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Combustion and flame spreading characteristics of diesel fuel with forced air flows

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ABSTRACT

Research on combustion and flame spreading behaviors in a system with forced air flow is crucial for actual fire protection design and scientific meanings. Flame spread tests over sub-flash diesel fuel are conducted by using a self-developed cross flow system, in both opposed and concurrent configurations. Some key parameters to characterize the flame spread performance, namely, flame tilt, flame spread rate, temperature distribution and scale characteristic of subsurface flow are achieved and analyzed. The variations of flame tilt angle in opposed and concurrent flame spreads follow well with Thomas's classical model, and the tangent value of the flame tilt angle is correlated with the wind Froude number with the power value of 0.8. The flame spread rate decreases monotonically with an increase in the opposed air flow velocity. By contrast, the flame spread rate decreases initially and increases afterwards as the concurrent air flow velocity increases, with the critical air velocity of 1.725 m/s. Furthermore, the step temperature rise remains stable in the range of 27 °C to 30 °C for opposed air flows, but it is not pronounced for concurrent air flows. The subsurface flow length increases with opposed air flow velocity, while it becomes irregular under concurrent air flows. The primary contribution of heat transfer to flame spread is liquid-phase thermal convection for opposed or low-speed concurrent air flow conditions, whereas it is flame radiation and gas conduction for high-speed concurrent air flow conditions. The finding of current study is favorable for the fire hazard assessment of spilling hydrocarbon fuel in air flow environments.

1. Introduction

Flame spread over the surface of a liquid fuel is a very complicated issue which involves multiphase flows (such as buoyancy-induced natural convection, vertical diffusion of combustion products and liquid convection in front of the flame) and heat transfer processes (convection, conduction and radiation) [1]. Previous studies mainly concentrated on the phenomena and mechanisms of flame propagation under different initial pool temperatures, and especially on alcoholic fuels [2–5]. Degroote and co-workers [6–8] studied the effects of initial temperature on the velocity of flame spread over methanol, ethanol, propanol and butanol, and classified the flame spread into five regimes: pseudo-uniform, pulsating, uniform, premixed and stoichiometric. In the first three stages, the initial temperature is lower than the flashpoint of the fuel. There is a subsurface flow in front of the flame tip, which plays the role of preheating the unburned cold oil. These stages are called liquid phase-controlled flame spread regime. In the last two stages, the initial temperature is higher than the flashpoint of the fuel. The initial concentration of fuel-air mixture is already above the lean flammability limit before the ignition is achieved. These stages are labeled as the gas phase-controlled flame spread regime, or the premixed flame spread regime.

Though many investigations have been conducted on flame spread over liquid fuels, most of those are focused on flame propagation in quiescent environment. For actual fire problems, the development of fire is usually accompanied by the environmental winds [9–11]. Studying on flame spread behaviors in a system with the forced flow possesses two meanings. For actual fire protection design, the development of flame spread caused by accidental fuel leakage is usually affected by the air flow environment [12,13]. Ambient air flows provide extra oxygen that may accelerate combustion and make the flame propagation more dangerous. For scientific significance, the forced air flow from a fan, wind or ventilation flow will affect the heat and mass transfer of the combustion process, which further influences the flame spread performance [14]. For instance, the flame spread rate is controlled by oxygen transport and fuel vapor movement in front of the

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flame tip when the fire is exposed to an external air stream. The flame spread rate, flame tilt angle, temperature distribution and scale characteristic of subsurface flow are key parameters that characterize the hazard of oil spilling fire. The flame spread rate determines the available escape time, and the flame tilt angle may directly ignite adjacent leaks or induce the increase of flame radiation to surroundings. The temperature distribution and scale characteristic of subsurface flow are essentially related to the heat and mass transfer mechanisms.

Some earlier studies have put emphasis on phenomena and mechanisms of flame spread in forced air flows. Burgoyne and Roberts [15] discovered that the flame spread rate changed slightly as the air velocity was smaller than 100 cm/s, no matter what the air flow direction was. Above 100 cm/s, otherwise, both the opposed and concurrent air streams had a more profound effect. Suzuki [16] investigated flame spread across super-flashpoint methanol surface in an air stream by using a high-speed schlieren photography. For opposed flame spread, the flame spread rate slightly decreased with an increase in air flow velocity until the air velocity was equal to the flame spread rate in quiescent environment. For concurrent flame spread, the flame spread rate remained constant until the air velocity approached to the no-wind flame spread rate, and then the flame spread rate was exactly equal to the air flow velocity. Ross [17] supposed that the overall flame spread rate was not affected by the opposed air flow velocity under both the normal and micro gravity conditions. Kim and Sirignano [18] revealed that the flame spread rate was enhanced by the opposed forced flow owing to the increase in the supply rate of fuel vapor and air mixture. The work of Ali et al. [19] indicated that the flame spread rate slightly decreased as the concurrent air flow velocity increased. Zanganeh and Moghtaderi [20–22] discovered that the velocity of flame spread for oil-soaked sand decreased rapidly with the increase of air flow velocity under both opposed and concurrent air flow configurations.

The temperature distribution of oil surface is affected by the forced air flow, which further influences the flame spread behaviors. Ross [23] found that the air flow velocity affected preheating phenomenon of flame spread. A twinning thermal vortex in liquid-phase surface flow occurred for low-speed concurrent air flow, while the subsurface flow lost its twinning vortex structure as the concurrent air flow speed increased. Later, Zamashchikov [24,25] reported that the temperature increasing rate of the fuel surface decreased as the forced air flow velocity increased.

Although a number of previous investigations have been conducted, some characteristics of flame spread in the air flow environment are still unclear. First, the influence of the external air flow on flame spread rate is contradictory, i.e., some researchers suggest that the rate is decreased by the opposed air stream, while others object to this point of view. Second, none of the previous researches reveals the flame inclination behavior in the forced air steam environment. Third, the temperature distribution of fuel surface is very crucial for flame spread but less work has been carried out. The present research aims at discussing the above-mentioned issues. In order to achieve these objectives, a series of laboratory-size tests and analyses are performed on flame spread over sub-flash diesel fuel. A self-developed cross flow system is employed to conduct flame spread tests in both opposed and concurrent environments.

2. Experimental apparatus

The experimental apparatus is depicted in Fig. 1. All tests were conducted in the room temperature (~20 °C). An open stainless steel tray with the size of 100 cm long by 4.4 cm wide by 2.5 cm deep was used for the flame spread tests. This tray was employed in our earlier work in the quiescent environment [26], so that the present results could be compared with the previous investigations. Diesel fuels were heated to the desired temperature by an electric heating plate and then they were transferred into the experimental tray. The fuel layer thickness was calibrated as 2.0 cm to prevent the overflow of oils in the air flow environment. The fuel layer thickness corresponded to the deep-pool condition [27], so that the flame spread should not be influenced by the bottom of the tray. The tray was put into a transparent flow duct. The internal dimension of the flow duct was 75 cm by 75 cm, and 140 cm long. The flow duct was made up of 0.8 cm thick Pyrex material which was resistant to the high temperature and the interference from the external air flow, i.e., walking out, or operating experimental instruments by the experimenters.

The design of the air flow tunnel referred to Hu et al.'s work [28]. A 1.1 kW axial flow fan with the diameter of 56 cm was used to generate the air stream. The maximum volume of air moved by the fan was 11,800 $\mathrm{m^3/h}$, and the total pressure was 230 Pa. A great number of 12 mm diameter PVC pipes were installed in front of the fan to constitute a 24 cm-long square honeycomb rectifying device. The wall thickness of these PVC pipes was very small (1 mm), to reduce the attenuation of the air flow. The air flow velocity generated by the fan gradually decreased with the increase of the distance from the outer border to the rotation shaft of the fan. Therefore, the length of the PVC pipe was decreased accordingly from 24 cm in the outer border of the rectifying device to 12 cm in the center. A 25 cm long transition section was set immediately downstream of the rectifying section. A Kanomax KA12-type anemometer that possessed four-probed channels was employed to measure the air flow inside the tunnel. The measurement accuracy of this anemometer was ± 0.01 m/s. The anemometer was placed at 5.0 mm above liquid surface. The anemometer was placed at different horizontal positions to check the variation of the air flow velocity in the longitudinal center line.

A 4 cm-long bottomless square metal segment was located at one end of the tray to establish an ignition zone. The fuels could swarm into the ignition zone through the bottom of the segment. Diesel fuel could not be ignited directly owing to its high flashpoint, so that a volatile fuel, heptane was poured onto the oil surface and initiated as a pilot flame. Once the heptane was burned out, the ignition segment was removed to allow the flame to move freely towards the remainder of the tray. At the end of each experiment, the burning tray was covered by a noncombustible gypsum plate. The fire was put out owing to the lack of oxygen. A CCD camera was positioned on the lateral side of the tray to allow luminescent flame visualization. In order to highlight the brightness of the flame, a black plaster board was placed approximately at 0.5 m from the opposite side of the tray. An infrared thermal camera (IR) was fixed at 1.0 m above the oil surface to record the temperature evolution of the oil surface. The emissivity of diesel fuel was 0.95 [29]. A Sartorius electronic balance was put at the bottom of the whole experimental device to measure the mass burning rate during the flame spread process. Three K-type fine-thermocouples were constituted to monitor the temperature distribution of the fuel surface. The horizontal distance of adjacent thermocouples was 10 cm. The diameter of thermocouple was 0.5 mm and the responding time was 100 ms.

The forced air speed changes with the frequency modulation of the transducer which controls the rotational speed of the axial flow fan. The measured data of the air flow velocity versus the transducer frequency are displayed in Fig. 2. After a linear fit, the relationship between the velocity of air flow and transducer frequency yields,

$$u = 0.025 + 0.17f, R^2 = 0.99 \tag{1}$$

where u is the velocity of air flow, and f is the transducer frequency. In the present test, the maximum value of transducer frequency is 12 Hz, so that the free air flow velocity ranges from 0 m/s to 2.065 m/s. Taking the tray length and the maximum air velocity as the characteristic length and characteristic velocity respectively, the Reynolds number, $Re = \rho_\infty ul/\mu$, is predicted as 1.5×10^5, where ρ_∞ and μ are the density and dynamic viscosity of air. As the Reynolds number for laminar-turbulent transition in flat plate flow is approximately 5.0×10^5 [30], the air flow is essentially laminar in this range of free air flow velocity.