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Proceedings of the Combustion Institute 36 (2017) 2291–2298

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Flame speed measurements in aluminum suspensions using a counterflow burner

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Received 3 December 2015; accepted 22 June 2016
Available online 21 July 2016

Abstract

The burning velocity is a fundamental parameter in combustion that has been accurately measured with different methods for a variety of gaseous and liquid hydrocarbon fuels. However, it is still unclear whether this concept also applies to the combustion of particulate-fuel suspensions. Attempts to measure the burning velocity in particulate suspensions have been made using a range of experimental techniques, but no study has yet attempted to reconcile the results from different studies. The present work reports the first realization of a stabilized aluminum flame using a counterflow burner. The flow is tracked using Particle Image Velocimetry and the flame speed is obtained as a function of aluminum concentration. The results are then compared to previous data obtained for stabilized flames, spherically-expanding flames, and flames propagating in tubes. The results are in reasonable agreement, given the experimental uncertainties in all of the techniques employed to date, suggesting that the notion of a laminar burning velocity may be applied to suspensions of particulate fuels.

Keywords: Aluminum; Burning velocity; Dust flame; Counterflow; Flat aluminum flame

1. Introduction

The burning velocity is a fundamental property of a mixture that reflects its reactivity and rate of heat transfer. It is defined as the speed at which an adiabatic, un-stretched, one-dimensional laminar flame propagates through a quiescent mixture of unburned reactants [1–3]. By definition, the burning velocity is an asymptotic approximation that is difficult to realize experimentally. Unavoidable complications, such as heat loss, flame stretch, and, in some experimental configurations, residual turbulence, all influence the flame speed observed in a given experiment that may differ significantly from the idealized laminar burning velocity. For gaseous and liquid fuels, these effects are generally understood and the laminar burning velocities obtained from different techniques, such as counterflow flames [4], spherically-expanding flames [1,4], and flat-flame burners [5], can be reconciled [4]. The

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http://dx.doi.org/10.1016/j.proci.2016.06.150
1540-7489

results from these different experimental geometries converge towards an accepted value of laminar burning velocity that can now be accurately calculated using advanced thermo-chemical models [4].

In contrast to gaseous and liquid fuels, attempts to measure burning velocity in particulate suspensions are scarce in the literature. Cassel first attempted to use the Bunsen flame technique to measure the burning velocity in aluminum suspensions [6,7]. A similar technique, with a different dust dispersion system and an improved measurement technique for the dust concentration, was used by McGill researchers to measure flame speed in aluminum suspensions [8] and hybrid mixtures of aluminum with methane and air [9,10]. Boichuk et al. [11] and Ballal [12] measured the flame speed in aluminum clouds within tubes under normal and micro-gravity conditions. Constant-pressure spherically-expanding flames propagating through aluminum suspensions, contained in latex balloons, were recently studied by McGill researchers [13]. This study enabled the measurement of the flame speed, and estimation of the laminar burning velocity, over a wide range of aluminum dust and oxygen concentrations [13]. Thermo-diffusive instabilities were also observed in flames propagating through lean particulate suspensions [13].

Although these recent studies on particulate-fuel flames have provided significant insight into the physics of flame propagation in such fuel clouds, the question remains as to whether the concept of burning velocity can be applied to flames propagating in particle suspensions. In comparison to a gas flame, dust flames are more sensitive to both scale and flow configuration. Creating a fuel suspension for flame studies requires a turbulent fuel-dispersion process, and maintaining large particles in suspension requires either a level of turbulence or an ascending laminar flow. The settling velocity of large particles can be comparable to or even exceed the burning velocity, and hence such particle sizes must be studied under microgravity conditions [14]. Solid fuel particles, unlike gases that are largely transparent to thermal radiation, can efficiently absorb the radiation emitted from the flame zone and post-combustion zone, effectively pre-heating the mixture [13,15]. Dust flames are also more sensitive to flow gradients due to velocity slippage between solid and gas phases, as discussed in this paper. Furthermore, the comparison of results obtained by different research groups is rendered difficult due to the unique nature of each powder used. Even powders with similar average diameters may have very different particle size distributions, which could affect the resulting flame speed. Powders also differ by purity, degree of initial particle oxidation, and particle shape, all of which increase the complexity of the problem.

To address this last issue, researchers at McGill University have performed a series of experiments, over a span of about 20 years, using different methodologies with the same batch of Ampal 637 aluminum powder hermetically stored in a container [8–10,13,15–17]. This unique dataset allows, for the first time, a comparison of burning velocities estimated from flame measurements in a variety of experimental configurations, including Bunsen dust flames [8], flames propagating in tubes [16], and freely-propagating spherical flames [13,15]. In continuation of this effort, the present experimental paper describes the first time the burning velocity in aluminum suspensions is estimated using a counterflow flat-flame technique with a modified Particle Image Velocimetry (PIV) diagnostic. The results from the present work are then compared with burning velocities obtained previously to assess whether the concept of laminar burning velocity can be applied to flames propagating through suspensions of particulate fuels.

2. Experimental methods and results

2.1. Counterflow particulate-fuel burner

The experimental setup is based on the McGill Bunsen solid-fuel burner [8], which was also recently used in experiments in hybrid mixtures of methane and metal fuels [9,10,18]. The aluminum powder is initially loaded in a piston that is driven upwards by a mechanical actuator, allowing the solid particulate fuel to be dispersed at the top of the metal-powder charge using a concentric sonic air knife. The two-phase flow is entrained into air that ascends through a 60 cm-long laminarizing tube and exits through the bottom nozzle, with a diameter of 1.5 cm, surrounded by a co-flow of air. A second, inverted, nozzle is placed directly on top of, and concentric with, the bottom nozzle with a separation of two centimeters, which forces a jet of air against the aluminum-air mixture. This counterflow generates a stagnation point between the two nozzles, which produces a flat aluminum flame, as shown in Fig. 1.

The dust concentration is monitored at all times during the experiment using a laser-light attenuation probe that is synchronized with the other diagnostic techniques. The probe was calibrated using the dust Bunsen burner for this specific batch of aluminum powder [9,10]. The aluminum powder used is Ampal 637 (Ampal, NJ) and has a mean Sauter diameter of about 5.6 μm. The powder is nodular in shape and the same batch has been used in previous experiments to measure the burning velocity in stabilized and propagating flames [8,15].

2.2. Particle image velocimetry in counterflow aluminum flame

Previous studies of flame speeds, and inference of burning velocities, in metal-particulate flames