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Dust ignition of pure and encapsulated paraffin phase change materials

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ABSTRACT

In this study, the dependence of the flammable concentration on particle size is investigated for Phase Change Material (PCM) and Encapsulated Phase Change Material (EPCM) particles using a novel continuous particle dispersion apparatus into which a propane flame is introduced creating a test akin to the flash-point test for liquids. The results show that the threshold concentration is a strong function of particle size. For tested particles with size ranging from 290 μm to 750 μm, the threshold concentration is above the predictions based on an instantaneous heat transfer limit, and is approximately linear with the particle size, following a heat transfer limited ignition model. For sizes above ≈1 mm, the particles behave like the bulk material, and ignition is not observed for the concentrations tested. The results obtained here are important for the safe construction, handling, and operation of systems using PCM and other particles.

1. Introduction

Paraffin phase change materials (PCMs) are receiving an increasing interest as thermal storage solutions for both industrial and construction applications. Phase change materials are used in a number of different thermal storage applications spanning from cooling vests to building heating and cooling (Zalba, Marı;n, Cabeza and Mehling, 2003). Some of these phase change materials are designed to melt near ambient or room temperature conditions, for example, by refining or blending different paraffins together. For applications such as concentrated solar power and building envelope, the phase change material is encapsulated in a thin polymer shell with a higher melting temperature to maintain its shape. These encapsulated phase change material (EPCM) particles commonly range in size from 50 nm to 3 mm (Liu et al., 2015; Regin et al., 2008). In addition, pure phase change materials are being considered as a thermal storage solution for indirect dry cooling towers of power plants (Sun et al., 2015) and can be produced through spray freezing processes in sizes varying from 100 μm to several millimeters.

When assessing the dangers of using these materials, one measure is their flammability rating. Paraffin ranging from $C_{17}H_{36}$ to $C_{23}H_{48}$ has an NFPA 704 flammability rating of 1 with a flash point above 93 °C (Alfa Aesar Safety Data Sheet n-Eicosane). Preheating of the bulk material is therefore required to create a flammable atmosphere. However, a dispersion of small particles is flammable without pre-heating (Eckhoff, 2003) and therefore both PCM and EPCM can create a flammable mixture by being either actively or accidentally dispersed in the air.

Some experimental data of ignition tests is available for dust mixture of various materials (Boilard et al., 2013; Eckhoff, 2003, 2012; Stahmer, 2015). However, due to the high number of possible flammable dusts, no data is available for the PCM of interest to current efforts such as eicosane. As a result, an experimental setup has been developed in this study to examine the flammability of candidate PCM materials. Specifically of interest are the flammability limits of particles dispersed in air and their threshold flammable concentration. To date, most experiments and analytical models for dust and spray ignitions have focused on the ignition temperature (Cassel and Liebman, 1959; Danzi et al., 2015; Huang et al., 2009; Proust, 2006), minimum ignition energy (Boilard et al., 2013), charge transferred, spark gap (Ballal and Lefebvre, 1979, 1981b; Proust, 2006; Schwenzfeuer and Glor, 1993), ignition time (Dreizin, 1996; Saitoh et al., 1982), quenching distances (Goroshin et al., 1996), flame speeds (Ballal and Lefebvre, 1981a), particle burning rates (DesJardin et al., 2005), and explosion

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pressure (Cashdollar, 2000; Cashdollar and Zlochower, 2007) which are critical quantities, but the question of this study is the fundamental relationship between the threshold flammable concentration and the particle size for a given type of PCM. In this study, ignition is treated as a statistical phenomenon due to the complexity of the contributing factors and a logistic regression analysis is performed on the available data. The prediction based on 50% chance for ignition is then placed into context of an analytical model to better understand the dependence of concentration on particle size.

The remainder of this paper is organized as follows. Section 2 describes the experimental setup, particles, and concentration measurements. The results from the ignition tests, the logistic regression analysis and analytical model are presented in Section 3. Section 4 reviews the conclusions drawn.

2. Experimental setup

2.1. Ignition test

Standard tests of dust flammability using the modified Hartmann apparatus or 20 L Siweck sphere are commonly performed to find the minimum explosive dust concentration, minimum ignition energies, and explosion pressures (Eckhoff, 2003; Kuchta, 1985). In the current study, a novel, simple test setup was constructed with a strong forced ignition source. The setup is constructed from off-the-shelf parts to give a Go/NoGo ignition result for the dispersed dust as its material, size, and concentration are varied. At the same time, the new experimental setup is designed to address the often-lamented non-uniform distribution of particles by improved dispersion and direct visualization of the test area.

The flammability test is modeled after flash point tests, such as the ASTM D56 Standard Test Method for Flash Point by Tag Closed Cup Tester (ASTM-D56, 1999) and the test setup created by Goroshin et al. used for quenching test of aluminum particles (Goroshin et al., 1996) with further inspiration from Eggelston and Pryor (Eggleston and Pryor, 1967). In flash point and aluminum quenching tests, a mixture of fuel (vapor or solid) and air is created and a forced ignition source in the form of a propane torch is introduced. Fig. 1 shows an image and a schematic of the experimental setup. It consists of two tubes with an inner diameter of 76.2 mm (3 in) and 304.8 mm (12 in) in length with a gap of approximately 30 mm between them. Both tubes are capped at each end with a fine metal mesh (0.15 mm opening, e.g. Mesh #100 or finer) to hold the test particles at the bottom and stop particles at the top. In the current version, the lower tube is made of clear polycarbonate to easily see the particle dispersion during experiment and the upper tube is made of aluminum to withstand the heat release during an ignition event. The particles are dispersed by utilizing the upwards suction of the exhaust hood and the upward air flow from a nozzle fed with compressed air. The combination of both is used to uniformly distribute the particles in the test area between the tubes as shown in Fig. 2. The air flow velocity in the test section varies between 0.4 ± 0.1 and 0.7 ± 0.1 m/s depending on the particles and desired concentration. For large particles, the dispersion by forced air is not feasible and particles are dropped from the top of the aluminum tube. The concentration is observed and measured using a high-speed camera and a uniform light source behind the particles as explained in the following section.

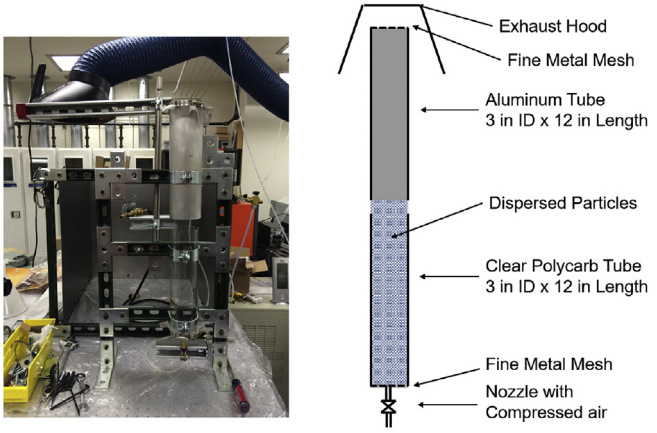

Fig. 1. Photograph and schematic of the particle dispersion and ignition tester.

After a uniform particle distribution has been established, the mixture flammability is tested by inserting a standard propane flame into the gap between lower and upper tubes at the room temperature. The ignition test is evaluated on a Go/NoGo basis, assigning a 0 or NoGo to a test where the flame does not spread beyond the introduced propane torch and a 1 or Go to a test where the flame propagates away from the propane torch. To assess the flame spread, a high-speed camera (Edgertronic Monochrome) is used to observe the gap between the lower and upper tubes at a frame rate of 1000 frames per second and a resolution of 768×768, and an additional digital video camera is used to observe the full experimental setup. The final experiment is performed in a four-sided chamber (3 sides of steel and 1 side of polycarbonate) to allow for optical access while shielding the operator during the test.

2.2. Concentration measurement

The concentration of the dust particles is the critical quantity under investigation in this study with the objective of assessing the threshold flammable concentration, c_{thr}, as a function of particle size, D, and material, M, i.e., $c_{thr} = f(D,M)$.

The concentration of particles is measured using the Beer–Lambert relation based on the light intensity observation on the high-speed camera. The initial, I_0, and final, I, light intensities are averaged over the observed illuminated test section as indicated in Fig. 2 and the Beer–Lambert equation is given as

$$\frac{I}{I_0} = \exp(-\alpha c l) \tag{1}$$

where α is calibration constant related to the absorption cross section, c is the particle concentration, and l is the imaging depth perpendicular to the viewing plane in Fig. 2. Noting that the product of the concentration and the imaging depth, cl, is the mass loading per unit cross-sectional area, m/A, the concentration measurements are calibrated using the following formula

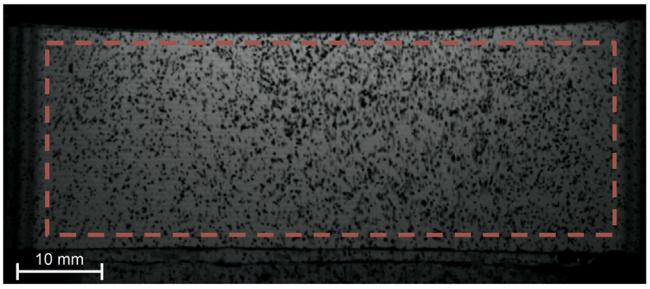

Fig. 2. Particle distribution visualization captured by a high speed camera (Edgertronic Monochrome) between the upper and lower test tubes. From the highlighted section of the image, the dust concentration of BASF UN 3088 Micronal DS 5038 X Encapsulated PCM in air is calculated using a prior calibration.