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Experimental study of spray deflagration mode in an enclosed compartment

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ABSTRACT

Spray explosions can bring serious hazards to the personnel and equipment, and hence the related safety issues deserve more detailed investigations. In this study, a series of spray deflagration experiments were performed in a 3 m × 3 m × 3.4 m enclosed compartment. Two modes of spray deflagrations were observed: strong and weak deflagrations. It was found that strong spray deflagration induces a large flame ball and causes the flame to quench within a second, while weak spray deflagration induces a spray flame with a period of tens of seconds. The overpressures in the strong spray deflagration are significantly larger than those in the weak spray deflagration. Because of the pulsations of the spray flame, the induced overpressure has more high-frequency fluctuations in the case of weak spray deflagration. However, no high-frequency overpressure fluctuations were observed in the case of strong spray deflagration. The deflagration strength is significantly determined by flow rate and ignition distance.

1. Introduction

Studies on a large number of accidents have shown that explosions of fuel spray and its vapour bring serious hazards to the personnel and equipment in chemical industries (Bai and Wang, 2015; Atkinson et al., 2017) or on ships (Su et al., 1998). Such hazards are likely to result from the spray release of highly pressurized fuel or the release of superheated fuel from parts such as broken pipe, unsealed flange, or worn-out valve etc. Spray release leads to the formation of a hybrid two-phase fuel-air mixture and causes droplet dispersion and evaporation, turbulence, formation of ignition zones etc. This adds considerable complexity to the problem of containing the spray explosion hazards. Therefore, spray deflagration hazards need to be considered seriously.

Spray deflagration is a complex phenomenon involving the injection of liquid fuel droplets, atomization, dispersion and evaporation of the fuel, chemical reaction of the fuel vapour with the oxidizer, etc. This phenomenon, especially the one in an enclosed compartment, has still not been investigated in detail. Several related investigations are described here. For example, Kim et al. (2007), Liu et al. (2003) and Su et al. (1998) conducted experiments on deflagration-type explosion of gasoline in a small compartment. He reported that the deflagration intensity is determined mainly by the ignition delay period, and the duration of the fire induced by deflagration. The composition of the fire gas generated in the explosion is determined by the total discharged fuel quantity. He also concluded that the deflagration-type explosion in an enclosed compartment poses a serious threat, even if only a small quantity of fuel is involved, since this explosion can induced a fire with the maximum overpressure of 2300 Pa. Hoover et al. (2006) from the U.S. Naval Research Laboratory reported that even the fuels having low volatility, such as 2190 TEP hydraulic fluid sprays, can result in a significant explosion in a test enclosure. The smaller droplets can lead to a larger deflagration overpressure, and the measured maximum overpressure in 22 experiments was 6.4 kPa. Willauer et al. (2006) studied the effect of the extinguishers on spray deflagration. It was found that the deflagration intensity is determined by the droplet size, number density, fuel flow rate, linear velocity of the droplet, etc. The maximum overpressure was approximately 5.5 kPa in the experiment. Chan and Jou (1988, 1989)

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focused on the effect of spray droplet size on spray deflagration, and concluded that the flame propagation speed increases initially to a maximum value and then decreases as the droplet size is reduced at a constant equivalence ratio. This can be considered as the transition from heterogeneous to homogeneous combustion of the fuel spray. Bai and Wang (2015) investigated spray explosions of diethyl ether with various concentrations in a 20 L spherical vessel. It was found that spray particle size has significantly effect on the explosion pressure, temperature, and flammability limits.

The above studies (Kim et al., 2007; Liu et al., 2003; Hoover et al., 2006; Willauer et al., 2006) mainly reported that spray deflagration can be induced with fuels having high or low volatility. Because extinguishing systems were employed in the experiment, the deflagration was not fully developed. In the experiments conducted by Chan and Jou (1988, 1989), the spray was not continuously released. Compared to the real compartment, the 20-L spherical vessel in Bai et al.'s experiments (Bai and Wang, 2015) is very small and the related results need to be further verified before being applied to the real scenarios. Moreover, the details regarding the deflagration mode, flame evolution and the maximum overpressure are still not known for continuous sprays. Therefore, in this study, spray deflagration experiments were carried out in a 3 m × 3 m × 3.4 m enclosed compartment, to study these problems and address the key phenomena or mechanism of spray deflagration.

2. Experimental setup

The spray deflagration experiments were performed in a completely enclosed compartment. The compartment has the size of 3 m × 3 m × 3.4 m, as schematically shown in Fig. 1. Four 10-mm-thick fire-resistant glass pieces are used to cover the entire front wall for view through a frame. The other walls are made of steel plates with a thickness of 8 mm. An access door with dimensions of 0.6 m × 0.6 m is provided on the side wall, so that it will be convenient to replace the nozzle, clean the glass, and locate the spark plug. The door is sealed to maintain the compartment airtight

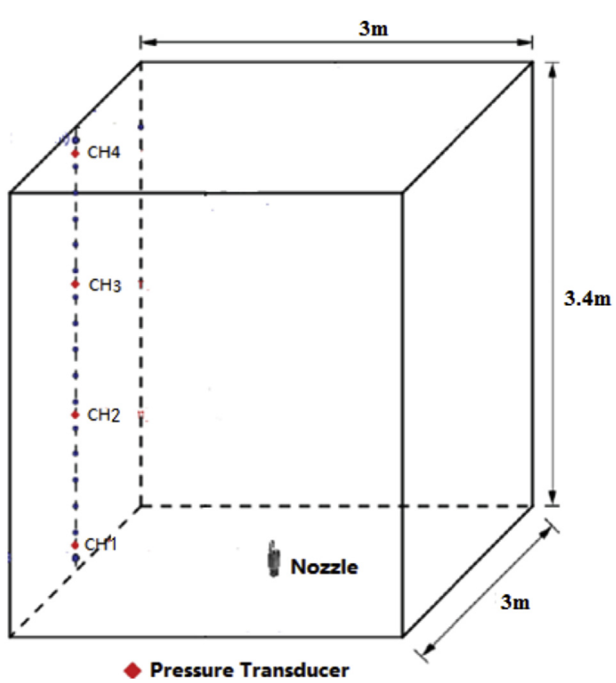

Fig. 1. Schematic of experimental compartment.

during the fire experiments.

In the experiments, one spray nozzle is located at the centre of the bottom plate. The type of nozzle used is BETE P-series (P40, P80), manufactured by BETE Fog Nozzle Inc. Table 1 presents the nozzle parameters. The droplet diameters vary in the range of 25–400 μm, and the spray angle is 90°. Because of the overpressure in the compartment, generated by the spray flame or deflagration, the injecting pressure less than 1.2 MPa is chosen in the experiment, considering safety. For the spark ignition system, a spark plug set above the nozzle is triggered by a high-voltage pulse from the AC power source. The spark has a pulse rate of 10 Hz, and each spark releases approximately 6 J of energy, to ensure successful ignition of the fuel spray. It may be noted that the spark is initiated before the fuel is injected. Additionally, a camera with a frame rate of 100 fps is set in front of the compartment for visualisation of the spray deflagration phenomenon. Four pressure transducers are mounted on the side wall at heights of 0.2 m, 1.2 m, 2.2 m, and 3.2 m.

3. Experimental results and discussions

3.1. Weak spray deflagration

Fig. 2 shows the sequence of flame images using BETE P40 nozzle at an injecting pressure of $P_j = 0.8$ MPa and flow rate of 1.69 L/min, highlighting the deflagration phenomenon and the evolution of the spray flame in the enclosed compartment. It should be noted that the distance D_{ig} between the nozzle and the ignition point is 0.2 m, and the ignition is initiated prior to the release of the spray. Fig. 2 (a) shows the flame images after the spark ignites kerosene spray droplets. A relatively small flame ball is formed around the spark plug and is held up by the spray. It can be seen that at this time, the spray envelop is relatively small. In other words, the region filled with the droplet-air mixture is small. The flame propagates in the premixed or partially premixed droplet-air mixture. Due to limited mixture region, the flame is not accelerated to a very high level. In Fig. 2 (b)–(e), four flames can be seen having nearly cylindrical appearance; these are associated with the spray droplets punching through the gaseous flame enveloping the bulk of the spray. Furthermore, the flames emit prominently luminous white light. The striking difference from the gaseous flames is that the volume of the flame shown in Fig. 2 (b) is approximately twice that of the steady spray flame shown in Fig. 2 (c)–(e); further, this flame lightens the entire compartment. This is attributed to the two-phase spray deflagration. Another significant difference is that the yellow diffusion flames cover the tip of the spray flames in Fig. 2 (c)–(e), but are not observed around the spray flames in Fig. 2 (b). Hence, this spray deflagration can be considered to be weak.

Another striking difference to be noted is that in Fig. 2 (f), the spray flame is stretched, and its tip clearly touches the ceiling wall. Because oxygen is limited in the closed compartment, the fuel-controlled combustion is shifted to oxygen-controlled combustion

Table 1
Nozzle parameters.

Nozzle No.		P40	P80
K factor		0.638	2.46
Orifice diameter (mm)		1.02	0.711
Coverage Diameter (mm)		610	460
Spray Height (mm)		305	600
Flow rate (L/min)	0.6 MPa	1.43	5.50
	0.8 MPa	1.69	6.51
	1.0 MPa	1.91	7.38