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Full Length Article

Experimental investigation on flame spread over diesel fuel near sea level and at high altitude

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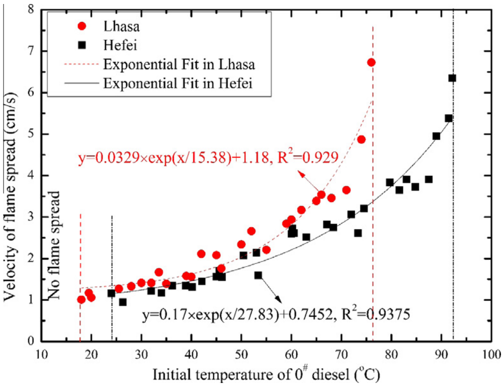
HIGHLIGHTS

- A premixed flame and a diffusion flame exist in flame spread over diesel fuels.
- The larger flame spread rate in Lhasa is predicted by variations in flashpoint and surface tension of liquid with altitude.
- The oil temperature of the subsurface flow is higher at elevated altitude.

GRAPHICAL ABSTRACT

Initial temperature effects on liquid phase-controlled flame spread in Lhasa and Hefei. 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, the flashpoint of a liquid fuel is lower at elevated altitude, so that the fuel vapor is easily volatilized from oil to establish a combustible mixture above liquid surface. Therefore, less time is required for the fuel vapor and air mixture in the elevated altitude satisfying the lean flammability limit. Secondly, the surface tension is predicted to increase with an increase in altitude because less air is absorbed into the liquid fuel in high-altitude areas than in low-altitude areas. The larger surface tension at lower ambient pressure facilitates the propagation of flame across the liquid fuel surface. Thirdly, during the spreading process, buoyancy induced natural convection in gas phase is opposed to the direction of flame propagation, so it is disadvantage for the propagation of flame leading edge. It is well accepted that this buoyant flow should be diminished in a high altitude due to the low air density.



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ABSTRACT

Flame spread over a petroleum-based diesel fuel was experimentally examined at two different altitude conditions (Lhasa plateau 3658 m, and Hefei Plain, 50 m). Based on the test results, the flame appearance, velocity of flame spread and temperature profile near oil surface were comprehensively characterized. Two types of flame are observed during the flame spread: a blue precursor flame and a yellow main flame. The main flame possesses a flame shape under diffusion combustion, whereas the precursor flame belongs to premixed combustion. The liquid temperature initiating flame propagation over diesel fuel is lower in Lhasa, indicating that oils can more easily catch fire at a higher altitude. For a wide range of fuel

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temperatures, the velocity of flame spread at low-pressure region is considerably larger than that near sea level. The intrinsic reasons are predicted by variations in flashpoint and surface tension of liquid fuel with altitude. Theoretical analyses confirm that the flashpoint of liquid fuel decreases with altitude while the surface tension increases. Moreover, the measured temperature distributions normal to the oil surface reveal that the oil surface temperature as well as the liquid temperature inside the subsurface convection flow is larger at high altitude, while the time interval between the flame leading edge and the subsurface convection flow front is smaller.

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1. Introduction

Petroleum-based diesel, also called petrodiesel or fossil diesel is extensively used to supply power to the diesel engines of ships or vehicles [1]. The potential fire hazards for practical usage of diesel fuel in boats and vehicles have drawn great attentions. A pool fire, accompanied by flame spread across a liquid fuel surface, is easily established when the leaking fuel is exposed to an ignition source. 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 may intensify the burning area of pool fire and bring great threats to oil safety. Therefore, it is imperative to study the characteristics and controlling mechanisms of flame spread over liquids.

The speed and behavior of liquid flame spread are dependent on the bulk of liquid temperature relative to the flashpoint of the liquid fuel, at which sufficient flammable vapor mixture is produced to satisfy the lean flammability limit [2]. The preheated (also called as sub-flash or liquid phase-controlled) flame spread regime occurs as the initial fuel temperature is smaller than flashpoint, otherwise the premixed (also called as super-flash or gas phase-controlled) flame spread regime is occurred [3]. The effects of ambient pressure on flame spread are our current interest. Flame spread over liquid fuels on plateau may occur following with the spillage of combustible fuels from long-distance pipes or high-altitude fuel storage tanks owing to cracks or destructions [4]. For instance, a serious oil-spilling fire occurred in Doilungdêqên County in Lhasa, China, on March 31, 2003. The fire spread across a pool of 2 m wide with the total length of fuel area larger than 1372 m, imposing great heat fluxes on the surroundings. It must be accepted that the ambient pressure and the amount of oxygen will reduce with an increase in altitude. These parametric variations may produce distinct fire behaviors between sea-level and high-altitude regions, like in ignition sensitivity, heat release rate, burning rate and flame appearance [5–13].

Our previous papers have tried to specify the effect of altitude on flame spread over liquid fuels [14,15]. It is predicted that the boiling point of oil decreases with an increase in altitude, so that the liquid fuel evaporates more rapidly in an elevated altitude. Then, the velocity of flame spread as well as the frequency of flame oscillation is larger at a high-altitude region. Nevertheless, the essential reasons for the influence of atmospheric pressure on velocity of flame spread have not been understood comprehensively. First, it is known that flame spread over liquid fuel is controlled principally by the surface-tension driven flow for liquid phase-controlled flame spread regime. Thus, analyzing the variation of surface tension of liquid with altitude is a key point to reveal the distinct flame spread characteristics at different altitudes. Second, the theoretical derivation of the relationship between flashpoint and altitude was not presented previously. Furthermore, the gas phase-controlled flame spread behaviors at high altitude are still unclear. In the present study, we will attempt to discuss these questions raised above.

2. Experimental setup

The experimental apparatus, which is introduced in detail in Ref. [14], is plotted in Fig. 1. An open rectangular tray, with the length by width by depth equal to 100 cm × 4 cm × 10 cm was employed. The diesel fuel with different initial fuel temperatures was poured into the tray till the oil surface reached the position of 1 cm from the top edge of the steel wall. The diesel fuel cannot be directly ignited using a pilot flame because of its high flashpoint and low temperature. Therefore, a baffle barrier was used to build a square ignition region (4 cm long) at one extreme of the tray. A small volume of heptane (approximately 2 mL) that was used as an ignition agent, was poured into the ignition region to establish a small pilot flame. The fuel temperature outside this ignition area was kept constant because the liquids inside the baffle barrier were separated from the remainders of the tray. The baffle barrier was removed after the heptane burned up, and then the flame was allowed to spread freely to the opposite end of the tray. When the flame had passed through the entire length of the tray, a noncombustible plate was applied to quench the fire.

All experiments were recorded by a CCD camera (Canon 6D, with the photographing frequency of 30 f/s) which was employed to provide a lateral view of the flame spread process. A huge black plate was placed behind the observation window to enhance the shooting clarity of the flame shapes. The positions of the flame tip versus time were determined using an automatic flame-tracking program, which eliminated the preconception of the operator. Nine 0.1 mm diameter Pt-Rh thermocouples with a response time of 7 ms, were installed in the longitudinal centerline of the tray. 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 mm, 0 mm and −5.0 mm with respect to the oil surface, where the negative value represented the thermocouple below the oil surface.

The ambient conditions and experimental parameters during each test conducted both in sea level and high altitude are displayed in Table 1. The local atmospheric pressure and the absolute amount of oxygen percentage in Lhasa are approximately two-thirds of those in areas near sea level. Air humidity, pool dimension, and environmental temperature were kept constant for both cities, and thus, flame spread behavior should not be affected by these factors. The major experimental variables for the tests are the initial fuel temperature and altitude. To distinguish sub-flash and super-flash flame spread phenomena in both altitudes, the initial temperature of diesel fuel ranges from

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