RESEARCH ON HOT SURFACE IGNITION CHARACTERISTICS OF LEAKING FUEL IN SHIP ENGINE ROOM

by

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Hot surface ignition is crucial in safety management of maritime industry. In present work, 3-D numerical simulations using FLUENT of ship engine room model and ignition process of a leaking marine fuel by a high temperature hot surface are carried out. The thermal mechanism and hot surface ignition characteristics are revealed. Meanwhile, effect of ventilation and wettability on influencing leaking fuel hot surface ignition process in ship engine room are further analyzed. Hot surface ignition process of evaporated fuel indicates different characteristics, such as ignition delay, stable combustion and extinguishing. The results suggest that the strengthen of ship engine room condition directly promotes liquid-flow and ignition of leaking fuel on hot surface.

Key words: *ignition characteristics, hot surface ignition, thermal mechanism, multi-factor influence, ship engine room fire*

Introduction

The potential accident in the ship engine room (SER) is the leaking fuel contacts with hot surface (*e.g.* engine oil, marine diesel, lubricating oil or hydraulic fluid), resulting in phenomenon of hot surface ignition (HSI). Compared with common ship cabins, SER is special in terms of internal lay-out and environment. It requires equally targeted safety practices compared to other ship cabins. In development of a fire accident, all kinds of equipment in SER cause ignition flame around them, which significantly affects the combustion characteristics of leaking fuel. Through statistical data [1], it is found that the ship fire accounts for high proportion of maritime accidents. It indicates a steady growing rate of the number of SER in ship accidents. The HSI that controls the operation of industrial gas-fired appliances with levels of safety management and system reliability. In Kim's experiment [2], the results indicate that the HSI temperatures have risen as the equivalence ratio increases. It is found that the HSI temperature decreases with thicker layer and smaller particle size [3]. The HSI temperature is sufficiently high to cause thermal runaway can be determined by comparison of non-dimensional heat generation rate with critical heat generation rate [4]. The HSI of flammable and combustible liquids are the most common risks in mechanical equipment where the high speed running and expected failures. Ebersole [5] have conducted the testing to show that several factors play a role in influencing HSI, such as the structure of fuel, fluid-flow rate, hot surface geometry and environmental factors. In unconfined environment, the mechanical ventilation flows over the hot surface and natural-convection moves the flammable, resulting in extension of HSI delay time

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[6, 7]. In *n*-heptane HIS's experiment [8], it indicates that the minimum hot surface temperature for fuel ignition is significantly dependent on time. From the results of HSI tests on common fuels used in applications [9] including gasolines, nitromethane, and methanol. The HSI is probabilistic in nature and cannot be defined by a fixed ignition temperature. Ignition height above the hot surface is studied by Bennett [10] and Wang *et al.* [11], the results show that the combustible liquid ignites in vertical space when the heat flux is small. As heat flux increases with a value of 130 kW/m^2, HSI occurs closer to hot surface. When the hot surface temperature is extremely high, the Leidenfrost effect influences on heat transfer characteristics significantly due to the gas gap between leaking fuel and hot surface [12]. Menon *et al.* [13] proposes a two-stage ignition behavior theory for the reaction pathway leads to initial and second stage HSI of combustible liquids. Further, numerical method using simplified kinetics shows that HSI evolution process should explained in detail by flow velocity, evaporation rate (ER) and temperature field [14, 15]. Ryu *et al.* [16] carried out the experiment to examine HSI characteristics of combustible fuel, the results present that the higher HSI temperatures with increasing flow velocity. Within the high velocity range, the ignition distance of fuel will increase.

Previous researches focus on important impact of flame propagation, combustion characteristics, combustion evolution and smoke movement with fire accidents. However, few researches on ignition mechanism and influencing factors of evolution process during the initial induction period of ship fire. This study investigates the interaction of a complex in leaking fuel, as it interacts with different HSI conditions in SER. The CFD-based model is built to evaluate of leaking marine fuel ignition process and elucidate HSI characteristics in SER. The HSI characteristics (*e.g.* temperature, delay time) are analyzed, and the effect of ventilation and wettability on influencing leaking fuel HSI process are revealed. This study contributes to better understanding multi-factor mechanism of HSI and behaviors of leaking fuel in SER environment, in the hope of preventing ship fire accident.

Methodology

Kinetics and HSI of leaking marine fuel

The main reason for leaking fuel in SER to ignition is heat effect by hot surface. On the hot surface, flammable steam will be generated when leaking fuel ignites at a certain temperature. It is mixed with the air in SER to form a combustible mixture, and continuous combustion occurs after contact with hot surface. After leaking fuel is ignited, continuous combustion can be ensured due to fast ER of fuel, so as to form a stable flame on hot surface in SER scenario, ER of leaking fuel should meet the conditions:

$$v_\mathrm{e} \le \frac{\varphi \Delta H_c v_\mathrm{e} + \dot{Q}_\mathrm{E} + \dot{Q}_\ell}{L_\mathrm{v}} \tag{1}$$

Ignition process of flammable fuel on hot surface is related to properties of liquid materials (*e.g.* composition, combustion heat, latent heat of evaporation*, etc.*) and environmental parameters. The special design in SER and the wettability changes at sea affect the heat loss from fuel and the thermal feedback. The HSI process of leaking fuel in SER is no longer determined by single physical parameter (flash point or the ignition point) [17], but is the result of interaction of multiple factors. Marine fuel leaks to hot surface, which is decomposed by heat generated by hot surface to produce active free radicals. As a result of the pressure gradient and buoyancy, flammable vapor containing the free radicals rise and mix with the air above hot surface, forming the premixed gas with higher temperature. When the concentration of premixed gas accumulates gradually, it reaches the limit concentration range of combustion gradually.

As hot surface continues to provide heat, the leaking fuel continues to evaporate until ignition occurs. If the equipment in SER does not stop running, hot surface formed by the shell always exists. The flame formed by leaking fuel continues to spread, and a larger SER fire accident occurs. Leaking fuel in the process of heat evaporation, it is due to effect of heat source, and produces heat loss to the air and equipment shell surface. In HSI process, leaking fuel is affected by factors such as air distribution in SER, ambient wettability and wall thermal feedback, so the HSI temperature and time will change accordingly. In the computational fluid domain of fuel HSI, the numerical process follows the basic equations of mass conservation, momentum conservation and energy conservation. In computational flow field, fluid-flows into control body from one control surface and out of control body through control surface of another part, during which the internal fluid mass of the calculated fluid domain changes. According to the mass conservation, the fluid mass increment in computational domain is equal to the difference between mass-flowing in and mass-flowing out. The integral form of continuity equation of fluid-flow can be deduced:

$$\frac{\partial}{\partial t}\iiint_{v}\rho \mathrm{d}x\mathrm{d}y\mathrm{d}z+\oint_{A}\rho vn\mathrm{d}A=0 \tag{2}$$

The momentum conservation equation represents that in SER system, the time rate of change of the momentum is equal to the sum of the external forces effecting on it, which can be shown:

$$\begin{aligned}\rho\frac{\mathrm{d}u}{\mathrm{d}t}&=\rho F_{bx}+\frac{\partial p_{xx}}{\partial x}+\frac{\partial p_{yx}}{\partial y}+\frac{\partial p_{zx}}{\partial z}\\ \rho\frac{\mathrm{d}u}{\mathrm{d}t}&=\rho F_{by}+\frac{\partial p_{xy}}{\partial x}+\frac{\partial p_{yy}}{\partial y}+\frac{\partial p_{zy}}{\partial z}\\ \rho\frac{\mathrm{d}w}{\mathrm{d}t}&=\rho F_{bz}+\frac{\partial p_{xz}}{\partial x}+\frac{\partial p_{yz}}{\partial y}+\frac{\partial p_{zz}}{\partial z}\end{aligned} \tag{3}$$

The energy equation can be presented as eq. (4). According to turbulence model, J_j, is diffusion flow of component j, S_h covers the heat of chemical reaction and other custom bulk heat sources:

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_i}\left[u_i(\rho E+p)\right]=\frac{\partial}{\partial x_i}\left(k_\mathrm{eef}\frac{\partial T}{\partial x_i}-\sum_{j'}h_{j'}J_{j'}+u_j\left(\tau_{ij}\right)_\mathrm{eff}\right)+S_\mathrm{h} \tag{4}$$

Geometrical modelling

The presented geometric model is building the HSI accident concentrated area, and simplifying by the stairs, pump, miscellaneous equipment*, etc.* The large-scale model contains the basic elements, including the diesel engine, generator set, steam boiler and other equipment and related pipe-lines, fig. 1. A special top inlet and outlet of SER is set in the model. Area size of SER model is set as 8 m (length) × 6 m (width) × 8.5 m (height). In addition building models of equipment and piping system, oil supply pipe-lines are set up near the hot surface. Oil supply pipe-line is broken to simulate fuel HSI in SER. This study focuses on the ignition process of the leaking fuel on the hot surface and the evolution characteristics under the changed environment in SER. The marine fuel in SER is a kind of mixed oil with complex components. It is found that the proportion of Cetane ($C_{16}H_{34}$) in this fuel is the highest, and this component is an important index to characterize and measure the ignition performance of marine fuel. The height of the local hot surface formed by the equipment shell of the SER is set as 1.0 m from the ground, and the size of the hot surface is 0.6 m × 0.6 m. In the geometric model, the supply outlet is set at the lower part of the model with a diameter of 0.5 m. The exhaust outlet is located at the top of SER, with the size of 0.5 m × 0.8 m. Due to internal structure of SER is complex, the calculation model is divided by unstructured meshes with strong adaptability, and the total number of meshes in the whole computational domain is 748930.

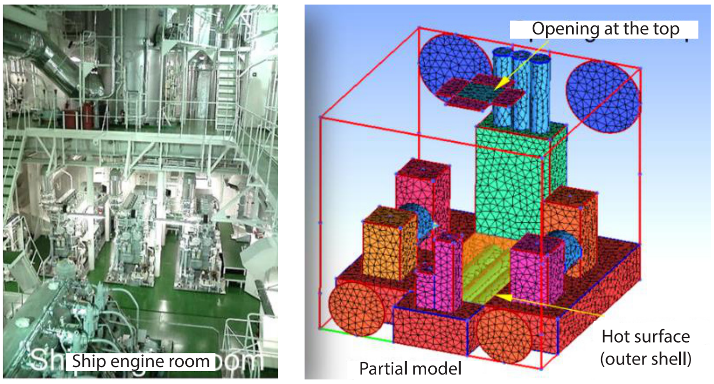

Figure 1. Schematic diagram of geometrical modelling in FLUENT

Initial and boundary conditions

Computational domain is divided into fluid domain and solid domain in model. Typical hot surface temperatures of model are set as 573.15 K, 623.15 K, 673.15 K, 723.15 K, 773.15 K, 823.15 K, and 873.15 K. The inlet is set as the velocity-inlet, which is applicable to the flow of incompressible fluids. The parameters to be set with velocity and volume ratio of material flowing into computational domain through the inlet, which is used to set ventilation velocity and wettability conditions. The SER ventilation velocities are set as 0 m/s, 1 m/s, 3 m/s, and 5 m/s, and the ambient humidity are set as 10%, 20%, 30%, 50%, and 80%, respectively. The outlet boundary is set to pressure-outlet without additional pressure value. The other conditions can be used as the boundary of the computational domain and set as the conventional wall. In this study, the data monitored during the simulation process of the SER model include the phase transition volume of the gas state and liquid state, and the standard temperature of the fluid domain. Among them, the collection of temperature field is based on setting up a total of 30 monitoring points in computational domain. The formation volume of gas state is realized by monitoring the surface of entire fluid domain. The dat. files can be imported into CFD-post for data processing, which meets to generate various results in computational domain, such as velocity vector diagram, trace diagram, and temperature distribution diagram.

Result and discussion

Flow structure and evaporation evolution of leaking fuel at hot surface

The movement of liquid molecules flowing on hot surface exists from the beginning, which is synchronized with the change of gas phase. Marine fuel leaks above the high temperature hot surface, and forms a gathering area with a thickness of about 0.02 m. The observation shows that the gas phase changes of the leaking fuel appear in the position the left of the center, and the shape is continuous and irregular in fig. 2(b), the gaseous molecules formed by the leaking fuel on the hot surface continue to escape upward, and the main part begins to shift toward the center. The gas phase region of the leaking fuel is still on the left, and the gas phase distribution of the leaking fuel gradually separates from the hot surface at the bottom. The vapor phase of the evaporated fuel suspends near the hot surface, which is no longer in a completely connected state from the bottom up. The gaseous molecules of the leaking fuel have shifted to the central position, and some gaseous molecules appear to settle down on the right side. The vapor phase molecules of evaporated fuel continue to diffuse outward, and their rising height stops increasing when they reach a certain height. Due to the continuous thermal effect of the hot surface, the marine fuel is completely transformed into the gaseous medium. The change velocity of the phase shape of the leaking fuel gradually decreases. The process from liquid phase to gas phase of the leaking fuel on the hot surface shows that the evaporating fuel appears as a continuous small area. Then, with the gradual increase of vapor molecular evaporation, it begins to break and separate in space. Evaporated fuel starts from the left side to escape up-

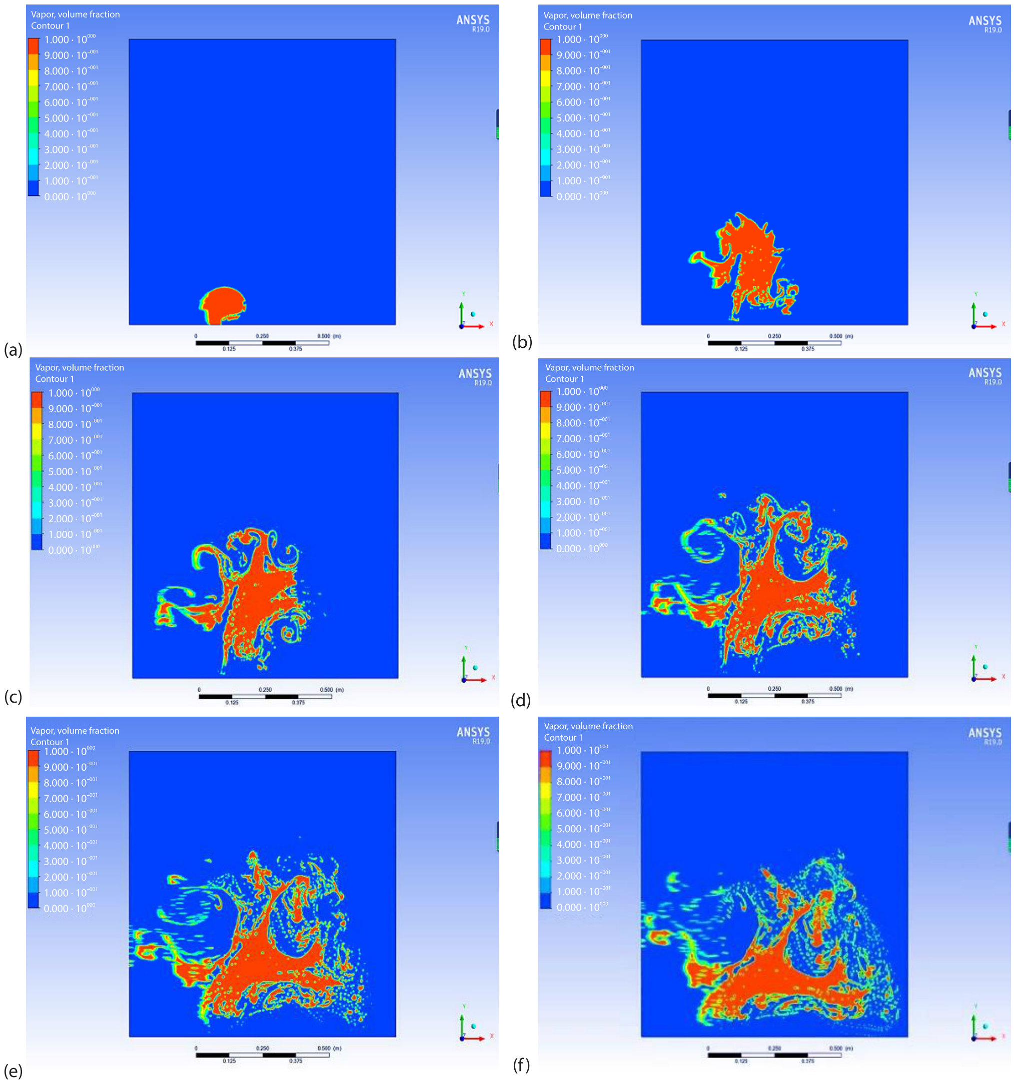

Figure 2. Gaseous phase of leaking fuel changes with temperature on hot surface

ward, which is related to the direction of leaking fuel. The initial evaporation position of the leaking fuel is where it flows to the edge to form a thinner slick, not directly above the center of the accumulation area. In the middle phase of fuel vapor phase change, the rising process of evaporated fuel appears on the hot surface. Then it gradually starts to escape to the surrounding, and the vapor molecules of the leaked fuel evaporated by thermal effect are uncertain on the micro level, and show the consistency of overall motion on the macro level.

After the leaking fuel is heated on a hot surface, the gaseous molecules that evaporate the fuel are transferred in two kinds of ways. The component transport or molecular diffusion caused by the macroscopic bulk flow of the fluid, including the conventional diffusive motion from the high concentration region the low concentration region and the thermal diffusion caused by the temperature gradient (Soret diffusion), can be expressed:

$$\dot{m}''_{\text{fuel}} = Y_{\text{fuel}} \left(\dot{m}''_{\text{fuel}} + \dot{m}''_{\text{air}} \right) - \rho D_{\text{fuel-air}} \tag{5}$$

In order to investigate the relationship between evaporation capacity and ER of the leaking fuel on the hot surface, the volume of fluid (VoF) model is used in FLUENT. The VoF model is applied to simulate the evaporation phase transition process of leaking fuel HSI, and the analysis process follows the control volume principle. In the computational domain of this model, each term is represented as a volume fraction, and the sum of the phase volume fraction under each grid is 1. The vapor volume fraction integral (VVFI) in computational domain is used to characterize the vapor phase formed by fuel on hot surface. The gas phase volume fraction of fuel vapor does not undergo phase transition in the early stage after contacting hot surface. It can be regarded as thermal effect of fuel HSI process. During this period, liquid phase gradually begins to heat steadily. Subsequently, the total phase transition of the leaking fuel increases with the initial temperature of the hot surface. In order to characterize the gas phase generation rate of leaking fuel, gas phase volume fraction is integrated into mass. Since the gas phase volume fraction generated by fuel on hot surface is the derivative integral of the volume fraction under each grid with respect to time, it can be transformed with mass:

$$m_{\text{g}} = V_{\text{frac}} V_{\text{mesh}} \rho_{\text{v}} \tag{6}$$

Figure 3 shows ER of leaking fuel changes with different initial temperatures of hot surface. The ER of leaking fuel increases at initial stage and decreases over time. When the leaking fuel in SER flows to hot surface, there is a brief transition period without fuel phase transition in the initial stage of thermal effect. The ER-time curve of fuel shows fluctuation state, by reason the process of evaporative phase transition is affected by multi factors in SER. Liquid phase of leaking fuel is in a continuous flow state, and its internal temperature field distribution is not uniform. Liquid fuel accumulation area is subjected to heat conduction from hot surface and heat convection with the air in SER. In addition, the evaporation and heat absorption of leaking fuel under the effect of hot surface transfer the internal temperature of liquid phase of fuel from high to low, which promotes the instability of surface temperature. Part of the leaking fuel evaporates into vertical

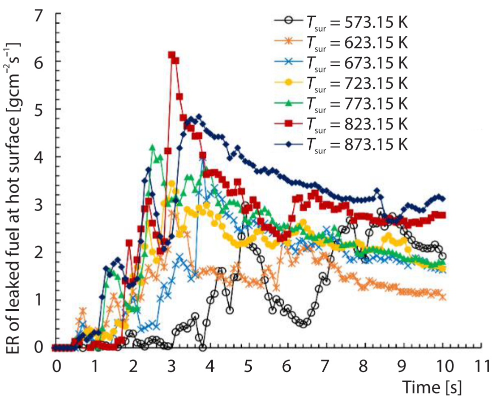

Figure 3. The ER of leaking fuel changes with time on hot surface

space above hot surface, forming gaseous molecules of fuel vapor and transferring heat to SER environment. Since the air temperature in SER is relatively low, heat loss causes the fuel vapor to condense back into liquid molecules. As shown in fig. 3, after ER of vapor phase molecules reaches the peak value, ER shows fluctuation with time. Due to large concentration difference between SER environment and leaking fuel, the diffusion power into environment is significantly higher, so ER increases accordingly. With molecular weight of gas phase increases in air, concentration difference between gas phase and vapor of leaking fuel drops gradually, and ER of leaking fuel on hot surface gradually tends to a stable change state.

Figure 4 shows the variation characteristics of average evaporation rate (AER) of leaking fuel under different initial temperature of hot surface. The AER of leaking fuel on hot surface is proportional to the thermal intensity of the hot surface. With the continuous increasing of initial temperature of hot surface in SER, leaking fuel can obtain higher heat transfer from hot surface per unit time. The time for leaking fuel to reach the critical temperature of evaporation phase transition is shortened, and the overall ER increases accordingly. In addition, the time node of fuel ER rising on hot surface is advanced, and the increasing of marine fuel ER is larger. Results focus on time for the leaking fuel to reach the peak value of ER on hot surface and the corresponding higher value. Through the numerical simulations, this study fitted the data and obtained the relationship between AER value and T_{sur}, as shown in eq. (7). This expression can be applied to evaluate the evaporation degree of leaking fuel in SER under elevated hot surface temperatures over time:

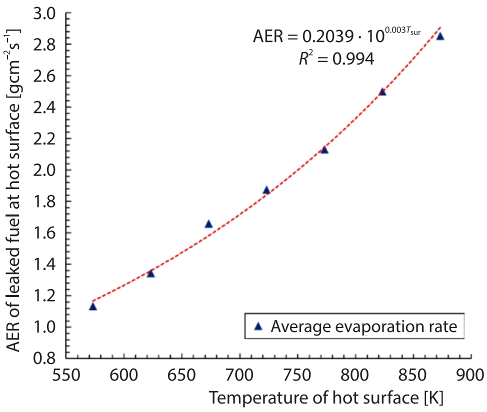

Figure 4. The AER of leaking fuel changes with hot surface temperature

$$AER = 0.2039\mathrm{e}^{0.003T_{\text{sur}}} \tag{7}$$

The HSI of leaking fuel with elevated temperature in SER

Figure 5 shows the temperature changes of evaporated fuel at different heights when the initial temperature of hot surface (T_{sur} = 573.15 K) in SER. Temperature of evaporated fuel at different heights fluctuates and then increases sharply with time. It is found that the fuel HSI process can be divided into four stages, including the stationary heating period (Stage a), oscillatory fluctuation period (Stage b), rapid heating period (Stage c), and flame development period (Stage d). The HSI process of evaporated fuel in SER shows different characteristics, such as ignition delay, stable combustion and extinguishing. In the fuel HSI process in SER, stage a is the initial thermal effect stage of fuel heated in SER, and the temperature fluctuation of the MP in this stage is small. In Stage a, the leaking fuel is covered over the hot surface of SER. Hot surface conducts heat conduction leaking fuel, which heats the fuel to the phase transition temperature and promotes the fuel to undergo phase transition. Stage b is the fluctuating evaporation period, and the temperature oscillation of evaporated fuel is remarkable in this stage. In Stage b, temperature-time curve oscillates violently, and heat transfer in the evaporation phase transition process of leaking fuel is unstable. In this stage, hot surface conducts direct heat conduction liquid phase of the fuel, and heat transfer modes to gaseous fuel are heat radiation and heat con-

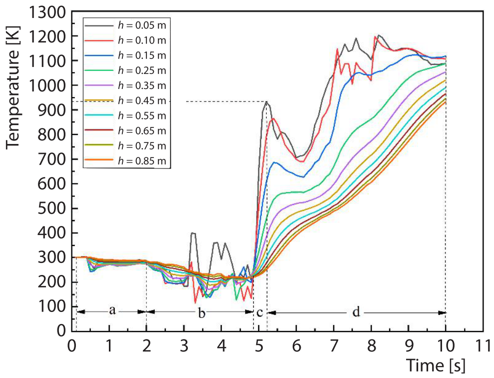

Figure 5. The HSI of leaking fuel with different heights in SER

vection. The natural-convection between SER environment and gaseous fuel, the heat absorption effect of liquid evaporation, and a variety of heat transfer mechanisms act accordingly. Stage c is the rapid heating stage, where the leaking fuel evaporates on hot surface and the temperature of gaseous medium rises rapidly. In Stage c, gaseous fuel absorbs heat and continues to rise. When the temperature reaches the ignition point of marine fuel, first HSI phenomenon of the fuel occurs. Figure 5 shows that the maximum temperature rise rate of the evaporated fuel reaches over 5.47 K per minute at the vertical height of 0.05 m. After reaching the ignition point, temperature rises rapidly, which is evaluated to be fuel HSI phenomenon. It is worth to note that during Stage d, leaking fuel still continues to undergo evaporative phase transition under hot surface effect. From Stage c to Stage d, the degree of phase transition of evaporated fuel above the hot surface is very drastic. After reaching the ignition temperature of marine fuel, it is still in a continuous and intense phase transition state. Meanwhile, temperature rise rate of the leaking fuel slows down. Because flammable gas-air mixtures are suddenly ignited, producing and releasing combustion products, resulting in a downward trend of temperature field. After temperature drops and tends towards stability, indicating the flame development in the space tends to the state of stable propagation. Results show that there is a strong correlation between the occurrence time of Stage c and HSI delay time of evaporated fuel in SER.

Figure 6(a) shows the temperature characteristics of evaporated fuel with height when the initial temperature of the hot surface is set at 623.15 K. The duration of the fluctuation period of evaporated fuel at the initial temperature of the hot surface increases incrementally. The result indicates that a sufficient amount of gas phase has been generated in the fluctuation and evaporation stage, reaching the combustible concentration range. During Stage b, several times of temperature jumps occurs at the vertical height of 0.05 m, which is on account of the flashover phenomenon on the fuel surface. The duration of Stage b is relatively long, and the temperature data after the jump drops again and returns to the fluctuating evaporation state. It indicates that although flashover occurs in this process, it does not reach HSI degree. Because the part of heat transfers to SER environment in this process, and necessary condition for a steady increase in temperature to reach HSI is missing. In Stage c, the temperature rise rate of the evaporated fuel increases, and the peak temperature of the region closest to the hot surface is nearly 850 K. Figure 6(b) shows the temperature characteristics of evaporated fuel with height when T_{sur} is 673.15 K. The curve indicates that the time experienced by stage b is gradually shortened, and the role of obtaining thermal feedback from SER environment is enhanced. It causes the temperature fluctuation amplitude of evaporated fuel above the hot surface to decrease gradually. When the heat accumulates and the temperature rises to Stage c, the temperature rise rate of the evaporated fuel increases to 9.17 K per minute. As the temperature of the hot surface further increases, the heat radiation and heat convection of hot surface are dominant. In addition, with the enhancement of thermal feedback on SER wall, leaking fuel on the hot surface can undergo rapid evaporative phase transformation, and HSI time can be shortened. When the initial temperature of hot surface rises to 723.15 K, variation of the evaporated fuel in the vertical space is similar to that when the initial temperature of the hot surface is 673.15 K. The duration

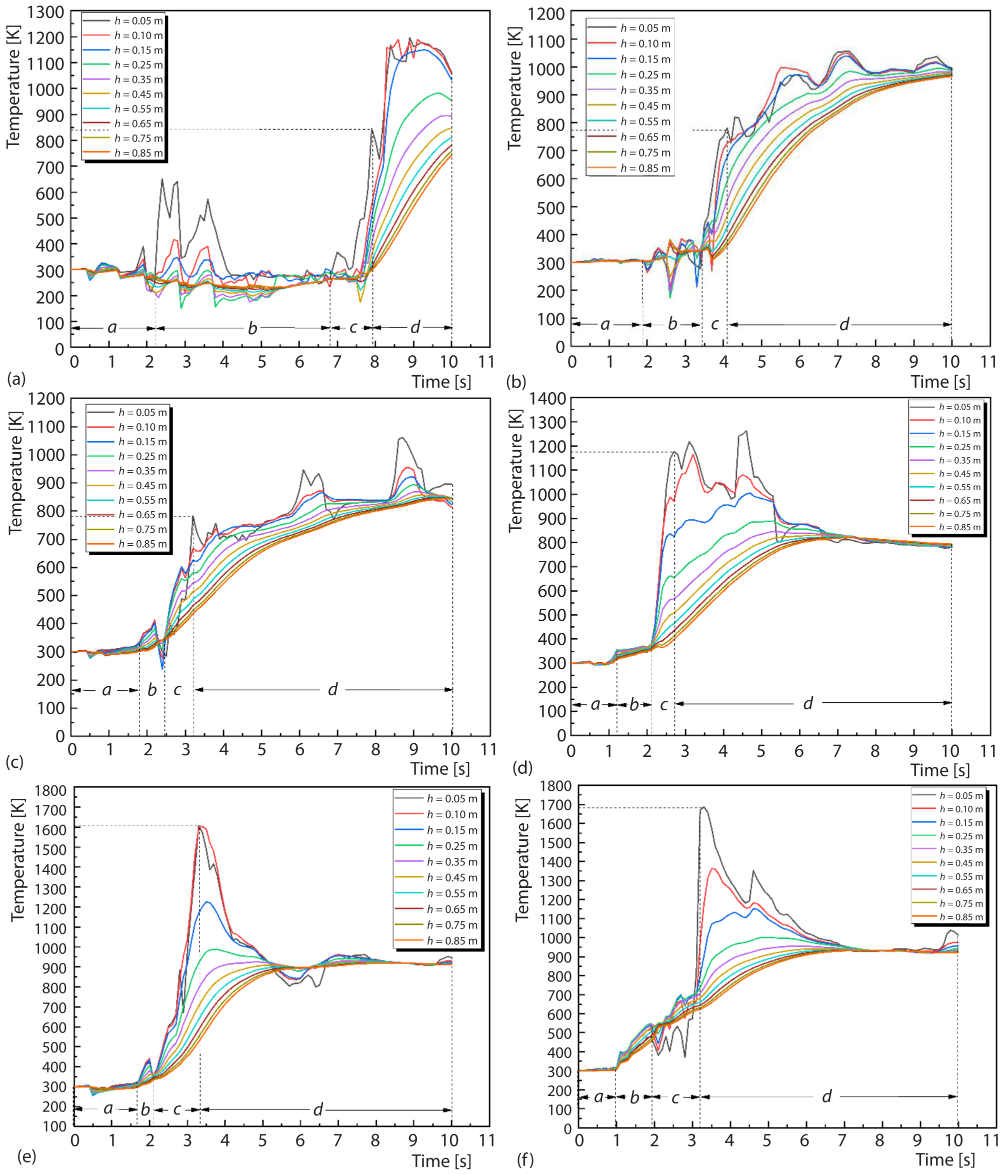

Figure 6. The HSI of leaking fuel with height-varying characteristics under different T_{sur}; (a) T_{sur} = 623.15 K, (b) T_{sur} = 673.15 K, (c) T_{sur} = 723.15 K, (d) T_{sur} = 773.15 K, (e) T_{sur} = 823.15 K, and (f) T_{sur} = 873.15 K

of Stage b reduces and the fluctuation range is increasing. Relatively, the duration of Stage d gradually increases, and there are some severe fluctuations of temperature rise rate in the stable flame development stage, which is closely related to the combustion characteristics of marine fuel. Figure 6(d) presents the temperature characteristics of evaporated fuel with height when T_{sur} is 773.15 K. The curve indicates that the temperature of evaporated fuel gradually shows a significant temperature difference with the increase of the height above the hot surface. With the increase of the initial temperature of the hot surface, the fluctuation range of the evaporated fuel during Stage b goes down. During Stage c, the peak temperature of evaporated fuel in the vertical region closest to the hot surface reaches over 1150 K. During Stage c, with the increasing of the space between vertical height and hot surface, the peak temperature of the evaporated fuel shows a significant downward trend, which indicates that the HSI area will occur near the fuel slick surface. When HSI occurs and a steady flame propagates, the temperature changes at different heights tend to be consistent gradually. When T_{sur} is 823.15 K and 873.15 K, respectively, the results show that temperature at the lower height fluctuates briefly before reaching HSI temperature, and then reaches the peak value. During this time, marine fuel is ignited in the area located near the fuel surface. The HSI process is accompanied by the phenomenon of air entrainment, which leads to the pulse phenomenon of temperature change in the area. According to figs. 6(e) and 6(f), when the initial temperature of hot surface rises to a certain value, the duration of the flame development stage after igniting the leaking fuel becomes longer, and the time node of this stage will be relatively fixed. With the different hot surface effects, the correlation between HSI time and vertical space can be obtained based on 10 MPa of different heights. The leaking fuel forms flammable vapor above the hot surface, and the ignition time is related to the initial temperature of the hot surface, vertical height, ignition temperature and the diffusion ability of fuel in the air. A prediction model is proposed for HSI time of leaking fuel, as shown as eq. (8). With the increasing of initial temperature of hot surface, HSI time of leaking fuel in SER gradually decreases. The HSI temperature of evaporated fuel has a certain regularity correlation with the occurrence time. The prediction model proposed by eq. (8) can be applied to assess HSI time in a certain height region in typical SER, it indicates that the HSI times of leaking fuel have the non-linear changing law with vertical heights. The results obtained by the prediction model show that the accuracy ranges from 98.38-99.82%. The prediction model can accurately characterize the relationship between HSI time of leaking fuel and vertical height under different hot surface strengths. In the real scenario, this prediction model can further provide a scheme and basis for the lay-out of monitoring sensors around the typical hot surface area of the SER:

$$H_{ig} = \frac{t_{ig} t_c}{1 + \left(\dfrac{T}{T_{sur}} \right)^{D_0}} + t_c \tag{8}$$

Influence of ventilation on HSI of leaking fuel in SER

According to SOLAS II-1/R35, adequate ventilation should be ensured in the SER for sufficient air supply when the equipment is operating. The ventilation forms of SER are divided into natural ventilation and mechanical ventilation. A total of four ventilation conditions are investigated in SER, with the ventilation velocity is 0 m/s, 1 m/s, 3 m/s, and 5 m/s. The vent temperature of SER is set to 300 K, and the whole ventilation process is maintained when the system is opened. Combustible vapor is formed when the leaking fuel is heated on hot surface, and VVFI of gas phase is used to characterize the evaporation volume of leaking fuel on hot surface. The scenario with T_{sur} of 573.15 K is selected for analysis. The evaporation volume of leaking fuel on hot surface has an increasing trend with time, and there is a significant cut-off point in the changing stage. In the first stage, evaporation volume of fuel under the low ventilation velocity is higher than that under the condition of high ventilation velocity. The larger the ventilation condition in SER, the stronger convective effect in SER environment. Heat loss from hot surface is not conducive to heat absorption and evaporation process of leaking fuel, so the HSI time of leaking fuel is advanced under the low ventilation velocity condition. When the inflection point of evaporation volume is reached, VVFI-time curve has a jump phenomenon. The main reason for this phenomenon is the transition process from natural evaporation boiling evaporation of marine fuel on hot surface. The leaking fuel in SER is subjected to intense thermal effect of hot surface, and when it reaches the vaporization temperature of fuel, it quickly transfers heat to the space around the hot surface. The bottom-up circulation ventilation mode in SER will consume the gaseous products of the evaporated fuel in the vertical space of the hot surface. Therefore, it promotes the rapid transformation of the leaked fuel on hot surface from the original liquid phase to the gas phase in SER. The results lead to a gradual increasing in the evaporation volume of the leaking fuel on hot surface with the enhancement of the ventilation conditions in SER. The ER of leaking fuel changes with time, as shown in fig. 7. When the ventilation velocities in SER are 1 m/s, 3 m/s, and 5 m/s, AER of leaking fuel on hot surface are 1.42 g/cm^{2}s, 1.51 g/cm^{2}s and 1.74 g/cm^{2}s, respectively. It indicates that the increase of ventilation velocities enhances the degree of evaporative phase transition of leaking fuel on hot surface. The ER of leaking fuel on hot surface presents a trend of rapid increase at initial stage and gradual decline. Ventilation velocity in SER is assumed to be 0 m/s when the top opening and mechanical system are closed simultaneously. Meanwhile, leaking fuel does not have remarkable phase transition behavior after contacting hot surface, so its ER changes stably with time. After the time of 3.01 seconds, ER of leaking fuel increases rapidly, and the increase is obvious. Subsequently, ER of leaking fuel fluctuates due to HSI consuming part of the fuel vapor. When mechanical ventilation starts in SER, the evaporation behavior of leaking fuel on hot surface is promoted for a period time. It is specifically reflected in the increasing trend of ER of leaking fuel in a short time. When the ventilation velocity is 1 m/s and 3 m/s, ER of leaking fuel fluctuates from 0.1-3 g/cm^{2}s, and the maximum ER is 3.09 g/cm^{2}s. As the fuel is ignited above the hot surface, ER in the scenario of ventilation condition is lower than that in confined SER environment. When the ventilation velocity in SER increases to 5 m/s, it can be observed that ER of leaking fuel on hot surface transitions at the time of 4.22 seconds with a peak value of 7.03 g/cm^{2}s. Then, ER of leaking fuel gradually decreases until it reaches a relatively stable trend. Results indicates that when the ventilation condition in SER is too strong, the transition from natural evaporation boiling evaporation of flammable liquid on hot surface is accelerated. A large number of mixed vapors formed by vaporization of combustible fuel are generated around the hot surface instantaneously. This study further indicates that the enhancement of ventilation condition in SER has a strong promotion effect on evaporation degree of leaking fuel near the heat source, which should be emphasized in design of SER ventilation system.

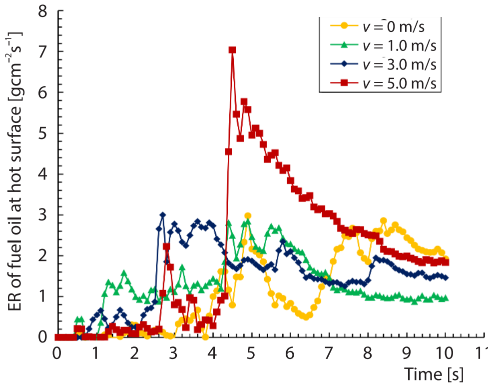

Figure 7. The ER of leaking fuel changes with different ventilation velocities

In this scenario of air supply at the bottom and exhausting vent at the top, the flow velocity in the area closer to hot surface presents a more significant fluctuation range. When the height is 0.05 m, particle velocity fluctuation range is between 0-0.8 m/s. At the time of 3.19 seconds, peak velocity at vertical height of 0.05 m reaches 0.781 m/s. With the increase of vertical height, the fluctuation ranges of flow velocity decreases gradually. When the vertical height increases to 0.1 m, the peak flow velocity in this area is 0.279 m/s. When the vertical height is between 0.1-0.25 m, the flow velocity ranges from 0-0.3 m/s. With the vertical height increases to 0.3 m or more, the velocity difference of the flow field in different height regions is getting small. At this time, in the vertical height region far from the hot surface, the flow velocity varies from 0.01-0.068 m/s. The results show that the flow velocity decreases with the increase of vertical height from ignition source. Peak velocities at different vertical area are concentrated between 3.0 seconds and 5.5 seconds after leaking fuel touches hot surface. During this period, the particles flow faster, which corresponds to an abrupt changing in ER of leaking fuel during the same period. It indicates that the leaking fuel has undergone a drastic evaporation phase transition process and the initial HSI preparation in this period. Combined with the ventilation system design in SER and field research, this study sets four different ventilation conditions for investigating the influence of HSI evolution process on leaking fuel. Ventilation velocity varies with 1 m/s, 3 m/s, 5 m/s, and confined SER without ventilation velocity. The SER scenarios (T_{sur} = 573.15 K) is selected for comparative analysis, fig. 8(a) shows the scenario where ventilation system is confined in SER (v = 0 m/s). Heat transfer pattern on hot surface is natural-convection caused by density difference, and the temperature gradient in the vertical space gradually decreases from bottom to top. When SER ventilation system is opened, heat transfers of hot surface changes in vertical space. Temperature gradient above the leaking fuel on hot surface gradually decreases. The temperature-time curve is relatively smooth, and the fluctuation range is narrow. Due to change of ventilation conditions in SER, heat transfer by forced convection in confined SER is formed and heat transfer efficiency is accelerated. With-

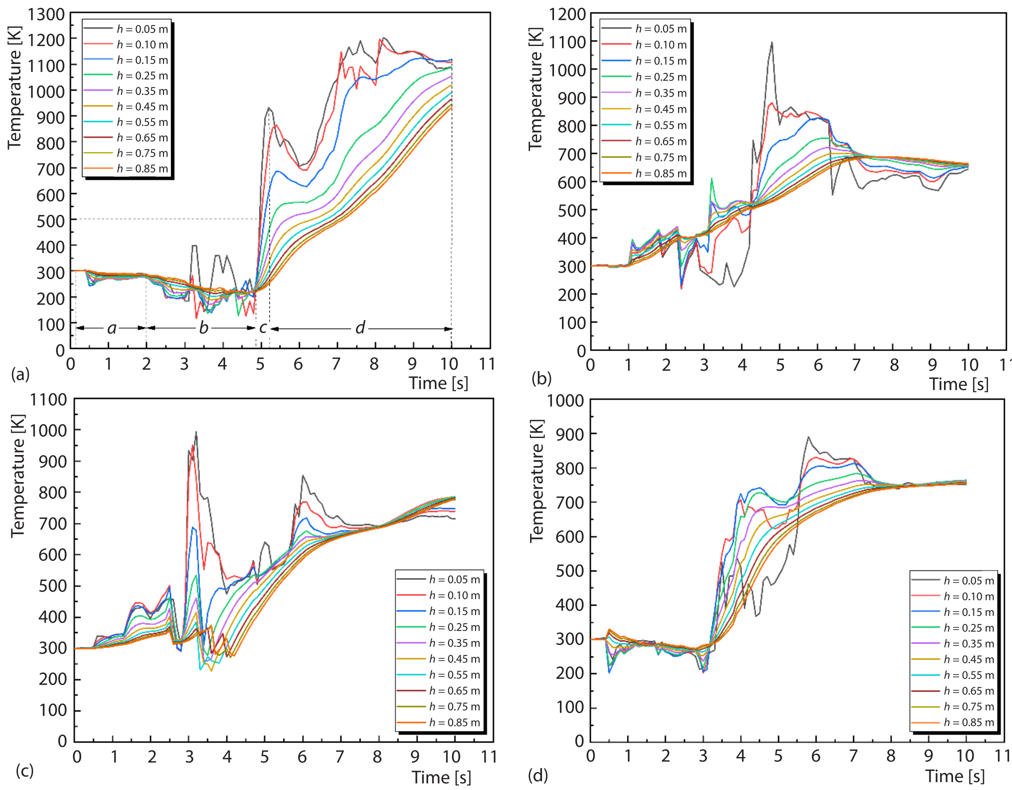

Figure 8. The HSI of leaking fuel with elevated ventilation velocities; (a) *v* = 0 m/s, (b) *v* = 1.0 m/s, (c) *v* = 3.0 m/s, and (d) *v* = 5.0 m/s

out the influence of other heat transfer mechanisms, the temperature field in the vertical space of hot surface tends to be balanced. After a short stable thermal effect period, figs. 8(b) and 8(c) presents that the temperatures of fuel evaporation on hot surface begins to rise. It is concluded that the convection heat transfers between the air and hot surface is enhanced when SER ventilation condition is improved, which leads to temperature dramatically increase in vertical space. At this stage, the heat transfers between hot surface and leaking fuel are dominant, and the temperature curve shows an upward trend with small fluctuations. Subsequently, liquid phase molecular evaporation and heat absorption of leaking fuel dominate, leading to the decrease of the temperature in vertical space of hot surface. In fig. 8(d), the temperature-time curve shows a trend of decreasing and then increasing as a whole. The strengthen of SER ventilation condition directly promotes the liquid-flow of leaking fuel on hot surface. Meanwhile, heat transfer from the hot surface to air attenuates because of the fuel covers hot surface. Analysis shows that HSI time is significantly shortened after forced convection. It mainly presents that HSI delay time of leaking fuel is shortened, which means that the enhancement of SER ventilation is conducive to HSI occurrence. With the increase of the ventilation velocity in SER, the temperature when environment reaches a stable status decreases gradually. Results show that the enhancement of ventilation condition in SER will promote the overall heat loss of hot surface. According to actual SER operation, the ventilation inlet is set in the lower location, it leads that the temperature disturbance in the bottom space has a greater impact.

Influence of wettability on HSI of leaking fuel in SER

In the HSI process of leaking fuel in the SER, the increment of HSI temperature is greatly inhibited by the wettability increases. This section of research aims to characterize the inhibition effect of changed wettability on the HSI temperature in the SER. The ambient humidity of the SER set as 10%, 20%, 30%, 50%, and 80%, which is took as five wettability conditions in the SER. Aforementioned humidity conditions in the SER are set based on the statistical data of the actual ship navigation and port operation process. In this study, the simulated result obtained by the condition without ambient humidity is selected and comparative analysis. When the initial temperature of hot surface is 573.15 K, the inhibition rates of temperature rise over time are collected in the numerical simulation. The average inhibition rate of temperature rise in the whole process is further chosen as the representation of inhibition rate of HSI temperature in the SER. The result shows that when the ambient humidity in the SER is 10%, the average inhibition rate of temperature rise in HSI process is 1.78%. When the ambient humidity in the SER rises up to 20% and 30%, the average inhibition rate of temperature rise in leaking fuel HSI process are 2.41% and 2.34%. When the ambient humidity in the SER increases to 50% and 80%, the average inhibition rate of temperature rise in leaking fuel HSI process is 4.75% and 7.26%. The inhibition rate of HSI temperature goes up with the increase of seawater volume ratio in SER environment. The analysis indicates that the seawater in air absorbs heat and converts it into vapor, which suppress the rise of HSI temperature. The wettability of the SER has an inhibition effect on the rise of ambient temperature, and the strength of the inhibition rate will gradually decrease with the increase of ambient humidity in the SER. When the ambient humidity of the SER is nearly 80%, the leaking fuel gradually begins to undergo phase transition at the hot surface until 6.0 seconds later. This result indicates that the high humidity in the SER would promote the increase of the HSI delay time of marine fuel. The AER of leaking fuel on hot surface of the SER under different wettability conditions are simulated by the numerical model. When the ambient humidity of the SER is 10%, 20%, 30%, 50% and 80%, the corresponding AER of the leaking fuel on hot surface are 0.308 g/cm^{2}s, 0.214 g/cm^{2}s, 0.117 g/cm^{2}s, 0.079 g/cm^{2}s, and 0.031 g/cm^{2}s. The result indicates that the strengthen of wettability in the SER will enhance the degree of evaporative phase transition of the leaking fuel on hot surface. Figure 9 presents the ER time-varying curve of the leaking fuel on hot surface under different wettability conditions of the SER. With the increase of ambient humidity in the SER, the ER of the leaking fuel on hot surface shows an overall downward trend. In the process of ship operation, the ambient humidity in the SER is relatively higher due to different regional climates, with a range of 50-80%. When the ambient humidity in the SER is 80%, the ER-time curve of the leaking fuel has a slight change within a period time. It indicates that the leaking fuel needs a long time to gradually start phase transition behavior after contacting the hot surface in high humidity environment. When the leaking fuel touches the hot surface at the time of about 6.0 seconds, the ER-time curve begins to present an upward trend. At this time, the maximum ER of the leaking fuel due to the thermal effect of hot surface is 0.168 g/cm^{2}s. When the ambient humidity of the SER drops to 50%, the fluctuation of ER-time curve of leaking fuel increases gradually. At the time of 0.8 second after the leaking fuel touches the hot surface, the ER-time curve has begun to fluctuate. Around 4.0 seconds, ER of the leaking fuel begins to rise steadily, and reaches the initial peak value of 0.181 g/cm^{2}s at 5.3 seconds. Subsequently, the ER of the leaking fuel decreases due to the inhibition effect of ambient humidity on the hot surface. When the leaking fuel is on the hot surface at the time of 8.0 seconds, the ER reaches the second peak value of 0.204 g/cm^{2}s. In the loading and unloading process in seaport, the relative humidity is lower than that of the sea environment, the scope of the ambient humidity in SER is 10-50%. When the ambient humidity in the SER is 30%, the ER-time curve of the leaking fuel on hot surface fluctuates greatly. The result indicates that although the wettability condition has influence on the HSI process of leaking fuel, it cannot completely inhibit the fuel evaporation on hot surface. During this period, the maximum ER of the leaking fuel on hot surface reaches up to 0.506 g/cm^{2}s. The time of peak value is further advanced, which indicates that the HSI delay time of leaking fuel is gradually shortened. The ambient humidity in the SER drops to 20%, the leaking fuel begins to rise gradually after 1.4 seconds when it contacts with the hot surface, and the increase rate is stable. During this period, the maximum ER of the leaking fuel on hot surface reaches 0.518 g/cm^{2}s. When the ambient humidity in the SER declines to 10%, the influence of wettability on the HSI delay is almost small. In this scenario, the ER of the leaking fuel can be observed that there are two changes in HSI process. The first one occurs at 2.5 seconds after the leaking fuel touched the hot surface, and the maximum ER is 0.809 g/cm^{2}s. Subsequently, when the leaking fuel is in contact with the hot surface at 6.5 secons, the ER achieves the second changes, with the peak ER of 0.925 g/cm^{2}s. By comparing the results of different wettability scenarios, it is shown that the increase of ambient humidity in SER has the inhibition effect on HSI delay of the leaking fuel with a certain range. With the strengthen of wettability in the SER, it directly affects the heat transfer effect of hot surface and the phase transition of the leaking fuel, resulting in shorten the fuel HSI time.

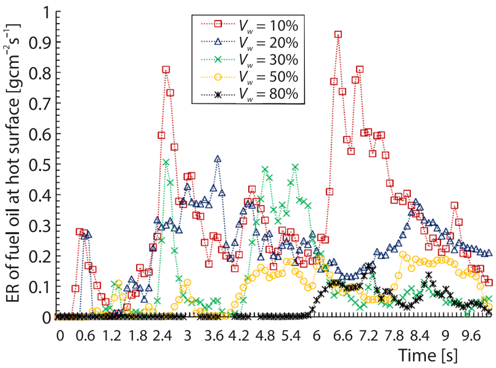

Figure 9. The ER of leaking fuel changes with the elevated wettability

There are five conditions of ambient humidity in the SER are simulated for different ship operating scenarios, including 10%, 20%, 30%, 50%, and 80%, respectively. Figure 10 shows the temperature distribution in vertical space above the hot surface when the ambient humidity in the SER is 10%. The wettability conditions in the SER has a great inhibition effect on the temperature rise rate. For a period after the leaking fuel touches the hot surface, the temperature field changes rarely. At 5.2 seconds, the region closest to the hot surface gradually begins to produce a temperature rise tendency. When the leaking fuel flows on the hot surface for 6.7 seconds, the temperature at vertical height of 0.05 m reaches the peak value of 980.51 K. Compared with the scenarios without wettability, the maximum temperature in this area increased. However, the peak time is delayed, and the duration of Stage d increases with different degrees. Before reaching the peak value, the temperature rise rate in this region exceeds 5.67 K per minute. When the vertical height form hot surface is less than 0.15 m, it shows that the temperature in this area exceeds the HSI temperature of fuel vapor. It indicates that the HSI process of the leaking fuel occurs in the area with vertical height of 0.15 m above the hot surface. Beyond this area, the temperature distribution presents a stable trend, and the overall temperature value is close to 400 K. With the increase of ambient humidity in SER, the HSI of leaking fuel is affected. When the temperature distribution in the vertical space when the ambient humidity in SER is 20%, the temperature rise rate of the vertical space on hot surface begins to be inhibited by the strengthen of wettability in SER. In the region of 0.05 m from the hot surface, the time-varying characteristics of temperature show obvious fluctuation as the ambient humidity rises to 20%. When the leaking fuel touches the hot surface for around 5.0 seconds, the peak temperature reaches up to 678.13 K in the vertical height of 0.05 m. Then, the temperature in this area gradually begins to drop, until 7.0 seconds later, it appears the second temperature rise phenomenon. Results show that the wettability in air near the hot surface inhibits the upward heat transfer process. However, it is difficult to suppress the phase transition behavior of the heated fuel continuously in the scenarios of weaken wettability. When the ambient humidity of SER rises to 30%, the temperature distribution of the hot surface is further suppressed. The temperature varies from 450-850 K within the range of 0-0.15 m above the hot surface. It indicates that the fuel vapor in this area is effectively ignited and propagated as a flame. With the ambient humidity of SER are 50% and 80%, the results show that the temperature rise behavior in the vertical space above the hot surface is significantly inhibited. The analysis believes that the seawater in SER air absorbs heat and converts it into vapor, and the leaking fuel above the hot surface absorbs environmental heat and converts it into combustible vapor. Because of the seawater in the SER environment, its specific heat capacity is higher than that of marine fuel, so the corresponding temperature rise rate of the same heat absorption is lower. In the case of absorbing the same heat, seawater and the surrounding environment form a larger temperature difference, resulting in the convection heat transfer process. Compared with the leaking fuel in SER, the seawater will absorb more heat. Therefore, when the heat transmitted by the hot surface in SER with the similar condition, HSI process of leaking fuel gradually becomes longer with the strengthen wettability. Due to increase of ambient humidity at sea, HSI process of the leaking fuel increases. If the inspection in the SER is lack of oversight, the potential risks of ignition and fire in SER will increase and outbreak.

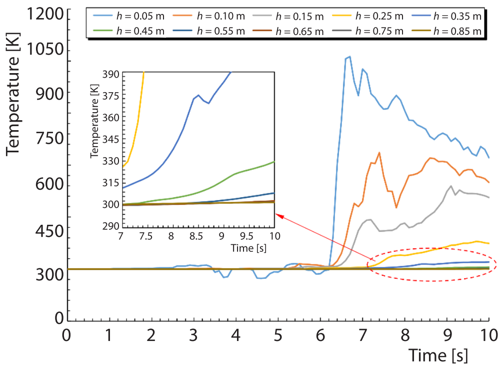

Figure 10. The HSI of leaking fuel with elevated wettability in SER

Conclusions

This paper presents detailed process of HSI in SER, relevant conclusions are as follows.

- This study focus on time for leaking fuel to reach the peak of ER on hot surface and the corresponding higher value. The fitted data and obtained the relationship between AER and Tsur, which can be applied to evaluate the evaporation degree of leaking fuel in SER under elevated HSI temperature over time.
- The fuel HSI process can be divided into four stages, including the stationary heating period, oscillatory fluctuation period, rapid heating period and flame development period. HSI process of evaporated fuel in SER shows different characteristics, such as ignition delay, stable combustion and extinguishing.
- The enhancement of ventilation condition in SER has a strong promotion effect on evaporation degree of leaking fuel near HSI. Strengthen of SER ventilation condition directly promotes the liquid-flow of leaking fuel on hot surface. Heat transfer from hot surface to air attenuates because of leaking fuel covers hot surface. HSI time is significantly shortened after forced convection. HSI delay time is shortened, which means the enhancement of SER ventilation is conducive to occurrence of leaking fuel HSI.
- Increment of HSI temperature is greatly inhibited by wettability increases. When heat transmitted by hot surface in SER, HSI process of leaking fuel gradually becomes longer with strengthen wettability. Due to increase of ambient humidity, HSI process of leaking fuel further increases.

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Nomenclature

A – control surface, [m^2]
AER – average evaporation rate, [gs^{-1}]
D – diffusion coefficient, [m^{2}s^{-1}]
F – directional components of mass force per unit mass, [Nkg^{-1}]
H_c – heat of combustion, [kJmol^{-1}]
H_{ig} – height where HSI occurs, [m]
k_{eff} – effective heat conduction coefficient, [–]
L_v – latent heat of evaporation of combustible liquid, [kJg^{-1}]
$\dot{m}''_{fuel}$ – mass flux of gaseous component of evaporating fuel per unit area, [kgs^{-1}m^{-2}]
m_g – total mass of gaseous molecules, [kg]
p – components of internal stress tensor in fluid, [–]
$\dot{Q}_E$ – heating rate of external heat source per unit area on liquid surface, [kWm^{-2}]
$\dot{Q}_\ell$ – heat loss rate per unit area of combustible liquid, [kWm^{-2}]
T – ignition temperature, [K]
T_{sur} – initial temperature of hot surface, [K]
t – time, [s]
t_{ig} – HSI time of occurrence, [second]
V – control volume, [m^3]
V_{frac} – volume fraction of gas phase, [–]
V_{mesh} – volume of grid, [m^3]
v – flow rate, [ms^{-1}]
v_e – ER of combustible fuel, [gm^{-2}s^{-1}]

Greek letters

ρ – density of marine fuel, [kgm^{-3}]
φ – percentage of thermal feedback, [–]

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