An Attempt to Observe the Discrete Flame Propagation Regime in Aluminum Dust Clouds

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1 Discrete Flame Propagation Regime

The heterogeneous combustion of solid fuel particles suspended in a gaseous oxidizer is typically modeled without consideration of the discrete nature of the thermal sources (i.e., particles). The heat release from each individual particle is assumed to be homogenized throughout the medium so that a propagating combustion wave is modelled as a uniform and continuous reactive front. Recent developments have shown that, under certain conditions, this continuous assumption is no longer valid, and the effects from discretely spaced fuel particles must be taken into account [1, 2]. The relevance of this new discrete regime depends on the relative magnitude of two competing time scales, the reaction time and the heat diffusion time. The reaction time, or combustion time, is a measure of for how long individual particles release heat. The heat diffusion time is how long it takes for heat to propagate from one particle to another, which depends on the thermal diffusivity of the mixture and the spacing between particles. The ratio of these two time scales gives the discreteness parameter,

$$\chi = \frac{\tau_c \cdot \alpha}{l^2}.$$

In the limit of widely spaced, fast reacting particles in a mixture with low thermal diffusivity, the discreteness parameter will be much less than unity and discrete effects will become prominent. In this discrete regime, the flame speed will be limited by the heat diffusion time. Particles will react quickly, but it will take a comparatively long time for heat to diffuse between particles. This makes the flame speed in the discrete flame propagation regime much less dependent on the particle reaction time. Theoretical models and simulations have predicted other unusual flame properties in the discrete propagation regime, such as front roughening and a percolating mechanism close to the propagation limits [3, 4]. Experimental evidence for the discrete propagation regime is, however, difficult to obtain, as by nature discrete flame have low flame propagations speeds which makes them difficult to stabilize under laboratory conditions. This is especially true for suspensions of large particle sizes where the flame structure can be more readily observed. Thus, a sounding rocket experiment (Maxus-9) aimed at experimental observation of the discrete flame propagation regime in particulate suspensions in the microgravity environment is in preparation by the European Space Agency and is planned to be launched in 2016. In this paper, we describe an attempt to observe discrete flame propagation effects in ground-based experiments in preparation for the microgravity experiment. In order to validate the discrete theory, the flame speeds of metal powders will be measured in different oxygen concentrations. Increasing oxygen concentration will reduce the reaction time of a particle, and so in the continuous regime, the flame speed is expected to increase approximately proportionally with the square root of oxygen concentration [5]. Conversely, in the discrete regime there should be no change in flame speed. The tests must be performed in fuel lean conditions to ensure that increasing the oxygen concentration does not change amount of fuel burned. The fuel used for the continuous case is iron, due to its slow burning time. Thus, in oxidizing mixtures of argon and oxygen, the discreteness parameter for iron is estimated to be larger than 2. For the discrete regime investigation reported here, aluminum powder will be used. The fast reaction rate of aluminum gives a typical discreteness parameter of less than 0.3 in mixtures of argon and oxygen for low dust concentrations.

2 Apparatus Description

The apparatus used disperses a cloud of metal powder into a vertical glass tube 5 cm in diameter and 60 cm long. Dispersion occurs from the bottom, and is achieved by driving a piston that pushes a vertical column of metal powder upwards into the path of a sonic radial air knife. The gas mixture flowing through the air knife is used to control the oxygen concentration within the tube. The air knife deagglomerates and disperses the powder through a diffuser and upwards into the tube. The top of the tube is open, and as the dust exits the tube it passes through and attenuates a laser beam that is focused onto a receiver. The voltage drop measured by the receiver can be correlated to a concentration measurement using the Beer-Lambert law. During operation, powder flows upwards from the base of the tube until a steady state concentration is reached. At this point, ignition occurs at the top of the tube by passing a high current through a 20 µm diameter tungsten wire. The flow of gas from the air knife is stopped simultaneously with ignition, so that a flame travels downwards through the quiescent suspension of powder. The flame propagation is recorded using high-speed cameras. Tracking the position of the flame front over time gives a measurement of the flame speed.

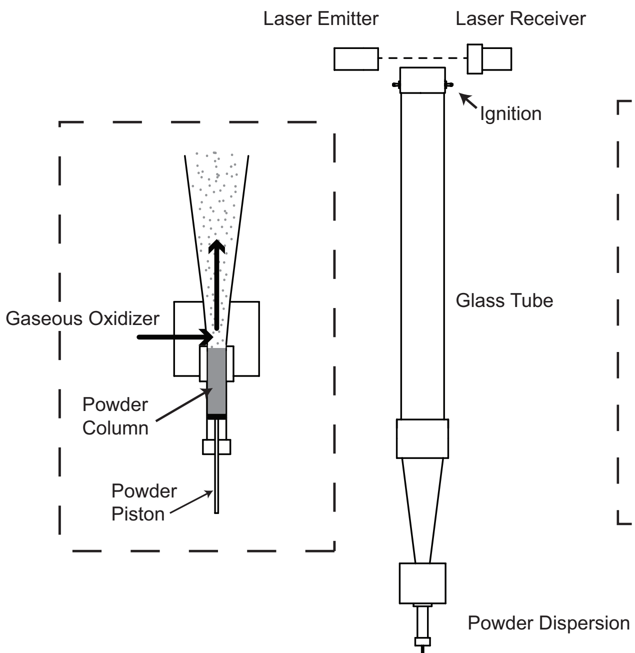

Figure 1. Center: Front view schematic of experimental apparatus. Left: Detailed cross-section view of dispersion. Right: Detailed cross-section view of ignition.

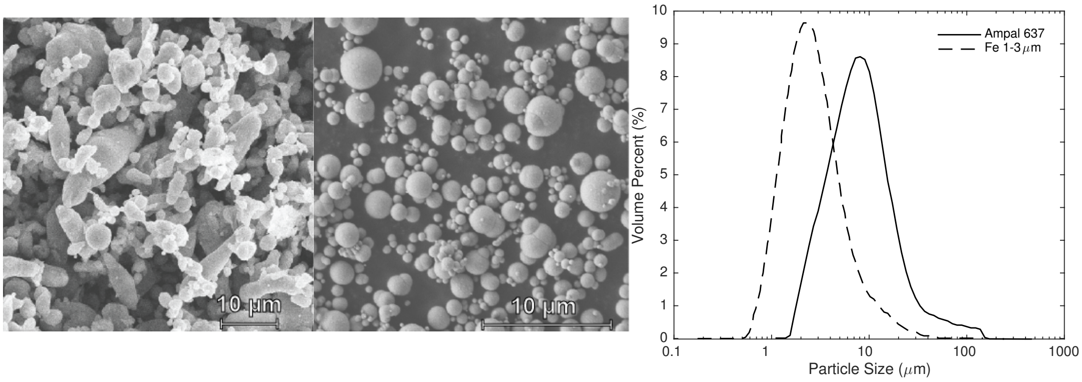

Figure 2. Left: SEM photo of Ampal 637 particles. Center: SEM photo of 1-3 µm iron particles. Right: Particle size distributions for each powder.

3 Instabilities

In addition to the technical difficulties associated with stabilizing heterogeneous flames under laboratory conditions, there are also a number of instabilities inherent to the system, which makes it difficult to observe steadily propagating flames. These include both thermo-diffusive and thermo-acoustic instabilities.

It has been shown that thermo-diffusive flame instabilities can occur when the Lewis number of a mixture is much above or below unity [5]. In practice, this is usually difficult to achieve with premixed gases [6]. For the heterogeneous combustion of metal powders however, their unique properties makes them susceptible to different types of instabilities. The Lewis number is defined as the ratio of thermal diffusivity to mass diffusivity of the deficient reactant. For rich mixtures of metal powders in a gaseous oxidizer, the Lewis number is less than one, and cellular instabilities can form [7]. This can be seen very clearly in figure 3.

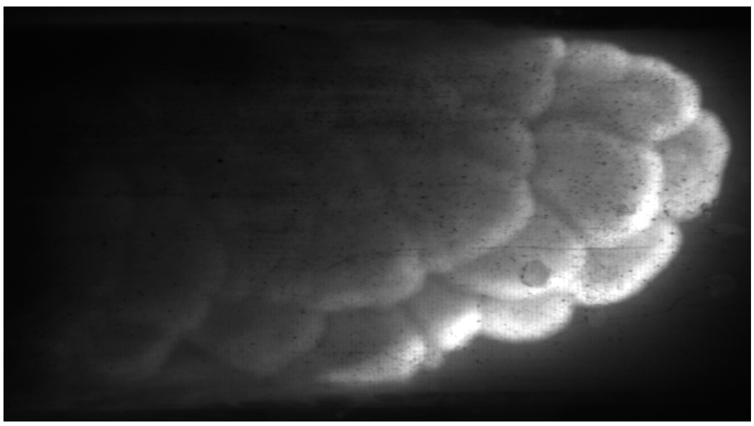

Figure 3. Cellular instabilities seen in rich mixtures of aluminum burning in 21% oxygen, 79% argon. Flame is propagating to the right.

For lean mixtures of metal powders in a gaseous oxidizer, the Lewis number approaches infinity. In this situation, thermo-diffusive pulsating instabilities can occur [8, 9]. Thermo-acoustic interactions can also create regimes of non-steady pulsating flame propagation [10]. Pulsating instabilities can be seen in figure 4.

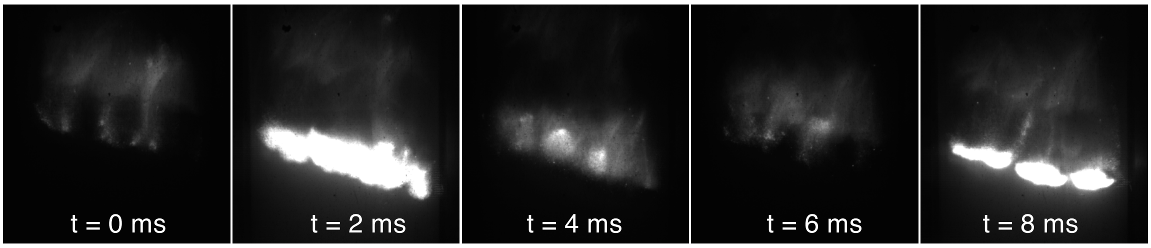

Figure 4. Pulsating instabilities seen in lean mixtures of aluminum burning in 60% oxygen, 40% argon. Flame is propagating downwards.

In order to characterize the pulsating instabilities, different diagnostics are used. A high-speed camera provides a visual representation of the pulsations, and the average frame intensities can provide a measurement of pulsation frequency. A photomultiplier tube provides a spatial average of light intensity with a high temporal resolution. A microphone attached to the tube provides an additional measure of the pressure waves produced by the pulsations.

For flames in tubes, the thermo-acoustic mechanism for pulsating instabilities complicates the characterization of the pulsations [10]. Unlike the thermo-diffusive instabilities that should be seen only in lean mixtures, thermo-acoustic pulsating instabilities can form in both lean and rich mixtures. The thermo-acoustic instabilities are characterized by pulsations at the harmonic frequency of the tube of around 100 Hz, while the higher pulsation frequencies of around 300 Hz seen only in lean mixtures are assumed to be thermo-diffusive in nature. Figure 5 shows the thermo-acoustic instabilities seen in a rich mixture of aluminum. The frequencies captured by the high-speed camera, photomultiplier tube, and microphone are all in agreement.

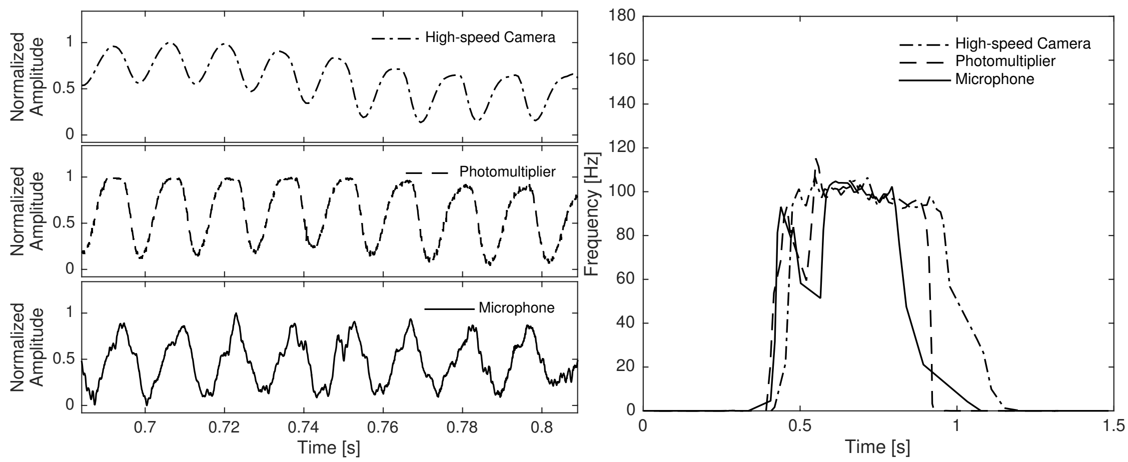

Figure 5. Left: Amplitude measurements from different diagnostics for rich mixture of aluminum burning in 21% oxygen, 79% argon. Right: Frequency over time data showing an average pulsation frequency of around 100 Hz.

Figure 6 shows the combination of higher and lower frequency instabilities seen in a lean mixture of aluminum. The pulsations begin due to thermo-diffusive instabilities characterized by pulsations in the 300 Hz range, followed by a drop in frequency indicating a possible transition to thermo-acoustic instability.

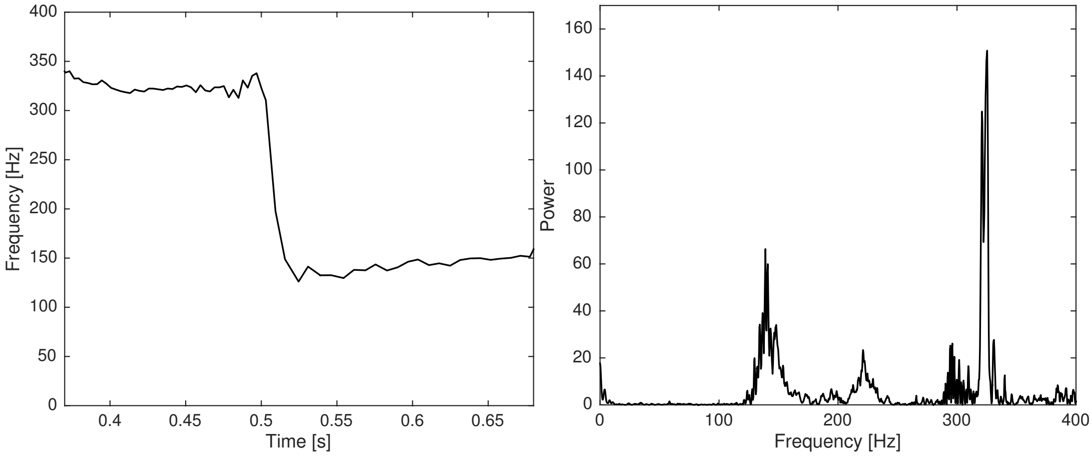

Figure 6. Left: Frequency over time data for lean mixture of aluminum burning in 42% oxygen, 58% argon. Right: Fourier transform of frequency data showing peaks at both 140 Hz and 310 Hz.

These instabilities do not occur in every trial, and they are often only seen in limited sections of the tube. Their occurrence depends on the oxidizing environment, the metal fuel used, and the concentration of fuel. With the iron powder tested, the pulsations occur rarely and only with high oxygen concentrations. For the aluminum trials, the pulsations can occur even at low oxygen concentrations, however in these cases there are still sections of the tube where steady propagation can be observed and a flame speed measurement can be taken. At high oxygen concentrations, however, the pulsations occur for the full length of the tube, preventing measurements of a steady front velocity. For this reason, the aluminum flame speed measurements were limited to oxygen concentrations between 15% and 30%. The stability of the iron flame permits reliable flame speed measurements up to 60% oxygen.

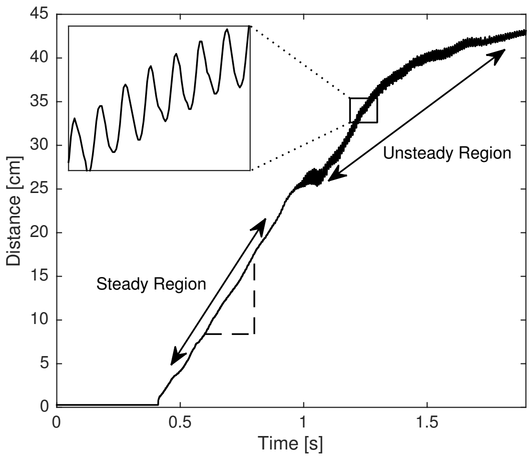

Figure 7. Distance-time graph showing steady and unsteady regions. The slope of the steady region gives front velocity.

4 Flame Speed Results

The experimental results confirm the theoretical predictions for both the discrete and continuous cases. For the iron mixture with a discreteness parameter above one, the flame speed increases with oxygen concentration, in agreement with the predictions of conventional flame propagation theory. For the aluminum mixture with a discreteness parameter less than one, there is no effect of oxygen concentration on flame speed, verifying a key feature of the discrete flame propagation theory. The scatter in the data can be attributed to local variations in dust concentration, and changes in the shape of the flame front.

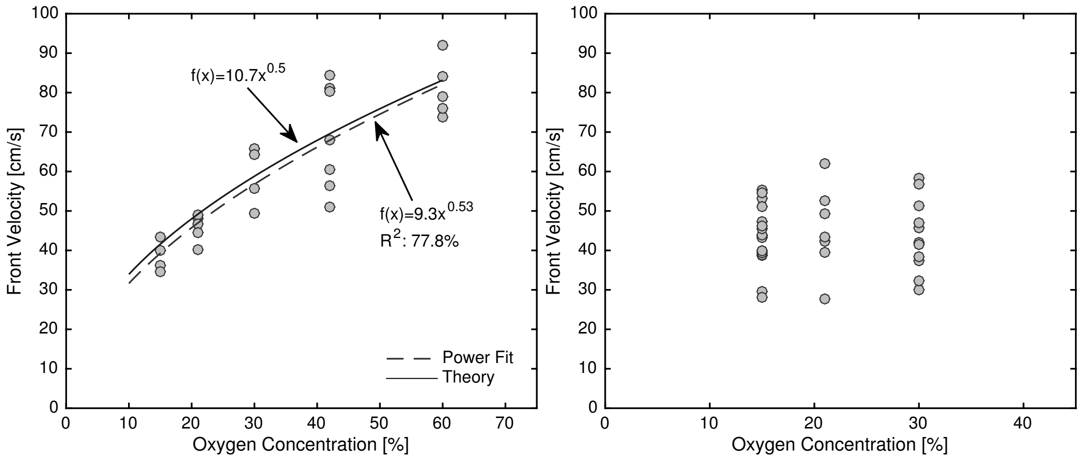

Figure 8. Experimental results of front velocity versus oxygen concentration for iron and aluminum powders.

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