental ignition of leakage. Safety supervisors in ship engine rooms must carry out monitoring tasks during inspection using infrared thermal imaging techniques.
(b) According to results of this section, the heat flow generated by flames is transferred to their surroundings in the horizontal direction, so it is particularly important to protect inflammable and explosive substances near areas of ship engine rooms in which incidents are likely to occur.

3.4. Effect of Hot Surface Temperature on the HSI Delay Time of Marine Diesel

The ignition delay time plays an important role in characterizing the ignition characteristics of marine fuel. Various marine fuels exhibit different ignition characteristics on high-temperature surfaces, and the time required for HSI has discrepancies. There are two basic prerequisites for the local ignition of marine fuel that has leaked onto a hot surface. One is a suitable ratio of fuel vapor/air in the ignition area, which can promote the formation of an initial ignition core. The other is a low-velocity environmental flow field, which can ensure that the initial ignition of the fire core is stable and self-sustaining in the local area, meaning the flame can achieve stable propagation. In a ship engine room, there are more complex influencing factors. Previous research suggests that a vapor layer may be formed between the fuel and the hot surface when the hot surface has a very high temperature. This vapor layer decreases the heat transfer from the heated surface to the fuel, resulting in a decreased evaporation rate of the liquid fuel. HSI delay time is attributed to the interaction between the different fuels and temperatures of the equipment's surfaces, as shown in Equation (11) [34].

$$w_{\mathrm{s}} = K_{\mathrm{os}} c_{\mathrm{fuel}}^{\mathrm{n}} c_{\mathrm{ox}}^{\mathrm{m}} \exp\left(-\frac{E_{\mathrm{s}}}{\mathrm{R}T_{\mathrm{r}}}\right) \tag{11}$$

where K_{os} is the frequency factor of the combustion reaction; c_{fuel} is the molar concentration of combustible material, mol/m^3; c_{ox} is the molar concentration of oxidizer, mol/m^3; E_{s} is the activation energy, J/mol; T_{r} is the temperature of the chemical reaction, K; and n and m are the reaction coefficients, respectively.

It is evident that the HSI delay time of combustible fuel is inversely proportional to vapor concentration. The mathematical model of HSI delay time can be deduced using the boiling heat transfer model and vapor plume model. Figure 7 presents an evolution of ignition delay time for marine diesel at various heated surface temperatures. The data indicate a clear decrease in the ignition time of marine diesel vapor on heated surfaces as the temperature increases. At lower heated surface temperatures, the ignition delay time for diesel is longer, thus increasing the difficulty of ignition, which is consistent with experimental observations. The reason for this is that the heated surface temperature does not reach the critical temperature required to ignite the evaporating vapor of marine diesel. Once the surface is heated to a temperature of 748 K, the ignition delay time of diesel vapor is 3.692 s. A significant amount of marine diesel/air mixture gas accumulates in the vertical space, and the probability of ignition reaches 50%. As the surface continues to be heated, the phase transition of marine diesel absorbs a significant amount of heat, resulting in an increase in the evaporation rate of fuel. This, in turn, reduces the time required to reach critical ignition conditions. The experimental data reveal that the ignition delay time of marine diesel is reduced to 2.048 s when the surface is heated to a temperature around 755 K. If the equipment surface continues to rise up 768 K, the ignition delay time drops to 0.802 s. Compared with the previous scenario, the ignition delay times decrease by 44.5% and 60.8%, respectively. The ignition delay time of marine diesel vapor decreases significantly as the heated surface temperature increases from low to high. However, further increase in the heated surface temperature does not result in a significant change in the ignition delay time. As the surface is heated to a temperature of 773 K, the ignition delay time drops below 0.58 s. After reaching this temperature, the ignition delay time remains around 0.48 s, regardless of how much the heated surface temperature increases.

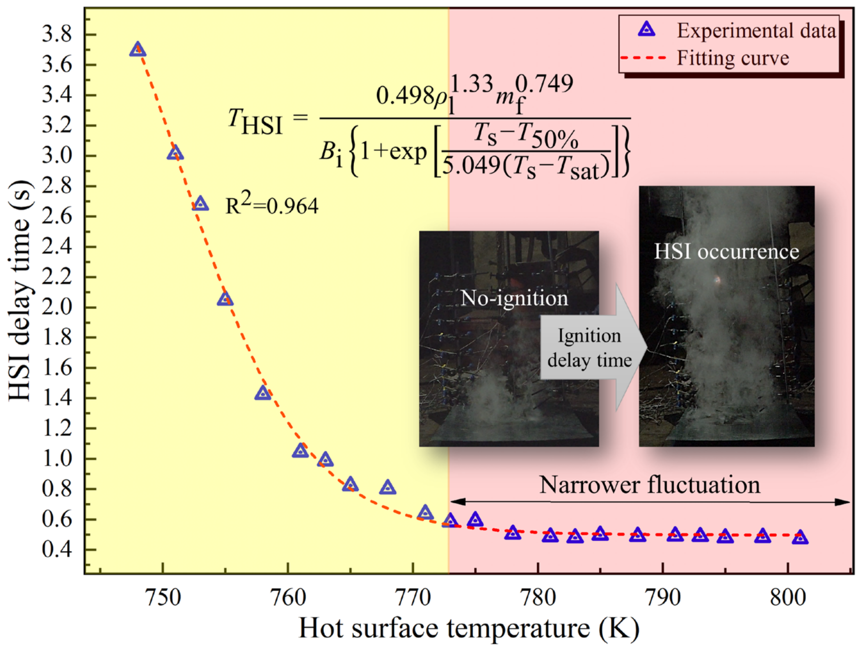


Figure 7. HSI delay time of marine diesel with changing heated surface temperatures.

This study proposes a predictive model to examine the ignition delay time of marine diesel on a hot surface in a ship engine room based on the fitting results of experimental data, as shown in Equation (12). This predictive model could be applied to determine the HSI delay time after marine diesel leakage by analyzing the change in the heated surface temperature. The extended predictive model helps to prevent the further expansion of such incidents by combining experimental data and theoretical mechanisms.

$$T_{\mathrm{HSI}} = \frac{0.498\rho_{\mathrm{l}}^{1.33} m_{\mathrm{f}}^{0.749}}{B_i\left\{1+exp\left[\frac{T_{\mathrm{s}}\text{-}T_{50\%}}{5.049(T_{\mathrm{s}}\text{-}T_{\mathrm{sat}})}\right]\right\}} \quad (12)$$

Regarding the HSI delay time and predictive model, the following conclusions can be drawn:

(a) The existence of ignition delay time means that the judgment of decision makers can be impaired. Therefore, once marine diesel leakage is found in a ship engine room, it is necessary to focus on the influence of surrounding heat sources on it and to strictly prevent sudden ignition accidents caused by ignition delay on hot surfaces.
(b) Using the predictive model proposed in this study, the ignition delay time of marine diesel on hot surfaces can be determined in advance so that initial ignition accidents in ship engine rooms may be prevented.

3.5. Overall Probability of Ignition of Marine Diesel on Hot Surfaces

Marine diesel used in machinery equipment and pipelines is a combustible liquid. If the leakage of marine diesel occurs during ship operation, it is prone to trigger further high-temperature HSI accidents. The HSI of a liquid in contact with a hot surface generally requires a temperature substantially greater than the published auto-ignition temperature of that liquid in handbooks. In this study, the types of marine diesel selected are designed for conducting experiments regarding the probability of HSI of marine diesel in ship engine rooms, and hot surface temperatures are raised to fixed values. The amount of fuel leaked in the current study is fixed from 5 mL to 20 mL. The number of experiments used to determine the HSI temperature of marine fuels is 30. The hot surface simulator can control the heating step of each experiment from 2.0 K to 3.0 K.

Figure 8 shows the distribution of the probability of HSI of marine diesel (with a leakage rate of 10 mL) given different hot surface temperatures; it also reveals the changing trend of HSI probability. It indicates that marine diesel does not always ignite after leaking onto a hot surface. According to the experimental data, when the hot surface temperature is less than 728 K, marine diesel is rarely ignited. The probability of diesel igniting is 3.33% when the heated surface temperature reaches 731 K. Although the HSI probability of marine diesel is low, it is worth noting that the probability of HSI accidents still exists. When the hot surface temperature rises to nearly 748 K, the probability of ignition is 50% ($T_{50\%}$). As the equipment surface continues to be heated to a temperature of 778 K, the marine diesel will be completely ignited. According to the variation in the HSI probability of marine diesel, the probability of ignition is distributed in three phases. In the initial phase of the temperature range (T_s < 728 K), marine diesel cannot achieve HSI. When entering the second phase of the temperature range (728 K < T_s < 778 K), the ignition process shows instability. The temperature range of the hot surface is 778 K < T_s, which shows that the probability of ignition is always 100%. This means that when the leaking marine diesel flows onto a machinery surface with a hot surface temperature higher than 778 K, ignition behavior inevitably occurs. It is necessary to determine whether the presence of fuel or surrounding items can intensify the risk of a fire source originating in the engine room. By fitting the experimental data, a predictive model for the probability of ignition of leaked marine diesel is proposed, as shown in Equation (13):

$$P_i = \frac{1}{1 + exp[-0.169(T_s\text{-}T_{50\%})]} \tag{13}$$

where T_s is the equipment surface temperature, K, and $T_{50\%}$ is the surface temperature when marine diesel has a 50% probability of ignition, K.

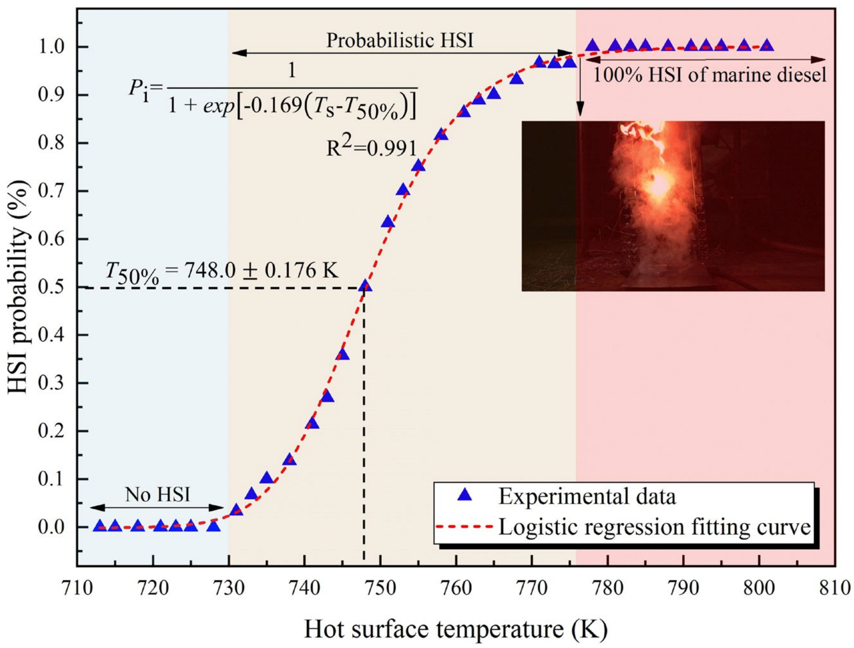


Figure 8. Trend of HSI probability with surface temperature for leaked marine diesel.

Through the results of HSI probability, it is clear that the ignition behavior of marine diesel on hot surfaces has a certain inevitability. In the ship engine room, when the equipment surface is in a high-temperature state for a long time, a safety manager needs to remind inspectors to pay attention to safety issues within this area. Therefore, the HSI probability of accidents occurring can be reduced by increasing attention to risk. In addition, using the model of HSI probability proposed in this study, combined with big data and optimization algorithms, an intelligent predictive model of ignition accidents can be further developed in future. In this way, it can better assist ship managers and decision makers in the safe management of ship operation.

4. Conclusions

Considering the practical difficulty of constructing a good predictive model using sufficient experimental tests of a ship engine room within limited conditions, this study designs and performs 120 sets (5 mL to 20 mL) of ignition experiments for constructing a predictive model of the HSI characteristics of marine diesel. With a series of experimental tests of marine diesel's HSI, this work presents the results and a relevant predictive models that are applicable to the initial ignition characteristics of leaked marine diesel in ship engine rooms. Some noteworthy findings are summarized in brief.

- As the hot surface temperature rises, the ignition height of leaked marine diesel remains around 0.18 m above the hot surface. An improved model has been developed and can be used to describe the relationship between HSI height and initial specific buoyancy flux in a certain vertical space. Moreover, it is recommended that an area covering the vertical space of the equipment surface is installed in ship engine rooms in order to monitor a possible initial fire core in different positions.
- The ignition delay time of marine diesel vapor decreases significantly as surface temperature increases from low to high. After reaching a temperature of 773 K, the ignition delay time remains around 0.48 s regardless of how much the hot surface temperature increases. Using the predictive model proposed as Equation (12), the ignition delay time can be obtained in advance, meaning we can prevent initial ignition accidents in ship engine rooms.
- The increase in air temperature is not the highest closest to hot surface. The temperature field distribution reveals a significant variation in the increase in temperature between 200 and 300 mm in vertical height, indicating a region of initial HSI. Meanwhile, the current result indicates that heat flux intensity during marine diesel HSI is transferred to surrounding area. The area in close proximity to hot surface may receive intense radiant heat, which increases a risk of reigniting leaked diesel in adjacent areas.
- The HSI probability is distributed in three phases: low probability, elevated probability, and certain ignition. Safety managers need to remind inspectors to pay attention to safety issues in the area, and the HSI probabilities of accidents can be reduced by increasing attention to risk. Using the model of HSI probability proposed in this study, combined with big data and optimization algorithms, an intelligent predictive model of the probability of HSI accidents in ship engine rooms can be further developed.

Author Contributions: Conceptualization, K.W.; methodology, K.W.; software, R.Q.; validation, Y.M.; formal analysis, K.W.; investigation, R.Q.; resources, K.W.; data curation, K.W. and H.X.; writing—original draft preparation, K.W. and R.Q.; writing—review and editing, Y.M. and H.X.; visualization, Y.M.; supervision, K.W.; project administration, K.W.; funding acquisition, K.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant number 52001196, Shanghai Key Projects of Soft Science, grant number 20692193100.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: All authors would like to express their sincere thanks to the editor and reviewers for their constructive comments.

Conflicts of Interest: The authors declare no conflicts of interest.

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