Effects of Initial Fuel Temperature and Altitude on Flame Spread over Diesel Fuel

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ABSTRACT

The flame appearance, flame speed and temperature profile of flame spreading over a liquid surface were experimentally investigated at two different altitude conditions (the Lhasa plateau at 3658 m, and the Hefei Plain at 50 m). The experiments were carried out with a petroleum-based diesel fuel over a wide range of initial fuel temperatures. Two types of flames evidently exist in flame spread over 0# diesel fuels: a blue precursor flame located ahead of a yellow main flame. The main flame is a flame shape under diffusion combustion, whereas the precursor flame belongs to premixed combustion. The initiation fuel temperature for supporting flame propagation over diesel fuel is lower in Lhasa, indicating that oils can more easily catch fire at a higher altitude. For both liquid phase- and gas phase-controlled flame spread, the flame spread rate at elevated altitude is considerably greater than at normal altitude. The intrinsic reasons for the influence of altitude on flame spread rate are predicted by variations in flash point and surface tension of liquid fuel with altitude. Moreover, the measured temperature distributions normal to the oil surface reveal that the liquid temperature in the upper layer is higher than that in the lower layer. The oil surface temperature as well as the liquid temperature inside the subsurface flow is higher in Lhasa. For a given initial fuel temperature, the time interval between the flame tip and the subsurface flow front is greater for higher ambient pressure.

KEYWORDS: Flame spread, diesel fuel, fuel spilling, high altitude.

INTRODUCTION

Diesel fuel is a petroleum-based fuel that is commonly used to supply power to the diesel engines of ships or vehicles [1]. There is always a concern on the potential fire hazards in using diesel fuel in boats and vehicles. Once leaking diesel fuel is exposed to an ignition source, a pool fire, which is accompanied by the typical phenomenon of flame spread across a liquid fuel surface, is easily established. Comparing the fire hazards established by pool fires, flame spread is merely a short-time process, but it determines the direction of fire expansion, flame growth speed and the measures to extinguish the fire. It causes the increase of the burning area as well as the fire scale, and brings more threats to oil safety. Therefore, it is imperative to study the characteristics and controlling mechanisms of flame spread over liquid surfaces.

The speed and behavior of flame spread across a liquid surface depend on the initial fuel temperature relative to the flash point of the liquid fuel, at which sufficient flammable vapor mixture is produced to meet the lean flammability limit above the oil surface [2]. The preheated (also called sub-flash or liquid phase-controlled) flame spread regime occurs when the initial fuel temperature is lower than the flash point, otherwise the premixed (also called super-flash or gas phase-controlled) flame spread regime is attained [3].
The effects of ambient pressure on flame spread rate over liquid fuels are our current interest. Flame spread over liquid fuels can occur following the spillage of combustible fuels from pipes or fuel storage tanks due to destructions or air crash accidents [4]. For example, a serious oil-spilling fire occurred in Doilungdêqên County in Lhasa, on March 31, 2007. The fire spread across a pool of 2 m wide with the total length of fuel area larger than 1372 m, imposing high heat fluxes on the surroundings. With an increase in altitude, environmental pressure and partial pressure of oxygen will reduce. These parametric variations may produce distinct fire behaviors between sea-level and high-altitude regions, like in ignition sensitivity, burning rate and flame appearance [5-11].

Our previous papers have tried to specify the effect of altitude on flame spread over liquid fuels [12, 13]. It is predicted that the boiling point of oil decreases with an increase in altitude, so that the liquid fuel evaporates more rapidly in a high-altitude environment. Then, the flame spread rate is also larger at high altitude than at low altitude. Nevertheless, the essential reasons for the influence of atmospheric pressure on flame spread rate have not been understood comprehensively. First, it is well known that flame spread over liquid fuel is controlled principally by the surface-tension driven flow as the initial fuel temperature is below its flash point. Thus, analyzing the variation of surface tension of liquid with altitude is a key point to reveal the influence of altitude on liquid flame spread characteristics. Second, the theoretical derivation of the relationship between flash point and altitude was not presented previously. Finally, the gas phase-controlled flame spread behavior at high altitude is still unclear. In the present study, therefore, the behavior of the flame propagation across diesel fuel in a low- and a high-altitude environment has been examined in detail.

**EXPERIMENTAL SETUP**

The experimental apparatus is sketched in Fig. 1. The experimental apparatus was described in detail in Ref. [12]. An open rectangular tray, with the length by width by depth equal to 100 cm × 4 cm × 10 cm was employed. The diesel fuels were poured into the tray where they were warmed or cooled to the desired temperature. Once the flame had spread over the full length of the pool, it was extinguished with a fire-retardant board. Nine 0.1 mm diameter S-type fine-thermocouples with a response time of 7 ms, were installed in the longitudinal centerline of the pool. These thermocouples constituted three thermocouple trees: TC-1 to TC-3, TC-4 to TC-6, and TC-7 to TC-9. Each thermocouple tree was intended to measure the spatial temperature distribution, at a horizontal interval distance of 10 cm. In each thermocouple tree, the positions of the three thermocouples were +5.0, 0 and −5.0 mm with respect to the oil surface, where the negative value represented the thermocouple below the oil surface.

![Figure 1. Schematic diagram of experimental apparatus.](image)

The ambient temperature and humidity during each test conducted in the two cities were recorded and are summarized in Table 1. The average altitude in Tibet is approximately 3650 m, with the
atmospheric pressure and partial pressure of oxygen approximately equal to two-thirds of those in areas near sea level. Since the atmospheric humidity and temperature were almost the same at both altitudes, the effects of ambient temperature and humidity on flame spread in this experiment are assumed to be negligible.

<table>
<thead>
<tr>
<th>Location</th>
<th>Altitude (m)</th>
<th>Atmospheric pressure (kPa)</th>
<th>Partial pressure of oxygen (kPa)</th>
<th>Relative humidity (%)</th>
<th>Ambient temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibetan Plateau</td>
<td>3658</td>
<td>65.5</td>
<td>13.5</td>
<td>36-47</td>
<td>19-22</td>
</tr>
<tr>
<td>Hefei Plain</td>
<td>50</td>
<td>100.8</td>
<td>21.2</td>
<td>36-39</td>
<td>13-20</td>
</tr>
</tbody>
</table>

**INTRINSIC REASONS FOR ALTITUDE EFFECTS ON FLAME SPREAD OVER LIQUIDS**

**Altitude effects on flash point**

With an increase in altitude, environmental pressure and partial pressure of oxygen will reduce. These parameter variations may essentially influence ignition sensitivity of the combustible liquids. According to the Clausius–Clapeyron relation [14], the saturated vapor pressure of liquid fuel ($P_d$) variation with fuel temperature ($T$) can be expressed as follows,

$$\frac{d \ln P_d}{dT} = \frac{\Delta_{vap} h_m}{RT^2},$$

(1)

where $R$ is the universal gas constant, and $\Delta_{vap} h_m$ is the latent heat of evaporation due to the phase change, which is a constant for a given fuel type. Integration of Eq. (1) yields [15],

$$P_d = P_0 \exp \left( \frac{\Delta_{vap} h_m}{R} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right).$$

(2)

The liquid temperature may reach its boiling point ($T_b$) when the saturated vapor pressure is equal to the atmospheric pressure. On the other hand, as predicted by the barometric formula [16], the ambient pressure at an altitude of $Z$, $P_z$, is given by the following formula,

$$P_z = P_0 \exp \left(-\frac{Z}{H}\right),$$

(3)

where $P_0$ is the atmospheric pressure at sea level (101.3 kPa), and $H = RT / (M_a g)$ is called the scale height of the atmosphere, 8.435 km. Combining Eqs. (2) and (3) yields the boiling point of liquid fuel at altitude $Z$,

$$T_{bz} = \frac{1}{\frac{1}{T_0} + \frac{Z \cdot R}{\Delta_{vap} h_m \cdot H}},$$

(4)

where $T_{bz}$ is the boiling point of the liquid fuel at altitude $Z$. Catoire and Naudet [17] developed an equation for the estimation of the flash point with a maximum absolute deviation of only 10 K,

$$T_{fl} = 1.48 \cdot T_b^{0.8} \cdot \Delta_{vap} h_m^{0.17} \cdot n^{-0.06},$$

(5)
where $\Delta_{\text{vap}}h_m$ in kJ/mol is the standard enthalpy of vaporization at 298.15 K; and $n$ is the total number of carbon atoms in the molecule. $T_{\text{FL}}$ in K is the flash point temperature and $T_b$ in K is the normal boiling temperature.

Supposing that $\frac{1}{T_0} = C_1$, $\frac{R}{\Delta_{\text{vap}}h_m \cdot H} = C_2$, so the flash point of a liquid fuel at altitude $Z$ is predicted as,

$$T_{\text{FL}} = 1.48 \left( \frac{1}{C_1 + C_2 \cdot Z} \right)^{0.8} \cdot \Delta_{\text{vap}}h_m^{0.17} \cdot n^{-0.06}. \quad (6)$$

In this expression, $C_1$, $C_2$, $\Delta_{\text{vap}}h_m$ and $n$ are all constant. Thus, under a certain initial temperature, Eq. (6) predicts that the flash point of a liquid decreases with an increase in altitude. In fact, the flash point of the 0# diesel fuel is measured as approximately 75 °C in Hefei and 54.5 °C in Lhasa. The fuel vapor is more easily volatilized from the liquid fuel at a high altitude than at a low altitude, so that the flame is expected to spread more rapidly in a higher altitude environment.

**Altitude effects on surface tension**

As discussed previously, flame spread across a liquid surface involves preheating by subsurface convection flow, which is driven primarily by variations in surface tension along the direction of spread over the pool. Therefore, investigating ambient pressure effects on the surface tension of a liquid is imperative to identify flame propagation behavior over a liquid fuel. According to Alberty’s work, the relation between the surface tension and air pressure is written as follows [18]:

$$\frac{d \sigma}{dP} = - \frac{\Gamma_0 RT}{P}, \quad (7)$$

where $\Gamma_0$ is designated as the amount of adsorbed molecules per unit surface. The surface of the condensed phase is assumed to be smooth, and adsorption hypothetically occurs only within a single molecular layer structure on the liquid surface. Based on both hypotheses, Langmuir [19] postulated that the amount of adsorbed molecules per unit surface could be predicted as follows:

$$\Gamma_\infty = \frac{bP}{1 + bP}. \quad (8)$$

In this equation, $\Gamma_\infty$ is the limiting adsorption at an extremely high gas pressure value, and $b$ is a constant. The following is obtained by combining Eqs. (7) and (8):

$$\sigma = \sigma_0 - \Gamma_\infty RT \cdot \ln(1 + bP). \quad (9)$$

Eq. (9) indicates that the surface tension of a liquid decreases as gas pressure increases. Therefore, less air is absorbed into the liquid fuel in high-altitude areas than in low-altitude areas, which results in higher surface tension of the liquid fuel. A strong subsurface convection flow is then induced, which further increases flame spread rate.

In summary, both the analyses of the flash point and surface tension of a liquid fuel predict that flames will spread more rapidly in a high-altitude environment. In the following discussion, flame spread rates under various initial fuel temperatures are measured in both Hefei (sea level) and Lhasa (high altitude). The flame speed rates of Hefei and Lhasa are then quantitatively compared.
RESULTS AND DISCUSSIONS

Basic flame appearances

Fig. 2 shows an array of flame images for flame spread over 0# diesel both in Lhasa and Hefei at an initial fuel temperature of 30 °C. Two types of flames evidently exist during the spreading process, that is, a blue precursor flame (also called flash flame) located ahead of a yellow diffusion flame (also called main flame) [20]. In the flame propagation process, the blue precursor flame does not always exist but periodically appears and disappears in front of the main body of the flame.

The maximum length of the precursor flame is defined as the pulsation wavelength of the precursor flame. At an initial fuel temperature of 30 °C, the precursor flame wavelength ($\Delta l$) is approximately 13.9 cm in Hefei and 15.9 cm in Lhasa. The shorter precursor flame wavelength in the higher pressure area is attributed to the length of the subsurface convection flow for flame spread in Hefei being smaller than that in Lhasa under the same initial fuel temperature [21]. The length of the precursor flame is proven to vary proportionally with the length of the subsurface convection flow ahead of the flame front [22]. Moreover, the speed of the precursor flame is measured as ~70 cm/s, regardless of altitude and initial fuel temperature. The precursor flame belongs to premixed combustion because the maximum value of the laminar diffusion flame spread rate is approximately 10 cm/s [23].

Fig. 3 shows the transient and average values of the main flame speeds for flame spread over 0# diesel both in Lhasa and Hefei. The data presented in Fig. 3 identify that the average flame spread rate is approximately 0.75 cm/s and 1.15 cm/s in Hefei and Lhasa, corresponding to diffusion burning [23], but changes with time. The maximum value of the flame spread rate does not change significantly with altitude and is in the range of 30 cm/s to 45 cm/s. This flame spread rate corresponds well with the burning velocity of premixed gas mixtures [24]. The characteristics of flame spread rate are systematically discussed in following section.

Figure 2. Sample flame fronts of flame spread over 0# diesel in Lhasa and Hefei.
Figure 3. Transient and average values of main flame speeds in Lhasa and Hefei.

Velocity of flame spread

Liquid phase-controlled flame spread

Flame spread rate is regarded as one of the most important parameters in characterizing flame propagation behavior because it is vitally connected to fire hazard assessment of fuel spilling accidents. The initial fuel temperature has an obvious influence on the speed of the liquid flame spread. Fig. 4 shows the flame spread rate variation with sub-fire point temperature of diesel fuel at normal and elevated altitude.

Figure 4. Initial temperature effects on liquid phase-controlled flame spread in Lhasa and Hefei.

The initiation fuel temperature for supporting flame propagation over diesel fuel is approximately 18 and 24 °C in Lhasa and Hefei, respectively. Below these temperatures, the flame established in the ignition region is very weak and dim, and it finally extinguishes after burning for a short time. The
lower initiation fuel temperature in Lhasa indicates that oils will more easily catch fire at higher altitude. For liquid phase controlled flame spread, the velocity of flame spread over 0° diesel in Lhasa is always higher than that in Hefei. Several factors are presented to account for this phenomenon:

Firstly, Eq. (6) predicts that the flash point of a liquid fuel is lower at elevated altitude so that the fuel vapor volatilizes and establishes a combustible mixture above the liquid surface more easily at high altitude. The gas diesel fuel/air vapor mixtures accumulate and satisfy the lean flammability limit at high altitude earlier than the counterparts in low altitude environments. Secondly, Eq. (9) predicts that the surface tension increases with an increase in altitude, which is attributed to less air absorption at the liquid surface. The larger surface tension at lower ambient pressure facilitates the propagation of flame across the liquid fuel surface. Finally, buoyancy induced airflow is opposed to the direction of flame propagation and it is reduced by the low air density at the elevated altitude [25].

Gas phase-controlled flame spread

Fig. 5 shows sample flame spread images in Hefei under gas phase-controlled flame spread. In this regime, the initial fuel temperature is higher than the fire point of the hydrocarbon fuel; thus, a flammable mixture layer with a concentration gradient should be established over the liquid surface. When an igniting source is present, a blue precursor flame propagates rapidly forward and immediately arrives at the other edge of the pool. A yellow flame then appears, which also passes rapidly across the entire length of the pool. Finally, the oil surface is sufficiently warmed and diffusion flames fuse together across the pool surface.

The data shown in Fig. 6 indicate that the flame spread rate is very large in contrast to any liquid motion assisted flame propagation. The flame spread rate rises dramatically with an increase in initial fuel temperature and it peaks at 80 °C and 98 °C for flame spread over 0° diesel in Lhasa and Hefei, respectively. These temperatures correspond to the stoichiometric temperatures, $T_{st}$, in both cities. As the temperature is raised, the air-fuel mixture ratio near the surface moves from the lean flammability limit towards the stoichiometric ratio and then to fuel rich mixture ratios. Then, one would expect that the flame spread rate would increase sharply from the flash point and reach a maximum for the liquid
temperature which gives a vapor pressure corresponding to the fuel fraction required for a stoichiometric mixture in air. Temperatures above $T_{st}$ give fuel rich conditions near the surface. As the partial pressure of liquid fuel decreases with the vertical distance from the oil surface [26], a point above the fuel surface where a stoichiometric concentration of fuel-air mixture occurs always exists. A flame propagating through a stratified air-fuel mixture system will be led by that part of it which flashes through the stoichiometric zone. Thus one can conclude that, as the temperature is raised above $T_{st}$, there will essentially be no change in the flame spread rate.

As shown in Fig. 6, under the same initial fuel temperature, the flame spread rate for flame spread over the diesel fuel in Lhasa is larger than the counterpart in Hefei. For gas phase-controlled flame spread, the first two reasons for liquid phase-controlled flame spread also apply. The laminar burning rate of fuel vapor decreased as ambient pressure increased [10]. By contrast, the low-pressure environment of Lhasa may accelerate the burning rate of premixed fuel-air vapor. Finally, our previous observations proved that a flame extends further off the fuel surface at a high altitude [13]. For gas phase-controlled flame spread, gas-conductive heat transfer from the premixed flame shape to the neighboring oil surface is one of the primary heat transfer modes for preheating [27]. Therefore, a higher flame height at high altitude may enhance preheating effects, which increases flame spread rate in the gas phase-controlled flame spread regime.

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Figure 6. Initial fuel temperature effects on gas phase-controlled flame spread in Lhasa and Hefei.

Temperature profile of liquid flow

The vertical temperature distributions in the centerline of the tray are simultaneously obtained from the temperature measurements of the three thermocouple trees (TC-1, TC-2 and TC-3), and the measurement results are presented in Fig. 7. The starting time is selected for clarity in these curves, so the horizontal axis shows only relative time.
As the front of the liquid-phase thermal vortex arrives at the welding spot of the thermocouple on the oil surface, the thermocouple reading of TC-2 (0 mm) starts to increase steadily. At the same time, TC-3 (-5.0 mm) also increases as the subsurface convection flow front arrives, but the temperature rise rate is significantly lower than that of TC-2. This phenomenon reveals that the heat penetration depth of the subsurface convection flow is greater than 5.0 mm. In fact, the liquid fuel near the oil surface should be preheated by the flame’s radiant effects, which are absent for the bulk of the cold oil in the lower layers. Additionally, warm oil is elevated to the pool surface by the liquid-phase buoyancy force [28], so the liquid temperature in the upper layer is higher than that in the lower layer. As time elapses, TC-1 (+5.0 mm) starts to steeply increase as the precursor flame tip arrives. Then, the readings of TC-2 fluctuate after the diffusion flame tip passes over the detection point of this thermocouple.

Fig. 7 also indicates that the oil surface temperature as well as the liquid temperature inside the subsurface flow is higher in Lhasa. This is due to the fact that the flame spread rate is greater at the elevated altitude. More energy should be carried forward by the subsurface flow, causing higher fuel temperature in Lhasa. In Hefei, the flame tip needs 18 s to arrive at the temperature measuring point after the subsurface flow front passes through it, while this time is merely 11 s in Lhasa. This phenomenon is attributed in part to the faster flame speed and in part to an intrinsic decrease in flash point of the liquid in the elevated-altitude environment.

CONCLUSIONS

A series of laboratory-scale tests has been conducted to study the flame spread behavior over 0° diesel fuel in a normal and an elevated altitude. Based on the experimental observations, theoretical analyses are proposed to seek the essential reasons for the flame spread differences in both altitudes. Major conclusions are summarized as follows:

Two types of flames evidently exist during spread over diesel fuel: a blue precursor flame located ahead of a yellow main flame. The main flame is a flame shape under diffusion combustion, whereas the precursor flame belongs to premixed combustion. The initiation fuel temperature for supporting flame propagation over diesel fuel is lower in Lhasa, indicating that oils can more easily catch fire at higher altitude.
For both liquid phase- and gas phase-controlled flame spread, the flame spread rate at an elevated altitude is considerably greater than at a normal altitude. The intrinsic reasons for the influence of altitude on flame spread rate are predicted by variations in flash point and surface tension of the liquid fuel with altitude.

The measured temperature distributions normal to the oil surface reveal that the liquid temperature in the upper layer is higher than in the lower layer. The oil surface temperature as well as the liquid temperature inside the subsurface flow is higher in Lhasa. For a given initial fuel temperature, the time interval between the flame tip and the subsurface flow front is larger at high than at low ambient pressure.

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