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Experimental studies on the extinction of methane/air cup-burner flames with gas–solid composite particles

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ABSTRACT

Fire suppression effectiveness of gas–solid composite particles consisting of 2-bromo-3,3,3-trifluoropropene (BTP) and zeolite 13X was evaluated on a cup-burner apparatus with coflowing methane/air flame. A series of composite samples with the weight concentration of BTP (ω) varying from 1.0 to 12.0% were tested. For comparison, extinction measurements were also conducted using neat BTP and zeolite 13X, respectively. Results indicated that the composite particles on a mass basis were much more effective than that of BTP and zeolite 13X used alone. A synergistic effect was exhibited by the BTP/zeolite 13X composites, which was affected by the ω values. Furthermore, significantly reduced HF concentrations (<70 ppm) were detected in the suppression tests with the composite particles, in comparison to that of neat BTP (1436 ppm). The composite particles extinguished the flame through a blowoff process, in which the flame base oscillated, detached from the cup-burner rim and extinguished eventually. Mechanism of the composite particles in suppressing the cup burner flame was studied.

1. Introduction

Dry powder are widely used to suppress various types of fires for their high efficiency, environmental friendliness and low cost [1,2]. Generally, the fire suppression effectiveness of dry powder was evaluated by fire tests in different scales. For example, Krasnyansky [3] assessed the fire suppression performance of mixed-phase agents of 5 μm ABC dry powder and nitrogen in combination with halon 2402 in a 100 m^3 chamber and a tunnel with a length of 180 m and a cross section of 3 m^2. Ewing [4] studied the extinguishing performance of several kinds of dry powder using n-heptane diffusion flame in a 422-liter chamber. Adam [5] examined the performance of non-pyrotechnically generated aerosols fire suppressants in an 8 m^3 chamber. These fire tests in relatively large scale gave direct check on the suppression efficiency of dry powder, however, they were usually expensive and difficult to run. Furthermore, there were many factors affecting the suppression efficiency, making the results from different experiments hard to be compared. Therefore, researchers turned to conduct the tests in well-controlled, simple, and inexpensive small scale flame configurations, such as counter flowing diffusion flame, premixed flames and coflowing diffusion flames, etc. [6–9].

Among these flame configurations, the cup burner flame with features similar to real fires, was considered suitable for studying the effectiveness of fire suppressants [10]. The cup burner flame consisted of flame segments subjected to various strain rates and exhibited flame flickering and tip separation, which then affected the air and agent entrainment into the flame zone [11]. It was proved that the cup burner flame was more difficult to extinguish than full scale fires of the same fuel, regardless of whether the fires were pool, spray, running, cluttered or obscured [12]. From a safety point of view, the agent requirements for extinguishment of the most hazardous situation of cup burner flames could be scaled to requirements in actual fires [9]. As a result, the cup burner served as a scale model of real fires for evaluating the agent effectiveness [13]. Great faith has been placed in the cup-burner minimum extinguishing concentration values, which served as the basis of many safety code and design practices.

Conventionally, cup-burner was used by industry as a standard apparatus for ranking the suppression effectiveness of gaseous agents, as specified in ISO 14520 and NFPA 2001 standards [14,15]. Recently, cup-burner has been extended to test the fire effectiveness of other fire suppressants, such as dry powder, water mist and foam agents. For example, Hamins [9] modified the cup burner apparatus to test the fire suppression ability of sodium bicarbonate solid particles. Joseph [16] tested suppression efficiency of water mist with additives with cup burner. Fleming and Sheinson [17,18] used cup burner to evaluate the flame extinguishing efficacy of water vapor and high expansion foams.

As a new kind of suppressant, gas–solid composite dry chemicals always show superior efficiency to that of the single

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constituent, which have been validated by different fire tests [19–21]. However, few investigations have been reported on their effectiveness assessment in bench scale experiments. Previously, we examined the efficiency of gas–solid composite particles consisting of zeolite13X and 2-bromo-3,3,3-trifluoropropene (BTP) by full scale cooking oil fire tests, revealing their much better performance than that of the commercial dry powder [22]. In this work, we attempted to further study the suppressing effectiveness of BTP/zeolite 13X composite particles through a cup-burner method with coflowing methane/air diffusion flames. A series of composite particles with the weight concentration of BTP varying from 1.0% to 12.0% were tested, whose results were then compared with that of neat BTP and zeolite 13X particles used alone. Characteristic parameters with respect to flame suppression were measured, including the mass based minimum flame extinction concentration and HF production. Mechanism of the composite particles in suppressing the cup-burner flames was discussed in detail.

2. Experimental

2.1. Experimental apparatus

Fig. 1 was a schematic diagram of the cup burner apparatus with the powder delivery system. The cup burner consisted of a cylindrical stainless steel cup (28 mm inner diameter, 45° chamfered inside burner rim) and a glass chimney (533 mm in height and the 100 mm inner diameter). The fuel cup was filled with glass beads with a diameter of 3 mm and covered by a 15.8 mesh/cm screen to give a uniform flow. The flow rate of the methane fuel was 0.3 L/min and the coflowing air gas was held constant at 40.0 L/min, which were controlled by mass flow controllers.

The powers were introduced into the air stream by a fluidized bed, which gave satisfactory performance for small particles [7]. The fluidized bed seeder was made up of a glass tube (19 mm in inner diameter and 300 mm in height) with porous plug connected at two ends, which permitted the passage of gas and stopped the solid particles. The oxidizer was a mixture of air and powder, which flowed through the glass chimney surrounding the fuel cup. The three layers of mesh screens fitted across the entire cross-sectional area of the chimney functioned as the flow straightener. The powder delivery rate was controlled by tuning the air velocity to the seeder through a mass flow controller. The air inflow was held constant throughout each flame extinction experiment.

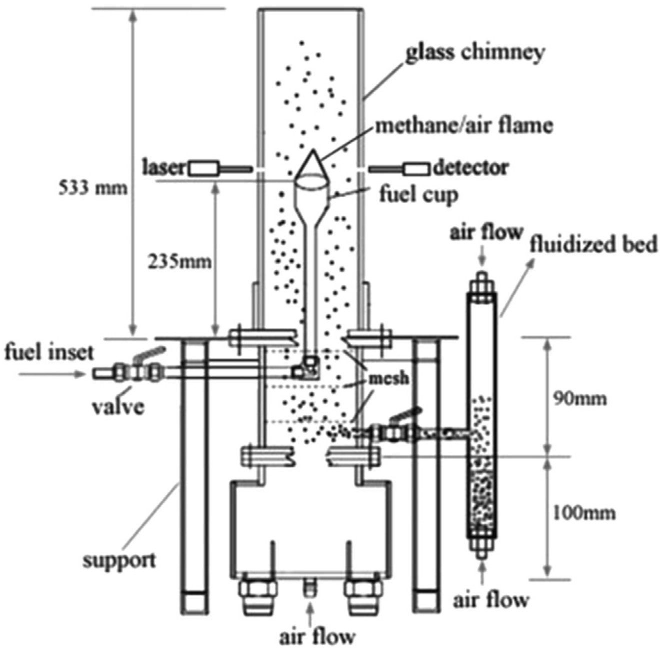

Fig. 1. Schematic illustration of the cup-burner apparatus for dry powder.

HF concentration in the chimney was measured by a LGA-4000 laser based gas analyzer, whose optical path located above the burner rim with a distance of 10 cm.

2.2. Determination of powder concentrations

According to method reported by Hamins [9], the minimum mass concentration of the powder required to extinguish the flames (denoted as MEC) were quantified on the basis of Lambert–Beer's law with laser attenuation measurement and gravimetric analysis. In a typical test, a Mie-scattering detection system of He–Ne laser beam with the wavelength of 632.8 nm was used to monitor the powder seeding rate. The fluctuation of particle concentration in the flow field was detected in time by the laser signal. Attenuation of the laser signal increased with the particle concentration in the oxidizer flow increasing. In the fire suppression process, the laser transmission signal gradually decreased until the flame was extinguished at a critical powder concentration. Relationship between the laser signal intensity and the mass concentration of particles could be expressed as:

$$-l_n\frac{I}{I_0} = K\cdot C\cdot L \tag{1}$$

where I_0 was the laser signal intensity without particles in the flow field, L was the path length (cm), C was the powder concentration (g/L), and K was the absorption/scattering coefficient (cm^{-1}). K was related with the particle characteristics of size, shape, composition, and etc. For each batch of powder, the value of K was re-determined. The K values of samples A–H were 0.02473, 0.02651, 0.02554, 0.2667, 0.2479, 0.02728, 0.02906, 0.02834 cm^{-1}, respectively. A typical calibration result for K value of sample E was shown in Figure S3 in the supplementary materials. As presented in Figure S4, it was observed that the K values kept constant in regardless of the weight concentration (%) of BTP in the samples (ω).

In the calibration tests (no flame present), the mixture flow containing gas and powder was sucked out continuously by an isokinetic tube for a certain period with the same velocity as that of the oxidizer. The particles trapped on the filter paper and adsorbed on the sampling tube were collected and weighed. Knowing the total air and particle mass flow rates, C in Eq. (1) could be estimated. Based on the measured values of I_0, I, L and C, the coefficient "K" was determined. In the fire suppression tests, the laser signal near flame extinction (I) was recorded and then taken into Eq. (1) to derive the powder concentration at the time of extinction (C).

2.3. Samples

The composite particles were prepared using an adsorption method as reported previously [22]. In a typical preparation, predetermined amount of BTP were injected into a vessel containing dried zeolite 13X particles for adsorption. Nine samples were used in the experiments. The composite particles with the weight concentration of BTP (ω) of 1.0%, 2.0%, 4.0%, 6.0%, 8.0%, 10.0%, and 12.0% were denoted as Sample A–G, respectively. Zelite 13X was denoted as sample H and neat BTP was denoted as sample I. SEM images showed that the zeolite 13X particles had a relatively narrow size distribution of 0.8–2.0 μm, with 90% particles showing size in a range of 1.0–2.0 μm. The average particle size was