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Experimental study of flame spread over oil floating on water

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The phenomena and mechanism of flame spread over oil floating on water were studied using temperature measurements made by fine thermocouples and an infrared camera, schlieren images of surface convection and video recordings of flame spread. The experimental results reveal that the floating-oil depth greatly affects the average rate of flame spread and average flame pulsation wavelength. The surface tension effect is the main cause of surface convection, which controls flame spread. Momentum loss and heat loss from forward-flowing hot oil to water play an important role in retarding flame spread for oil thicknesses less than about 8 mm.

floating oil, flame spread, temperature profile, surface tension, convection

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With the development of the exploitation of offshore oil and marine transportation, there have been frequent fires resulting from oil spills. Because of the quick diffusion of oil leaked on water and the fast spread of flames over an oil surface, such fires usually have catastrophic consequences. Although flame spread is only a short process during a fire, it determines the direction of flame spread and the best time to put out fires. On the other hand, controlled combustion is an important way to clean up floating oil, but the precondition is that the flame can spread over the floating oil. Therefore, it is necessary to study the phenomena and mechanism of flame spread over floating oil. Flame spread over liquid fuel has been a hot topic of combustion theory and fire safety science since the 1960s and has been investigated experimentally and numerically [1–9]. Such researches have mainly focused on the effects of parameters such as the initial fuel temperature and tray width on the rate of flame spread and on the qualitative analysis of surface convection. However, little has been done to study flame spread over floating oil, which has the distinguishing characteristics that the floating oil is usually thin and water greatly affects the flame-spread phenomena. Mackinven et al. [10] experimented with decane floating on water and found that the average rate of flame spread increased with an increase in fuel thickness. Neil et al. [11] confirmed that fuel thickness has a large effect on the rate of flame spread. However, the researchers [10,11] obtained only qualitative results, and the reason why fuel thickness affects the phenomena of flame spread remains unclear till now.

In the present study, the flame spread over different thicknesses of aviation kerosene (with a flash point of about 66°C) floating on water was investigated simultaneously employing a schlieren system, an infrared camera, fine thermocouples and charge-coupled device (CCD) cameras. The paper presents the variation in the average rate of flame spread with floating oil thickness, gives reasons why the oil thickness affects the flame spread rate and presents the mechanism of flame spread.

1 Experimental

Figure 1 shows the experimental apparatus in the present study. Experiments were conducted in a 100-cm-long ×

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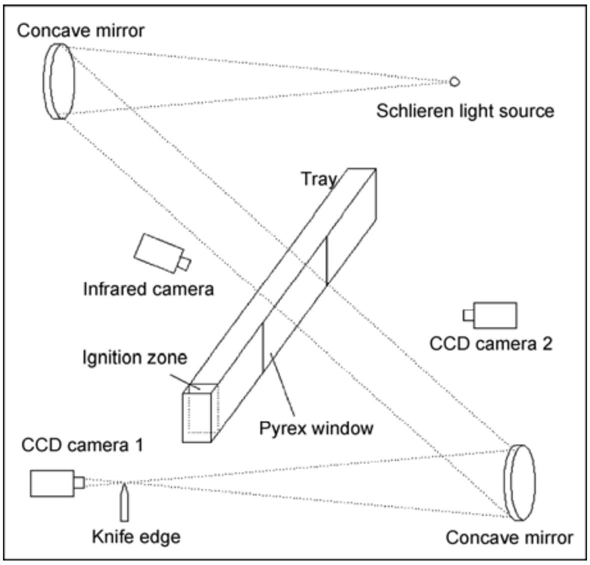

Figure 1 Schematic diagram of the experimental apparatus.

10-cm-deep × 4-cm-wide steel tray. Along both longitudinal sides of the tray, there was a 40-cm-long by 10-cm-high Pyrex widow to pass schlieren light. Three different techniques were used simultaneously in the experiments. First, two 0.1 mm fine Pt/Rh13-Pt(R) thermocouples with response times less than 7 ms were used to measure the temperature evolution during flame spread; the first thermocouple was fixed at the oil surface and the second was fixed at the water surface immediately below the first. Second, the surface convection preceding the flame front was visualized and recorded by a schlieren system and CCD camera 1, respectively. Additionally, the average rate of flame spread and the average flame pulsation wavelength were obtained from the video recording of flame spread by CCD camera 2 from the center of the Pyrex window. Third, an infrared camera located above the tray was employed to measure the two-dimensional temperature profile of the oil surface ahead of the flame front. The infrared camera has a detecting spectral range of 8–14 μm and temperature resolution of 0.08°C.

Before each experiment, certain amounts of water and aviation kerosene were poured into the tray in turn, and the oil surface and water surface were flush with the welding joints of the first and second thermocouples, respectively. Ignition was achieved using a pilot flame with a barrier located about 3 cm from one end of the tray. About 2 mL of heptane was trickled into the ignition zone; after the heptane was ignited, the flame spread from the ignition zone to the other end of the tray along the oil surface.

2 Results and discussion

2.1 Fame spread rate and pulsation wavelength

Pulsating flame spread was observed in the experiments, which means that the flame front jumps forward and backward along the surface of the floating aviation kerosene. Although oil thickness has no effect on the forward and backward spreading mode, it greatly affects the average rate of flame spread. Experimental results obtained for flame spread over floating aviation kerosene with thickness of 1.0–20 mm reveal that there are three obvious stages in the variation of the average flame spread rate with floating-oil thickness. As shown in Figure 2, when the layer of floating oil is thicker than about 8 mm, the average rate of flame spread is almost constant. However, the average spread rate decreases linearly from 10 mm/s at oil thickness of 8 mm to 3.8 mm/s at oil thickness of 2 mm. Additionally, the flame cannot spread when the oil layer is thinner than about 1.8 mm, and it is thus clear that a flame spreads only when the thickness of floating oil is greater than certain value.

The thickness of floating oil greatly affects the average flame pulsation wavelength, which is defined as the average distance covered by one pulsation period, apart from the average flame spread rate. Similar to the variation in the average rate of flame spread with oil thickness, the average flame pulsation wavelength remains nearly constant when the thickness of the oil layer is more than about 8 mm, and it is a strong function of oil thickness when the floating oil is thinner than about 8 mm; as Figure 3 shows, the average flame pulsation wavelength decreases from 5 cm for a 8-mm oil layer to 3 cm for a 4-mm oil layer.

2.2 Mechanism of flame spread

If the equilibrium vapor pressure of the liquid fuel at the initial temperature is high enough for the concentration of the oil-gas mixture to exceed the lower flammability limit, the premixed flame spreads over the liquid fuel. If the liquid fuel is cold or highly viscous, the spread mechanism resembles those for solids. Between these two extremes, surface convection plays an important role in the flame spread process [12]. As illustrated in Figure 4, there is a long thin convection layer below the oil surface ahead of the flame

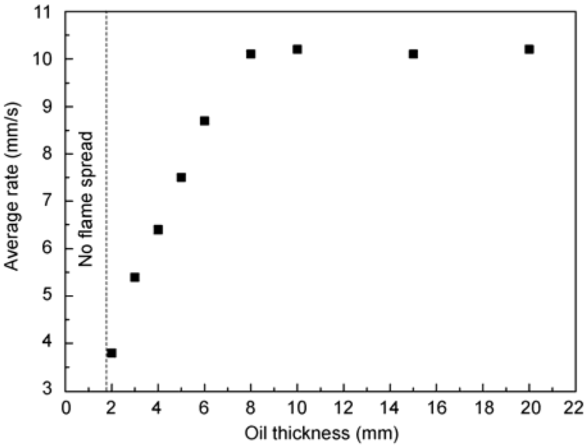

Figure 2 Average rate of flame spread vs. oil thickness.

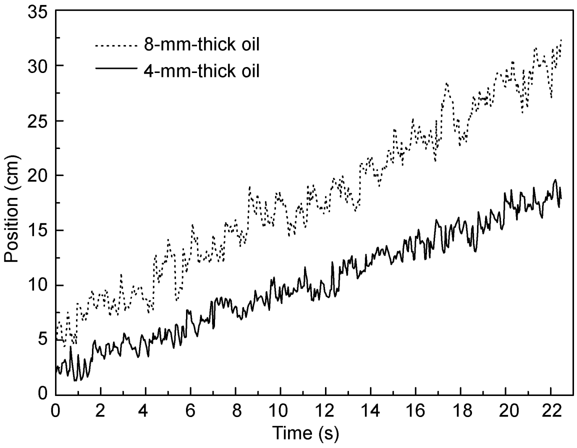

Figure 3 Flame front position vs. time for two oil thicknesses.

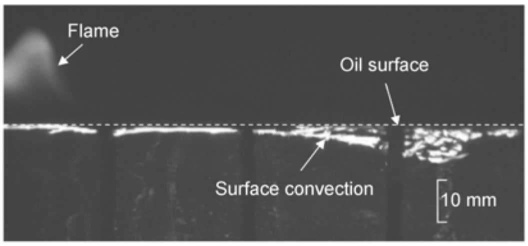

Figure 4 Schlieren image of surface convection.

front, where oil flows forward clockwise, whereas the length of the surface convection preceding the flame front above alcohols has been found to be much less [13]. The difference between oil and alcohols is likely due to physical fuel properties, such as viscosity and surface tension, and the effect of the tray width. For example, the tray used by Ito et al. [13] was only 5 mm wide and the viscous friction from the tray wall may obstruct the movement of the subsurface flow and thus decrease the length of surface convection. Schlieren images show that the convection layer does not have uniform thickness; most of the layer is only about 2 mm thick, whereas the layer is about 8 mm thick at the surface flow front for a thick fuel layer. For an oil thickness beyond 8 mm, the ratio of the thickness of the convection layer to the length of the convection layer remains nearly constant, which is consistent with Takahashi et al.'s results [6] of thick butanol layers.

The thermal expansion effect and/or surface tension effect contribute to surface convection [1,12], and the ratio of the Rayleigh (Ra) to Marangoni (Ma) numbers was used to judge which is of greater importance. When $Ra/Ma \leqslant 1$, the surface tension effect is dominant, and when $Ra/Ma \gg 1$, the thermal expansion effect controls the surface convection [14]. The Rayleigh and Marangoni numbers are defined as

$$Ra = \frac{\beta \rho g h^3 \Delta T}{\mu \alpha}, \tag{1}$$

$$Ma = \frac{\sigma_T \Delta T l}{\mu \alpha}. \tag{2}$$

The variables in eqs. (1) and (2) are the volume thermal expansion coefficient (β), gravitational acceleration (g), oil thickness or boundary layer thickness (h), temperature difference between the surface temperature under the flame front and the initial temperature (ΔT), kinetic viscosity (μ), thermal diffusion coefficient (α), temperature coefficient of surface tension (σ_T) and length of the surface convection layer (l). For the aviation kerosene used in this study, $\beta = 1.25\times10^{-3}$ K^{-1}, $\sigma_T = -0.147\times10^{-3}$ N m^{-1} K^{-1} [15] and $l \geqslant 10$ cm [7]. Thus, Ra/Ma is less than 0.34 for flame spread over floating aviation kerosene, and the surface tension effect is the main cause of surface convection.

The surface temperature under the flame front ranges from 90°C to 105°C [16], and it remains low far ahead of the flame. A temperature gradient is thus established along the oil surface. For liquid fuel, surface tension varies inversely with temperature, and the temperature gradient thus drives the hot oil from under the flame front forward to preheat the cold oil far ahead. As shown in Figure 5, there is a clear preheated zone preceding the flame front. The temperature profile of the preheated zone explains the mechanism of flame spread. In this study, temperature profiles of the longitudinal central line of the preheated zone are calculated from the infrared images.

Two such temperature profiles separated by an interval of one second are presented in Figure 6, and the solid line corresponds to the middle line of the preheated zone illustrated in Figure 5 at time t. Figure 6 shows that the trends of the two lines are similar and the temperature profile of the preheated zone varies nonlinearly. At the front of the preheated zone, the surface temperature rises quickly and reaches a plateau, and then rises gradually with a decrease in the distance from the flame front. The surface temperature approaches and surpasses the flash point of aviation kerosene several centimeters ahead of the flame front, where the oil evaporates quickly. Once the concentration of the gas-oil mixture exceeds the lower flammability limit, the flame jumps forward and then retreats quickly. Figure 6 also shows that the front of the preheated zone moves forward a distance ΔL in 1 s (i.e., at time $t + 1$), and the surface

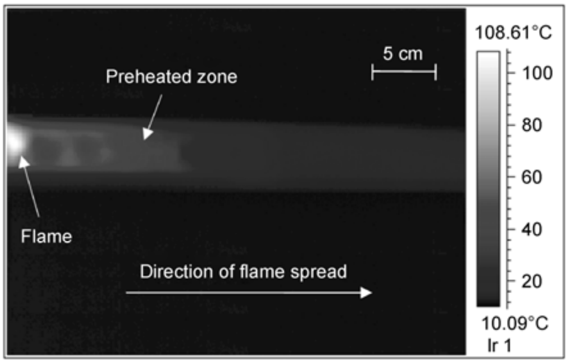

Figure 5 Infrared image showing the oil surface temperature ahead of the flame.

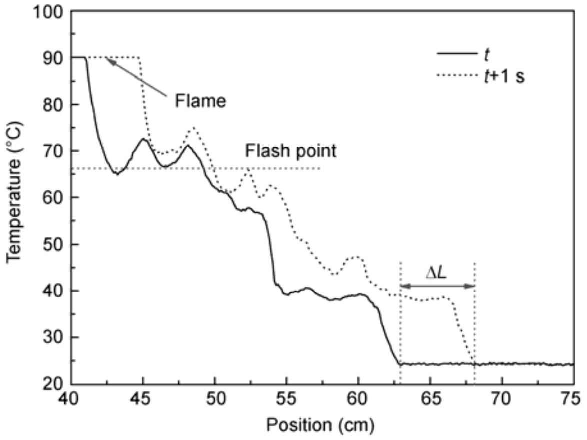

Figure 6 Two temperature profiles of the longitudinal central line of the oil surface.

convection rate is thus easily calculated. The results show that the surface convection rate decreases with oil thickness when the oil thickness is less than 8 mm.

2.3 Effect of oil thickness on the rate of flame spread

The surface convection rate and the boundary layer thickness reach their maxima and do not vary with oil depth when the oil depth exceeds 8 mm; that is, the oil depth has no effect on the preheating effect of the surface convection. Therefore, the average rate of flame spread remains nearly constant. However, for an oil thickness less than 8 mm, various factors result in the variation of the average spread rate with oil thickness.

Figures 7 and 8 depict the details of the thermocouple readings during flame spread over floating oil with thicknesses of 4 and 3 mm, respectively. Figure 7 shows that when the temperature of the water surface begins to rise, the temperature of the oil surface is about 95°C, which implies that the flame front has gone beyond where the thermocouples were fixed according to our former experimental results [16]. It is thus certain that heat loss from oil to water has no effect on the flame spread. However, schlieren images show that the surface convection is blocked by water when the oil thickness is less than 8 mm, and momentum loss of the forward flowing hot oil, which weakens the preheating effect of surface convection during the flame spread, increases inversely with oil thickness; thus, the average flame spread rate decreases accordingly.

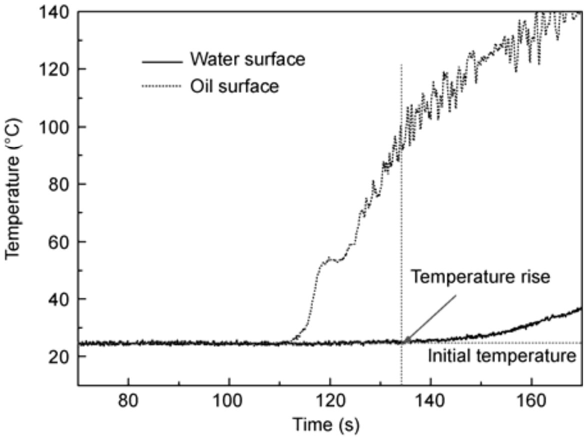

Figure 7 Details of the thermocouple readings for 4-mm-thick oil.

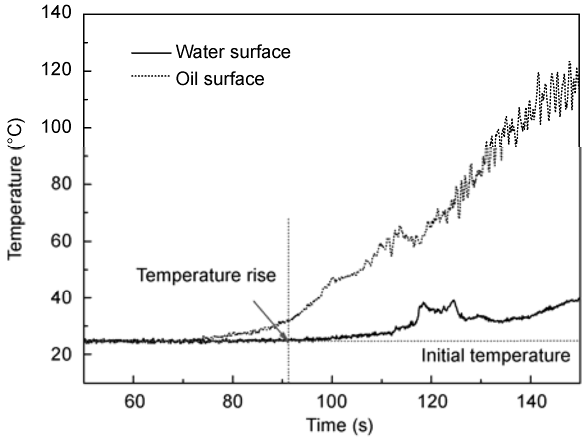

Figure 8 Details of the thermocouple readings for 3-mm-thick oil.

For 3 mm oil, however, Figure 8 shows that the temperature of the oil surface is only about 35°C when the temperature of water surface begins to rise; that is, heat loss from oil to water also weakens the preheating effect of surface convection besides momentum loss. In addition, there is an abrupt rise in the water surface temperature; in contrast, the temperature of the oil surface falls because water is entrained by surface convection and cools the hot oil. The thinner the floating oil is, the greater the momentum loss and heat loss to water. When the floating oil thickness decreases to 1.8 mm, the flame cannot spread owing to the combination of momentum loss and heat loss.

3 Conclusions

The following conclusions are drawn from our experimental study of flame spread over aviation kerosene floating on water.

(1) For an oil thickness exceeding 8 mm, the average rate of flame spread remains nearly constant. For an oil depth between 2 and 8 mm, the average flame spread rate has linear dependence on oil thickness, and oil thickness has a large effect on the average pulsation wavelength. A flame cannot spread when the oil thickness is less than 1.8 mm.

(2) The surface tension effect is the main cause of surface convection, which controls flame spread. The surface temperature surpasses the flash point of fuel several centimeters ahead of the flame front.

(3) For floating oil with thickness ranging from 4 to 8 mm, momentum loss from oil to water decreases the average flame spread rate, and the combination of momentum

loss and heat loss retards flame spread in the case of the thinner oil layer.

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