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Experimental study on characteristics of flame spread over diesel and n-butanol pool fires in tunnel

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ABSTRACT

Comparative tests were conducted to investigate the flame spread characteristics of a typical hydrocarbon fuel mixture (0# diesel) and a typical pure alcohol fuel (n-butanol) in a reduced-scale (1:10) tunnel model. Experimental data with regard to flame spread appearance, flame spread rate, temperature profile, and subsurface convection flow were obtained and discussed in this study. Results showed that: (1) The diffusion flame of n-butanol propagated in a forward-stop-forward pattern, while diesel fuel pulsated in a forward-back-forward manner with less stability. The flash flame of diesel appeared periodically with significant higher spreading velocity than the enduring flash flame of n-butanol. (2) The average main flame spread rate of n-butanol was faster than that of diesel fuel, whereas the transient flame spread rate showed an opposite trend. (3) No sensitive difference was found in surface temperature profile between two fuels, but n-butanol retained higher vertical temperature due to its higher flame height than diesel. The infrared images discovered that the subsurface convection flow of diesel had a larger size and noticeable temperature gradient. Diesel burned with more luminous flame and denser soot than n-butanol, owing to its more complex fuel components.

1. Introduction

Fuel leakage accidents are common phenomenon in tunnel transportation, with high potential to cause catastrophic tunnel fire. Petroleum product, such as diesel fuel, is world widely used in modern transportations. Compared with flame spread over solid fuels, the spreading flame across a liquid surface carries greater risks due to the shorter ignition time as well as the faster flame spread rate. The study of liquid fuel flame spread behavior is crucial to evaluate the fire characteristics, contributing to fire precaution and the extinguishment in early fire stage (Ji et al., 2016; Li and Chow, 2000; Li et al., 2016a,2016b; Delmastro et al., 2016).

The behavior of flame spread over liquid fuel has been the subject of study by numerous researchers, including experimental study (Ross and Miller, 1996; Miller et al., 2000; Degroote and Garcia-Ybarra, 2005), theoretical analysis (Burgoyne and Roberts, 1968; Williams, 1977) as well as numerical models (Di Blasi et al., 1991; Kim et al., 1998). Initial temperature was considered as an important factor which considerably influence the flame spread behavior. Liquid phase-controlled flame spread regime or gas phase-controlled flame spread regime was classified in relation to the value of initial fuel temperature, whether it was lower or higher than the fuel's flashpoint (Akita and Fujiwara, 1971). White et al. (1997) discovered that the critical transition temperature from liquid-phase-controlled to gas-phase-controlled was approximately 15 °C higher than the flashpoint of aviation kerosene, where the similar conclusion (17 °C) was proposed by Li et al. (2016a, 2016b) in a recent experiment. The four common spread patterns (pseudo-uniform, pulsating, uniform, and super-flash) observed for alcohol by Akita (1973) were also demonstrated by Tashtoush et al. (1998) for flame spread over JP8. A gas-phase recirculation cell ahead of the main flame front was firstly discovered by Glassman and Dryer (1981), which was further confirmed by later researchers (Di Blasi et al., 1991; Schiller et al., 1996). The formation of a gas-phase circulation cell was believed to be the necessary condition for flame pulsation (Schiller et al., 1996), rather than the subsurface convection flow (Glassman and Hansel, 1968). The flame spread velocity varied with pool dimensions in liquid-phase controlled flame spread regime while it made no sense in gas-phase controlled (Ross, 1994). The previous studies demonstrated that the flame spread behaviors over the liquid fuels were affected by factors like initial fuel temperature (Degroote and Garcia-Ybarra, 2000; Degroote, 2007; Ito et al., 1991), pool dimensions (Takahashi et al., 2005; Li et al., 2015a), ambient wind (Cai et al., 2003), gravity condition (Miller et al., 2000; Miller et al., 2002), fuel types (Cai et al., 2003; Li et al., 2017), oxygen concentration (Takahashi et al., 2007)

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and atmospheric pressure (Li et al., 2015b).

However, it should be noted that the majority of previous studies focused on investigating the flame spread characteristics over alcohol and hydrocarbon fuels with single component, such as methanol, ethanol and butanol (Ross and Miller, 1996; Miller et al., 2000; Kim et al., 1998; Schiller et al., 1996; Ross, 1994; Degroote and Garcia-Ybarra, 2000; Miller and Rose, 1992; Konishi et al., 2000). Very little research has addressed the multi-components fuels like diesel fuel, which was widely used in modern transportations and had more complex combustion characteristics (Ji et al., 2016). Combustion and evaporation characteristics for multi-component fuels have been studied by some researchers (Arias and Rosner, 2003; Gopalakrishnan and Abraham, 2004), with most of theoretical analyses but rare experimental study. Comparative tests were made on single- and three-mixed multi-component fuels to investigate the effect of fuel properties, such as liquid density, viscosity, latent heat of vaporization, on the evaporation process (Myong et al., 2006). It suggested that liquid phase length would be similar if fuel density is same between single-and multi-component fuel. Though it is similar, evaporation, fuel-air mixing and diffusion process would be different due to different boiling point, latent heat of vaporization and diffusivity.

Except combustion characteristics, flame spread behavior could be largely influenced by fuel types, due to different fuel properties. As suggested by Miller and Ross (1992), the pulsating flame spread across alcohol (single-component fuel) is a coupling and periodical switching process between a crawling and a jumping phase. Whereas the flame spread of aviation kerosene (multi-component fuel) showed a totally different forward-back-forward pattern (Li et al., 2015b). Some outstanding issues in relation to the above two different pulsating manners considering different fuel types need reexamined and further verified by experimental data. Once the fuel properties can be assessed according to the flame spread characteristics, the effective fire precautions can be applied to prevent fires in advance (Ji et al., 2016). On the other hand, almost all the previous studies were performed in open space. Due to the effect of confined structure of tunnel, the characteristics of flame spread in tunnel fires will be different from those in open space (Chen et al., 2017; Carvel et al., 2001). Accurate data regarding flame spread over liquid fuel in confined space like tunnels are extremely lacking but highly required.

A series of experiments were conducted in a reduced-scale (1:10) tunnel model to investigate flame spread characteristics over liquid fuels. Comparative tests were performed on a typical hydrocarbon fuel mixture (0# diesel) and a typical pure alcohol fuel (n-butanol). These fuels were chosen because they have different flash points and fuel properties. Accurate data pertaining to the flame spread velocity, the temperature profile and the flame pulsating appearance were obtained and discussed. This paper aims to provide a better understanding of flame spread characteristics and pulsating behavior on different liquid fuels, contributing to fire precaution, fire extinguishment and fire rescue work.

2. Experimental setup

As shown in Fig. 1, the experiment was conducted in a reduced-scale (1:10) tunnel model, with dimension of 16.5 m (length) × 1.3 m (width) × 0.65 m (height). The tunnel side walls were made of fire-resistant glass material for easily observing the experimental process. A size of 105 cm × 10 cm × 3 cm (length × width × height) fuel pan was placed in the tunnel center axis. The detailed structure of the fuel pan was clearly illustrated in Fig. 2. A 5-cm-long ignition region, separated by a steel plate, was set at the left side of the pan. During each test, liquid fuels (0# diesel or n-butanol) were firstly poured into the fuel pan, and then ignited by a small volume blend of diesel (3 ml) and ethyl alcohol (2 ml) in the ignition region. Experimental conditions and fuel properties are listed in Table 1. The total length of flame spread process was 100 cm. Each test was repeated three times to minimize the discrepancies less than 10%.

An infrared thermal imager was used to monitor the temperature profile of the flame front. A digital video camera was utilized to record the flame spread process. Thirty-three K-type micro-thermocouples were placed at the centerline of the liquid surface and the upper zone, with a spacing of 5 cm. The ambient temperature (12–14 °C) was lower than the flash point of the 0# diesel (65 °C) and n-butanol (38 °C), thus the results of this paper revealed the characteristics and mechanisms of flame spread across sub-flash liquid fuel surface. That is, the liquid-phase controlled regime or pulsating regime (Degroote and Garcia-Ybarra, 2005).

3. Results and discussion

3.1. Flame appearance

Fig. 3 compares the sample images of flame spread over 0# diesel and n-butanol. It can be seen that the flame was composed by two different parts, a weaker blue premixed flame (flash flame) in the front of the flame area and a brighter yellow diffusion flame (main flame) in the trailing portion of the flame. The main flame existed constantly for both fuels, while significant difference could be identified in the flash flame characteristic between these two fuels. From Fig. 3(a), it could be seen that the flash flame of 0# diesel did not always exist during the flame spread process, but appeared and disappeared periodically. Compared to 0# diesel, the flame spread process of n-butanol presented a more stable pulsating pattern, as shown in Fig. 3(b). The blue flash flame remained continuously at the front of the yellow main flame.

To reveal the difference in flash flame appearance between 0# diesel and n-butanol, Fig. 4 illustrates the flame spread mechanism. At first, the liquid evaporation rate was very slow, due to low fuel temperature. A subsurface flow slowly developed in front of the diffusion flame, which was driven by coupling effect of surface tension and buoyancy flow. As time elapsed, the flame front was gradually preheated by the subsurface flow. The liquid evaporation rate increased, owing to increasing temperature. Then the flame propagated forward when the concentration of fuel vapor reached the lean flammability limit and the fuel temperature reached the flash point, that is, the flash flame was formed. Finally, the flash flame suddenly retreated and disappeared for 0# diesel since the combustible mixture was consumed, but it lasted constantly for n-butanol. The significant difference observed for flash flame between two fuels is primarily due to different temperature of flash point. The n-butanol had a lower flash point (38 °C) than 0# diesel (65 °C), thus it was more difficult for 0# diesel to reach the lean flammability limit, while n-butanol can easily maintain the combustion owing to the low flash point.

The topic of flash flame had been reported in the literatures. Schiller et al. (1996) considered the flash fire as the premixed combustion flame. Instead, Remick (1981) assumed that the flash fire was the diffusion combustion flame in a numerical model. So does the flash flame belong to premixed combustion flame or diffusion combustion flame? The average flash flame spread rate of 0# diesel was 64 cm/s in this study, where similar results were provided by Li et al. (2015c) in investigating the flash flame spread rate of JP8 (55–70 cm/s). Ross (1994) demonstrated that the maximum spread velocity of the diffusion flame was about 10 cm/s. Therefore, the flash flame of 0# diesel essentially belonged to the premixed combustion flame, whose spread velocity was considerably faster than the diffusion flame. The average flash flame spread rate of n-butanol was 2.4 cm/s, indicating that the flash flame of n-butanol was essentially a diffusion combustion flame.

Fig. 5(a) presents the flame image of 0# diesel and n-butanol during the spread process, while the completely spread flame image is shown in Fig. 5(b). It can be seen that the flame of 0# diesel was more luminous than n-butanol, with constantly lower flame height. This is due to that the chemical structure of n-butanol contains oxygen atoms, resulting in improving combustion efficiency and decrease soot