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Freely-propagating flames in aluminum dust clouds

Philippe Julien*, James Vickery, Samuel Goroshin, David L. Frost, Jeffrey M. Bergthorson

McGill University, Department of Mechanical Engineering 817 Sherbrooke West, H3A 0C3, Montréal, Québec, Canada

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ABSTRACT

The free propagation of isobaric flames through aluminum dust clouds is investigated in an extensive series of experiments using two facilities with different scales. In small-scale laboratory experiments, spherical flame propagation occurs in aluminum dust clouds contained within 30-cm-diameter latex balloons, whereas in large-scale tests, flames propagate vertically through unconfined aluminum dust clouds with a vertical scale of about 4 m. The balloon experiments are performed with suspensions of aluminum powder in oxygen mixed with nitrogen, argon, or helium with various concentrations of oxygen and aluminum. It is found that stable flame propagation is only observed for aluminum concentrations near stoichiometric to rich conditions. Pulsating and spiral-like flames are discovered in fuel-lean mixtures, and flames with cellular patterns occur in very-fuel-rich suspensions. The burning velocities in the stable propagation regime derived from the balloon experiments correlate well with data previously obtained with stabilized Bunsen-type flames. The flame speed of stable flames is found to be a strong function of the heat conductivity of the gas mixture. In addition, the oxygen concentration has a strong influence on the flame speed for fuel-rich mixtures but dependence is reduced for fuel-lean mixtures. In the large-scale experiments, the burning velocity is estimated to be about two times larger than for the small-scale experiments. The increase in burning velocity is attributed to preheating of the unburned mixture by radiation from the condensed-phase combustion products. The degree of preheating, determined with an array of fine thermocouples, is found to be in the range of 150–200 K. The propagation of stable flames is discussed in light of existing qualitative dust flame models, whereas the pulsating flame propagation regime observed is interpreted in terms of the thermo-diffusive instability theory developed for high Lewis number flames in gases and solid reactive powder mixtures.

1. Introduction

Suspensions of combustible particles in oxidizing media are ubiquitous in industry, agriculture, transportation and propulsion technology [1–6]. Though often amalgamated together under the term “combustible dusts”, solid fuels are very diverse, ranging from very volatile organic substances, such as plastics, flour, sugar or cornstarch, to refractory materials, such as carbon (graphite) or iron that do not volatilize or evaporate. Organic dusts have melting and volatilization temperatures well below their flame temperature, such that their combustion behavior differs little from the combustion of hydrocarbon droplets. The evaporation or decomposition of the organic volatile fuel and hydrocarbon sprays in the flame preheat zone might lead to the formation of a continuous flame sheet in the case of small particles and large fuel concentrations or, for large particles in fuel-lean mixtures, result in the combustion of particles surrounded by individual diffusion micro-flames [7]. Complex fuels, such as coal, contain both volatile and refractory substances and burn partially in the vapor phase by volatilization while leaving a charred core that burns heterogeneously.

Irrespective of the boiling temperature of the metal, the extremely fast and non-activated reaction kinetics of metal vapors with oxygen precludes formation of a premixed metal-vapor mixture in the flame preheat zone [8,9]. This excludes complex mixed heterogeneous/homogeneous flame regimes typical for combustion of solid and liquid hydrocarbon fuel suspensions which, combined with the fact that metals are pure elemental substances with well-defined properties, available in a wide range of particle sizes, makes flames in metal suspensions well-suited for the academic study of heterogeneous dust flames. Among all metals, aluminum is of special interest since it is often used as an energetic additive to propellants, explosives and pyrotechnics.

In contrast to hydrocarbon flames, the field of dust combustion remains vastly under-developed. This is partly due to the experimental difficulty of obtaining a laminar suspension of solid particles which is required to measure the fundamental combustion parameters, such as the burning velocity. Dust particles rapidly settle in a quiescent environment, and, in order to maintain the dust in suspension, an ascending laminar flow or some level of flow turbulence is required. For large particles that are tens of microns or more in size, the flow

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* Corresponding author.
E-mail address: philippe.julien@mail.mcgill.ca (P. Julien).

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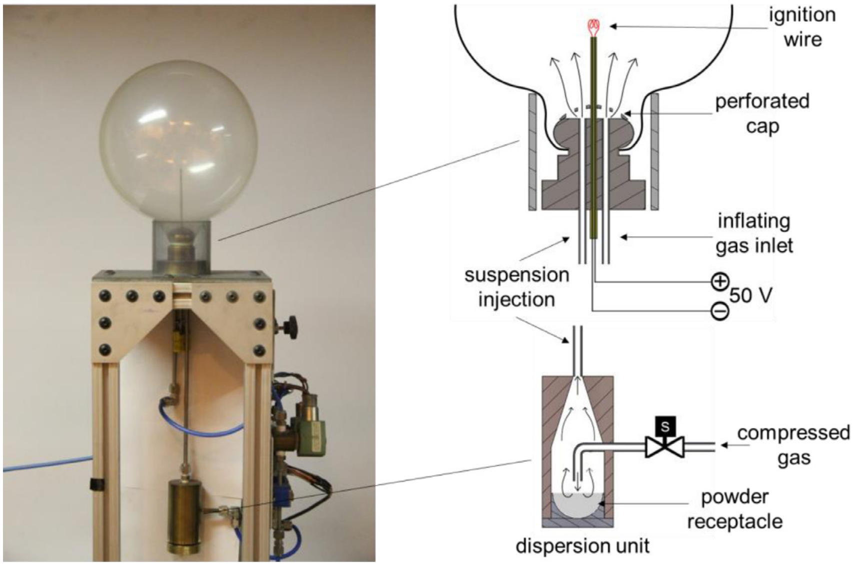

Fig. 1. Schematics and photograph of the laboratory apparatus for observation of spherical dust flames in transparent latex balloons.

velocity that is required to counteract particle settling may even exceed the flame burning velocity. Thus, performing dust combustion experiments over a wide range of particle sizes ultimately requires a microgravity environment [10]. Furthermore, the combustion behavior of a dust suspension depends on the particle morphology and size distribution, which makes it difficult to compare experimental data, obtained from different research groups using dissimilar powders. Due to the large flame thicknesses and the possibility of heat transfer from the flame to the fresh unburned mixture by radiation, dust flames are also more sensitive to the system scale than gaseous flames.

The vast body of literature on dust combustion is mostly based on experiments in closed bombs with no visual access, where the pressure history within the vessel is the only parameter measured. This experimental technique is primarily used to empirically classify the explosivity of dusts based on the rate of pressure rise, in accordance with the explosion hazard scale, while leaving the scientific questions of the flame structure and flame propagation mechanism unresolved. Only a small number of experimental groups, using different techniques, have provided direct measurements of the flame propagation speeds from which the burning velocity can be extracted. For example, Cassel employed stabilized Bunsen-type flames [11], Ballal [12] performed experiments with flat flames in a tube in microgravity, and Sun et al. [13–15] explored freely-propagating flames at very small scales. For the past 20 years, researchers at McGill University have systematically used visual observation of metal dust and hybrid hydrocarbon/metal-dust flames stabilized on Bunsen burners [16–19], propagating in tubes in normal and microgravity environments [20–23], and, more recently, spherically expanding in transparent latex balloons [24], to determine flame speeds and flame structure. The systematic use of the same batch of aluminum powder in the different experiments has facilitated the accumulation of a unique dataset of aluminum dust flame properties such as burning velocity, flame quenching distance, and flame spectral characteristics. This comprehensive compendium of data allows for the direct comparison of properties using different methods to fully characterize the combustion properties and flame structure.

As a continuation of this systematic work, the present study introduces two new experimental facilities allowing the observation of freely-propagating dust flames with different scales [24]. The first laboratory-scale apparatus uses transparent latex balloons to observe nearly-constant-pressure spherically-expanding flames up to 30 cm in diameter [25]. The aluminum is suspended within the balloon by a pulsed dispersal system in different gaseous mixtures of oxygen with nitrogen, argon or helium. Special care is taken to minimize the influence of the residual turbulence induced by the dust dispersal process by introducing an ignition delay time of appropriate length. The second apparatus creates aluminum dust clouds that are about 2 m wide and 4 m high inside a large-scale indoor experimental fire tower. The flame is initiated at the bottom of the cloud with a pyrotechnic igniter. A grid of thermocouples of different sizes placed inside the dust cloud is used to measure the level of long-range preheating of the dust mixture through the radiative flux ahead of the flame. The burning velocity results from the laboratory and larger scale experiments are compared with the data previously obtained from stabilized Bunsen-type dust flames [16]. Pulsating and spiral instabilities in spherical aluminum flames are discovered in fuel-lean mixtures and are discussed in reference to the general thermo-diffusive theory of flame stability developed for gaseous flames and condensed systems [26–28].

2. Experimental methods

2.1. Small-scale flames in balloons

The transparent latex balloons have a diameter of about 30 cm and volume of about 14 L when inflated prior to injection of the powder (Fig. 1). As the flame propagates, the balloon expands, maintaining essentially isobaric conditions up until it bursts with a pressure rise that is less than 0.01 bar. The aluminum powder is initially placed in a hemispherical cup at the bottom of a cylindrical dispersion unit that has a maximum capacity of 8 g of powder. The powder is fluidized within the cylindrical chamber by an impinging pulse of high-pressure gas. The particles become entrained in the flow, and the aluminum-gas mixture travels upward through a hemispherical cap before entering the pre-inflated balloon. The cap is pierced with multiple holes to separate the two-phase flow into many particle-laden jets that move up through the center of the balloon. The suspended particles recirculate within the balloon, mixing with the gas mixture until a uniform gas-particle mixture is created within the balloon, as shown in Fig. 2. The powder suspension is then centrally ignited by a heated tungsten wire following a 4 s delay after the initial powder injection to allow the initial turbulence to decay, as described in a previous publication [24]. The dust dispersal

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