Flame Propagation through Cornstarch Dust-Air Mixtures in a Vertical Duct

Shuangfeng Wang, Yikang Pu, Fu Jia, Shixin Wan
National Microgravity Laboratory, Institute of Mechanics, Chinese Academy of Sciences,
Beijing 100080, China

Corresponding author, S. F. Wang: sfwang@imech.ac.cn

Introduction

Dust combustion is a very important area due to safety problems related to dust explosion hazards, as well as to utilization of solid fuels. In spite of significant efforts to obtain information about the combustion properties of dusts (Echoff 1996, 1994, Proust and Veyssiere 1988, Jarosinski et al. 1986, Smoot and Pratt 1979), our knowledge on the fundamental mechanisms of flame propagation in dust clouds is still far from sufficient. This could be mostly attributed to the complexity of such phenomena. However, an equally great obstacle is the special experimental difficulties in generating a uniform and stable dust suspension with repeatable dust concentration (Goroshin and Lee 1999, Goroshin, Bidabadi and Lee 1996). Microgravity provides a unique opportunity to examine dust combustion mechanism. In a microgravity environment, it is practically possible to produce a dust cloud of arbitrary concentration and keep the dust particles in suspension during the entire experiment. Recently, a research program on dust combustion was carried out at the National Microgravity Laboratory, CAS, which will address flame propagation mechanism in dust clouds under normal and microgravity conditions. Presented in this paper are some preliminary results of the experimental studies, including a newly designed dust dispersion mechanism, measurements of dispersion-induced turbulence by means of PIV method, measurements of dust concentration and its variation with time, and optical observations of flame propagation through cornstarch dust-air mixtures under normal gravity.

Experimental Methods

The experimental system mainly consists of a vertical duct of 78 cm height and 16 × 16 cm square cross section. The duct is made of glass in order to obtain visualization of flames in combustion experiments and dust particles (illuminated by a laser light sheet) in dust dispersion experiments. The duct is open at the top end, and at the bottom of the duct is a porous metallic plate which separates the duct and an air chamber of the same cross section. The metallic plate functions like the distributor in a fluidized bed reactor. The chamber is connected with a compressed air reservoir via solenoid valves. Before each run of test, a given quantity of dust particles was evenly distributed on the plate. Dust suspensions in air were generated by a puff of compressed air through the porous plate with pressure of 0.15 MPa. The duration of the dispersion process was 3.2 s. In the present experiments, cornstarch ($C_6H_{10}O_5$) was used as the fuel. The particles were nearly spherical in shape with a mass mean diameter of 14 μm. For the determination of dust concentrations, two horizontal shutters were installed. One is near the bottom of the duct, and the other near the top end. In experiments, the shutters were closed simultaneously at a certain time. The mean concentration was evaluated by weighing dust particles settled on the shutters. In this way, the variation of dust concentration with time can also be obtained.

The determination of the feature of dispersion-induced flow was accomplished by means of a particle image velocimetry (PIV) measurement system. The flow was seeded by the starch dust particles themselves, which were illuminated by a laser light sheet. The movement of dust particles was recorded by a high-speed camera at 100 frames/s, and was subsequently analysed using a digital image processing system for the quantitative measurements of instantaneous particle velocities. More than 90 dust dispersion tests have been performed. For each test, instantaneous velocity fields at different times from the end of dust dispersion were acquired by PIV method, and the time variation of the root-mean-square (RMS) of the velocity fluctuation was calculated using space average. These RMS values were then averaged at corresponding times over the various tests (namely ensemble average) to obtain a single representative of the velocity fluctuation in dispersion-induced flow. The result of such process is given in Fig. 1. Noteworthy is that the maximum value of RMS velocity is less than 20 cm/s, while for previous dispersion systems this value is as high as several meters per second (Pu 1989, 1988). The much lower level of velocity fluctuation obtained with the present dispersion mechanism is significant to laminar dust combustion studies.

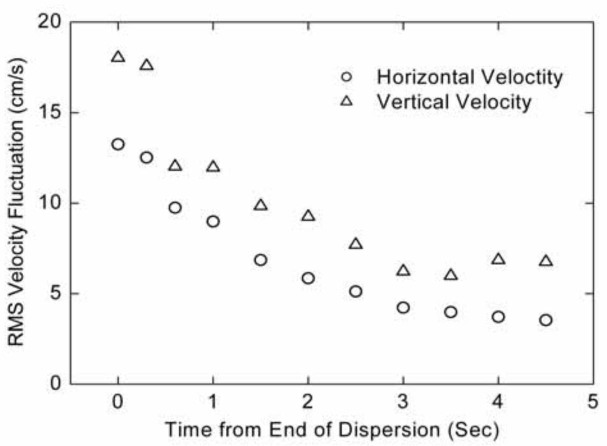
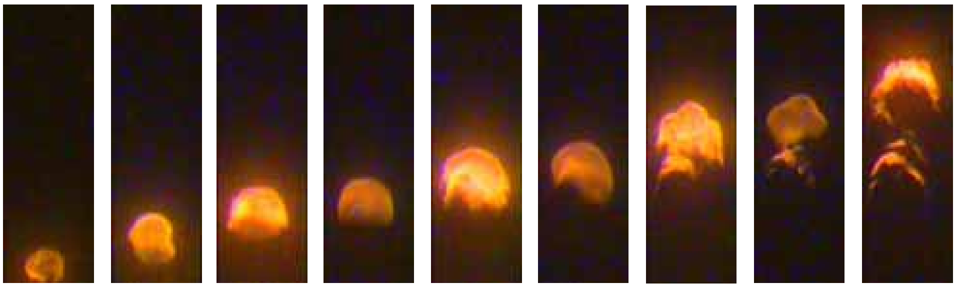


Figure 1. RMS Velocity Fluctuation in Dispersion-Induced Flows as a Function of Time.

The dust-air mixture was ignited at the bottom end of the duct by a device resembling a cigarette lighter. A spark with very small energy ignited a small amount of butane-air mixture, and then the gas flame ignited the dust clouds. The process of the upward flame propagation was recorded by the high-speed camera with framing rate of 250 frames/s.

Experimental Results

According to the ignition delay time from the end of dust dispersion, two kinds of flames were observed in the present study: laminar and oscillating flame, and turbulent flame. Shown in Fig. 2 are sequences of a typical laminar flame propagation. It can be seen that the flame front propagates upward with a parabolic-like form, which is a feature of laminar propagating flames. When the flame reaches about 1/3 of the duct length, it starts to oscillate (jerky movement of the flame) with a frequency of about 10 Hz. The luminosity of the flame also changes periodically with the same frequency. Fig. 3 shows the flame propagation process for a greater ignition delay time. The scenario is essentially the same as in Fig. 2. But the oscillatory feature of flame propagation is more obviously illustrated by stages in which the flame is invisible, and its frequency increased to 14 Hz. The turbulent flames have been observed when the ignition delay time is shorter than 1.1 s (corresponding to greater dust concentrations and initial RMS velocities). The flame front seems irregular (Fig. 4). During its propagation, no flame oscillation was noticed.



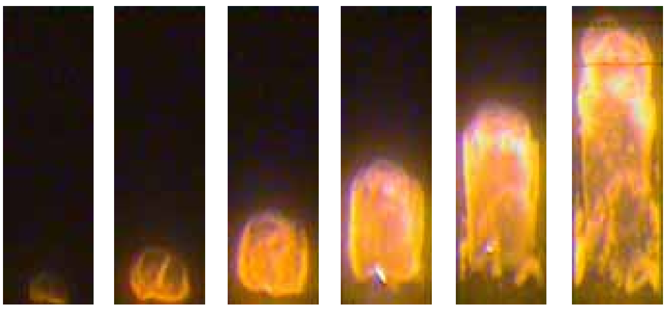
Time from Ignition Moment t_1= 40 ms, Δt = 52 ms.

Figure 2. Records of a Flame Propagating in Starch Dust-Air Mixture.
Ignition Delay Time 1.7 s, Dust Concentration 146 g/m^3.

Time from Ignition Moment t_1= 160 ms, Δt = 40 ms.

Figure 3. Records of a Flame Propagating in Starch Dust-Air Mixture.
Ignition Delay Time 3.2 s, Dust Concentration 110 g/m^3.

Flame propagation speeds were deduced from the photographic records as a qualitative measure of the burning rate. The variation of the flame speed during propagation process is shown in Fig. 5 for different ignition delay time. It was found that the turbulent flame undergoes rapid acceleration, while the propagation speed of laminar flames fluctuates about a mean speed, and in the stage when flame oscillations appear, the flame speed varies with the characteristic frequency. The mean flame speed was found to decrease with the increasing ignition delay time.



Time from Ignition Moment t_1= 40 ms, Δt = 40 ms.

Figure 4. Records of a Flame Propagating in Starch Dust-Air Mixture.
Ignition Delay Time 0.47 s, Dust Concentration 210 g/m^3.

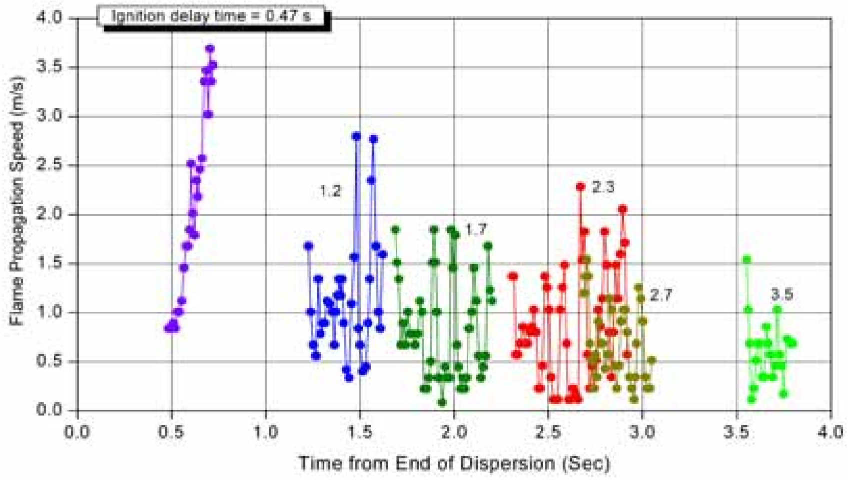


Figure 5. Variation of Flame Speed during Propagation Process.

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