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Experimental study on the vapor explosion process of a water drop impact upon hot molten-ghee surface☆

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ABSTRACT

In order to deepen the understanding of the mechanisms of liquid pool fire suppression with water mist/spray, preliminary experimental studies on vapor explosion as a water drop with or without additives impacting upon the hot molten-ghee surface were carried out. Pure water and water with 5.0% NaCl and 2.2% AFFF drops, and the molten-ghee oil with 393 K, 433 K and 493 K temperature were tested. The impacting processes were recorded using a high-speed digital camera with 2000 fps. The results show that when the water drops with 5.0% NaCl ($We = 299$) impact on a 493 K molten-ghee surface, a violent vapor explosion occurs rapidly at the fuel surface accompanying with splash of a liquid line and then a second violent vapor explosion occurs, while for the impacting of a pure water drop ($We = 258$), several bubbles firstly formed and then brief violent vapor explosion occurred. But for the cases of water drop with 2.2% AFFF ($We = 652$), there is no violent vapor explosion occurring during the whole process. The time interval between two vapor explosions of pure water drop at the temperature of 493K, 533K and 573K decreases with the increasing of fuel temperature. The first explosion time, the interval of time between two vapor explosions and the radius of first vapor explosion decrease with the order from pure water drops, water drops with 5% NaCl to water drops with 2.2% AFFF. In addition, the height of the liquid jet would be enlarged when the liquid fuel temperature increases, especially to the cases with additives. The vapor explosion behavior of the water drop with additives would be weaker than that of pure water drop, which should be valuable for suppressing liquid fires by water based technologies.

1. Introduction

Dynamic processes of a drop impact upon different surfaces are important to several technical applications, such as combustion engine, oil extraction, surface cooling, fire suppression, thermal spray coating, etc. (Strotos et al., 2008; Vaikuntanathan et al., 2010; Chen and Wang et al., 2011). The behavior of a drop after collision with the hot surface depends on the physicochemical characteristics of the drop as well as those of the surfaces themselves. Manzello and Yang (2002) pointed out that the different initial impact velocities and surface temperatures have important effects on forming jet height, and the critical Weber number of splash. John and Issam (1997) found that the surface roughness has important effects on heat transfer regimes and dynamic process of droplets impacting on hot metal surface, which are also related to surface temperature and droplets Weber number. The studies on the water drop impacting on wood surfaces by Chen and Wang (2011) showed that the critical impact Weber number of droplet splashing decreases as basic density of the wood surface increases.

The above studies mostly focused on the droplets impacting on solid surface. Water mist has been regarded as the better substitute of conventional means for liquid pool fire suppression (Wang et al., 2002; Huang et al., 2011; Zhu et al., 2017), few study considered the microcosmic mechanism, such as the dynamic impact process as a droplet impinging upon a hot liquid fuel surface. Cai (1989) investigated the collision of a water drop on water, i.e., the impact of a water drop with various velocities, ranging from 0 to 600 cm/s, on to a water surface. Molten-ghee as a typical fuel applied in many Chinese historic buildings, such as the Potala

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Palace in Tibet, has been concerned as a fire hazard, although it is a high flash point hydrocarbon fuel. Chen et al. (2011) found that vapor explosion occurred during the pure water drop impacting upon hot molten-ghee and peanut oil surfaces, but they did not consider the cases of the water drop with additives. Lan et al. (2015) studied on the vapor explosion process of a water drop with additives impacting upon hot alcohol surfaces, but they did not consider the cases of the hot molten-ghee fuel surface with different temperatures.

Additives usually are mixed into water to improve the efficiency of water based fire suppression technologies. Therefore, a series of experiments are conducted to study the dynamic process of water drops with or without additives impacting upon molten-ghee surface which with different temperatures. The results would be helpful to reveal the pool fire suppression mechanism with water mist/spray.

2. Experimental apparatus and materials

The experimental apparatus of this study is similar as that described elsewhere (Chen et al., 2011), which consists of a drop generator system, an illumination system, a heater system and a high-speed video camera. As discussed by the previous research works (Cong et al., 2004; Joseph et al., 2013; Rotander et al., 2015; Wang et al., 2009a), the additives, such as NaCl (Sodium chloride) and AFFF (Aqueous Film Forming Foam), may have important effects on water based fire suppression technologies. So the additives of 5%NaCl and 2.2%AFFF which were tested with better efficiency are considered in this work.

The surface tension of the drops was previously measured with a SL201 Surface Tension Meter. The initial drop diameter is determined by,

$$D_0 = 2\sqrt{N_p a/\pi} \tag{1}$$

where N_p is pixel number of the drop spread area and a is the area of each pixel of the imaging device. The initial diameter of the pure water drop and 5%NaCl additive water drop are about 2.4 ± 0.1 mm, while the drop with 2.2%AFFF is about 1.8 ± 0.1 mm.

The drops falling can be considered as a free fall and the droplet impacting velocity at the fuel surface can be calculated by the formula of $V = \sqrt{2gh}$ through neglecting the air resistance, where g is the gravity acceleration, h is the distance between the syringe needle and liquid fuel surface. The distance of h in current study is 40 cm, so the droplets impacting velocity can be calculated to about 2.8 m/s. The Weber number of the drop, which is the ratio of kinetic energy to surface energy of the impinging droplet can be determined by (Hsiao et al., 1988),

$$We = \frac{\rho V^2 D}{\sigma} \tag{2}$$

where ρ is the droplet density, V is the droplet impacting velocity, D is the droplet initial diameter, σ is the surface tension of the droplet. The detail properties of the drops are listed in Table 1. The calculated Weber numbers of the three kinds of drops are 258, 299, and 652, respectively.

In practical liquid pool fire, the fuel surface temperature is approximate to the boiling point of the fuel. And during the fire suppression, the large droplet may penetrate the fire plume and then reach the hot fuel surface, which would enhance the flame combustion due to the hot fuel splashing. Therefore, the hot molten-ghee fuel with temperature of 393 K, 433 K and 493 K were tested. All tests were conducted under ambient temperature and pressure. Each test was repeated for three times to insure its reliability.

Table 1
Initial diameter, surface tension and density of the different drops.

Drop type	Diameter (mm)	Surface tension (mN/m)	Density (kg/m^3)
Pure water	2.4 ± 0.1	72.0	1.0×10^3
With 5% NaCl	2.4 ± 0.1	59.4	1.05×10^3
With 2.2% AFFF	1.8 ± 0.1	21	0.97×10^3

3. Results and discussion

3.1. The dynamic process of droplet impacting on hot molten-ghee fuel surfaces

When a cold liquid drop impacts on a hot fuel surface, a vapor explosion may occur due to the rapid evaporation of the drop. Such an explosion has been termed as vapor explosion, explosive boiling, or rapid vapor explosions (Reid, 1983). Fig. 1 shows the results of a pure water drop impacting on molten-ghee surface with different temperatures.

As shown in Fig. 1(a) and (b), there is no vapor explosion for pure water drop impacting on the hot fuel surface with temperature of 393K and 433K. In process of impacting, a crater is formed firstly, and then a small liquid column is formed, and finally moves down to the bottom of the fuel. Fig. 1(c) shows that the results of pure water drop impacting on the hot fuel surface with temperature of 493K, where distinct vapor explosion behavior occurs. At the initial stage, a crater and a relative large liquid column are also formed. After that, a larger liquid bubble is first formed at the bottom of the fuel and then splashed to several daughter drops. At about 1774 ms, the first vapor explosion occurs and many small pure water droplets are formed. At the same time, the liquid splashed at the fuel surface. Then the similar dynamic process of the droplets impacting would be repeated several times, but the dynamic and explosion become more violent. The cause of the vapor explosion may be due to the evaporation of the cold pure water droplet within the hot liquid fuel, which is that the evaporation of pure water droplet produced many small pure water droplets and then move up to the fuel surface, and ejecting oil in any directions.

Fig. 2 shows the results of water drop with 5%NaCl impacting on the molten-ghee surface with different temperatures. There is also no vapor explosion behavior for water drops with 5%NaCl impacting on the hot fuel surface with temperature of 393K and 433K, as shown in Fig. 2(a) and (b). Similarly, at the initial stage, a crater and liquid column are formed firstly, but the maximum height of liquid increased obviously comparing to the cases of pure water drop impacting on hot fuel surfaces. Although the vapor explosion occurs to the case of water drop with 5%NaCl impacting on the hot fuel surface with temperature of 493K, but the extent of explosion becomes relatively weaker comparing to the cases of pure water drop. Therefore, it can be seen that the water drop with additive of 5%NaCl has a relative weak dynamic behavior when impacting on hot fuel comparing to the pure water drop, and it would show better effect in liquid pool fire suppression.

Fig. 3 shows the results of water drops containing 2.2%AFFF impacting on the molten-ghee surface with different temperatures. The initial stage is similar as the cases of pure and 5%NaCl water drop, but the height of the liquid column is small. Only for the case of the 493K fuel, a bubble is formed, but it does not sink into the bottom of the breaker. Only the weak vapor explosion occurs to the case of 493K fuel surface about 1.3 s after the impact. These may be mainly caused by the lower surface tension of the water drop

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