Microgravity Apparatus and Ground-Based Study of the Flame Propagation and Quenching in Metal Dust Suspensions.

Sam Goroshin, Massimilliano Kolbe, Julie Bellerose, and John Lee
McGill University, Montreal, Quebec, Canada

Introduction

Due to particle sedimentation and relatively low laminar flame speeds in dust suspensions, microgravity environment is essential for the observation of laminar dust flames in a wide range of particle sizes and fuel concentrations [1]. The capability of a reduced-gravity environment to facilitate study of dust combustion was realized by researchers long before current microgravity programs were established by the various national Space Agencies. Thus, several experimentalists even built their own, albeit very short-duration, drop tower facilities to study flames in particle and droplet suspensions [2,3]. About ten years ago, authors of the present paper started their dust combustion reduced gravity research with the investigation of the constant volume dust flames in a spherical-bomb on board a parabolic flight aircraft [4]. However it was soon realized that direct observation of the constant-pressure flame might be more beneficial. Thus, microgravity apparatus, permitting examination of the freely propagating flames in open-end tubes, was tested in parabolic flights three years later [5]. The improved design of the newly-constructed apparatus for the experiments on board the NASA KC-135 aircraft is also based on the observation of the dust flame propagating in semi-opened tubes with free expansion of the combustion products that are continuously vented overboard. The apparatus design and results of its extensive ground-based testing are presented below.

Description of the Microgravity Apparatus.

The microgravity experimental package (Fig 1) is assembled in two separate frames. The first frame contains the control panel, computer data acquisition system, magazine of 8 combustion tube assemblies, and spare dust filters. The second frame (Fig. 1B) contains the combustion system and consists of three major components: the dust dispersion system, the combustion tube assembly, and the filtering and venting system. The dust fluidization system is modeled after our dust dispersion device that was used in numerous ground-based experiments [6,7] and has also demonstrated the ability to produce a uniform and well disaggregated dust suspension in the microgravity environment [5].
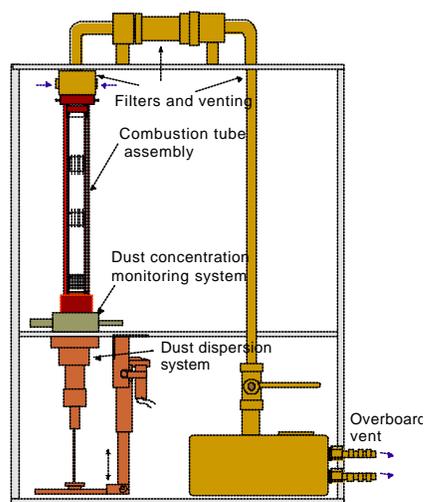

Figure 1 Photograph of the microgravity experimental package and schematic of the frame containing the dust combustion assembly.

The dust concentration is monitored directly within the dust supply tube by a laser light extinctiometer (Fig. 2). The use of the focused laser beam in combination with the pinhole aperture minimizes collection of the scattered light and makes deviation from the Beer-Lambert light attenuation law negligible even for optically-thick dust clouds. A narrow bandwidth interference filter protects the photodetector from ambient light.
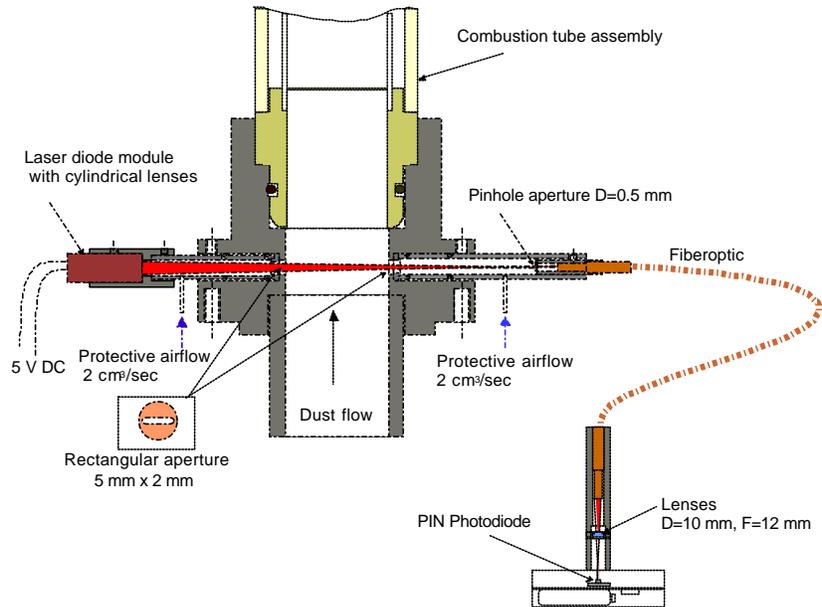

Figure 2. Laser dust concentration monitoring system.

For every powder used, the light extinctiometer was calibrated in the laboratory. For this a complete aspiration of dust from the flow was performed with a set of fine filters and a vacuum pump for a known time. Dust mass concentration in the flow is then determined by dividing total mass of aspired dust by the volume of the gas that passes through the dust dispersion during the same time. The example of the dust concentration measurements by the extinctiometer during the dispersion process is shown in Fig. 3
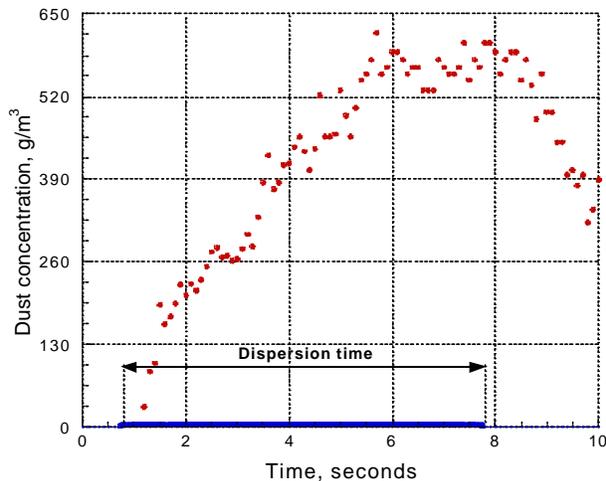

Figure 3 Results of dust concentration measurements by the extinctiometer during the dust dispersion process. Note that the ignition in ground-based experiments is usually performed 0.5 seconds after dispersion is switched off.

As it can be seen from Fig. 3, in approximately 5 seconds after the start of the dispersion process, the dust concentration in the flow reaches a plateau. The plateau extends for about 3 seconds until the end of the dispersion process. With a flow speed in the combustion tube of about 30 cm/s, the plateau duration is sufficient to fill the full length of the tube with a suspension of known and uniform dust concentration.

The flame propagates in 70-cm long, 5-cm ID Pyrex tube that is sealed inside another concentric transparent acrylic tube. An electrically heated ignition coil made from 0.25-mm tungsten wire is used to ignite dust at the open end of the tube. An O-ring seal at the lower end of the combustion tube provides a hermetic connection of the tube assembly with the dispersion system and allows its fast replacement in flight. Up to three sets of the steel quenching plates can be installed within the single combustion tube. The plates are about 0.8 mm thick and are soldered at equal distances with the help of thin stainless-steel rods. More than 40 quenching sets with quenching distances that range from 3 to 15 mm are prepared. Nine combustion tube assemblies that contain, in total, about 27 quenching assemblies will be prepared and used in each flight.
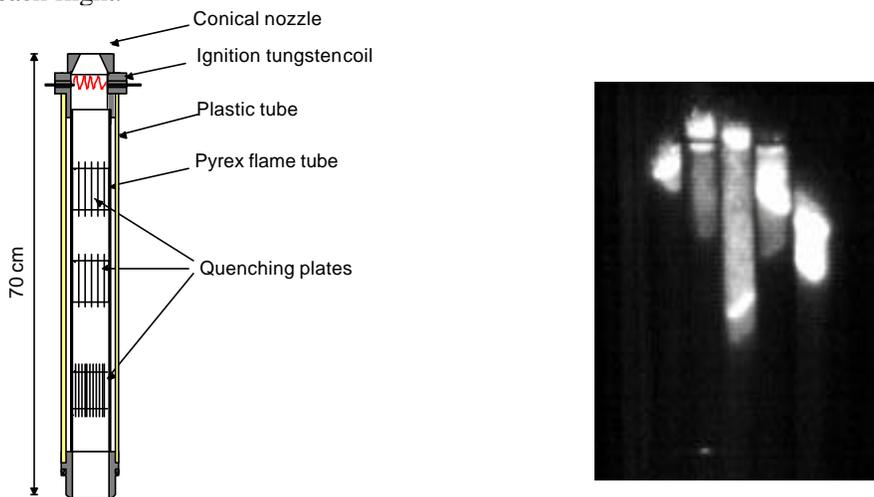

Figure 4 Combustion tube assembly and photograph of the aluminum dust flamelets propagating between quenching plates.

MotionScope[?] high-speed digital video camera records the flame propagation process at rate of about 1000 frames/sec before and inside the first set of quenching plates. The second, regular digital camera records the flame along the total length of the tube. A miniature microphone with enhanced low frequency response is installed near the exit of the dispersion system and allows registration of pressure oscillations in acoustically-exited flames.

Flame propagation and quenching in micron-size metal particle suspensions.

Microgravity apparatus was extensively tested on the ground using gaseous methane-air mixtures and micron-size (d_{32} = 3-5?m) suspensions of pure metal powders of Al, Fe, Cr, and Ti. The tests with methane-air stoichiometric compositions found flame propagation speeds and quenching distances that are very close to those reported in the literature [8] (see Table). Experiments with aluminum and titanium powders revealed the existence of strong acoustic flame oscillations that appear almost immediately after the ignition. The frequency of the oscillations was close to the basic acoustic mode of the combustion tube, (100-120 Hz) and the flame behavior was similar to the dust oscillatory combustion previously observed by the author in longer tubes [9]. It was found that the intensity of coupling between flame and acoustic wave is not uniform along the tube length (see Fig. 5A). The amplitude of pressure oscillations was the highest at the open end and in the lower section of the tube. At moderate, close to stoichiometric dust concentrations, the upper section of the tube was often free of acoustic coupling. It is also interesting to note that if the acoustic coupling above quenching plates is not very intense, pressure oscillations nearly disappear when the flame travels between quenching plates. They, however, reach the maximum amplitude almost instantly as soon as the flame emerges out of the quenching plate assembly (Fig. 5B). Special experiments were performed to investigate the influence of the intensity of acoustic oscillations on flame quenching distance.
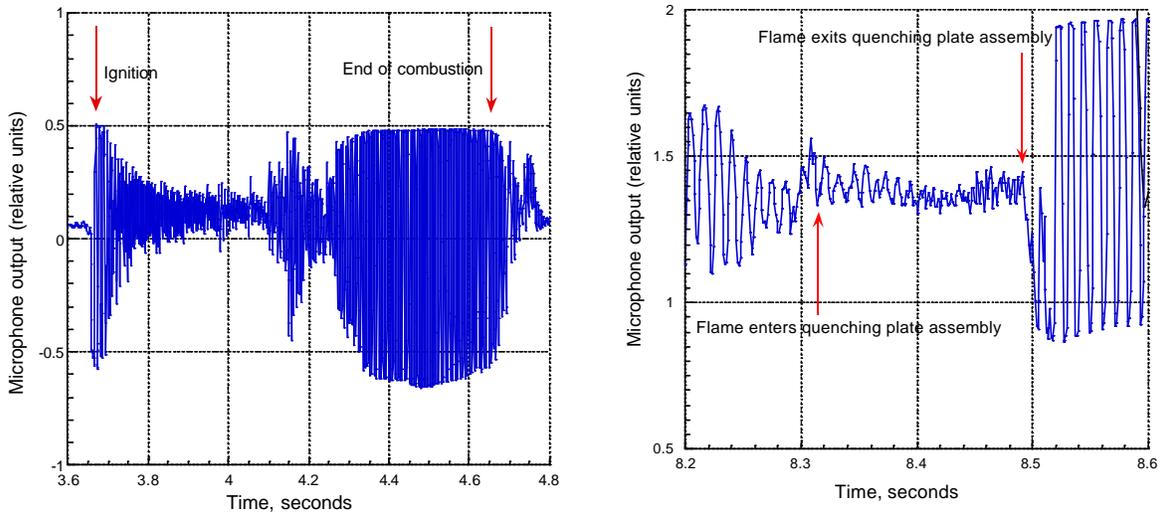
Figure 5 - (A) Acoustic oscillations during flame propagation along combustion tube; (B) Acoustic oscillations before, inside and after flame passes quenching plate assembly.

It was found that the quenching distance of the dust flame does not depend on the position of the quenching plates along the tube length and accordingly on the intensity of the acoustic flame oscillations outside quenching plates. Oscillating flames, however, demonstrate much lower average flame speed than an unperturbed one. Thus only flame speeds measured in the absence of acoustic coupling are shown in the table below. The table also summarizes obtained experimental data on flame quenching distances in methane-air mixtures and metal-air suspensions at fuel concentrations close to stoichiometric. Note that no acoustic coupling was observed for flames in Fe and Cr dust suspensions.

Fuel	Aluminum Al	Titanium Ti	Iron Fe	Chromium Cr	Methane CH_4
Metal density, g/m^3	2.70	4.59	7.87	7.19	-
Metal boiling point, K	2792	3550	3134	2944	
Stoichiometric concentration, g/m^3	310	415	725	600	160
Adiabatic flame temperature, K	3540	3300	2295	2800	2170
Quenching distance: Flame propagates, mm Flame quenches, mm	4 3	3 2	8 7	7 6	3 2
Flame speed in 5 cm ID tube (? 5 cm/s)	55	60	20	30	80

References.
1. Goroshin, S., Lee, J.H.S., *NASA/CP-1999-208917*, 123-126, 1999
2. Kumagai, S., *Combustion,* Iwanami Shoten Pub., Japan, 1976 (in Japanese)
3. Ballal, D.R., *Proc. Royal Soc. London, Ser. A,* 385:21-51, 1983
4. Peraldi, O., Lee, J.H.S., Landry, C., Shemie, M., *Proc. Spacebound'93,* Ottawa, 95-96, 1993
5. Goroshin, S., Kleine, H., Lee, J.H.S., Frost, D., *NASA/ CP –1995-10174*, 141-146, 1995
6. Goroshin, S., Bidabadi, M., Lee, J.H.S., *Combustion and Flame* V.105, 147-160, 1995
7. Goroshin, S., Fomenko, I., Lee, J.H.S, *Proc. Comb. Inst*, V. 26, pp. 1961-1967, 1996
8. Lewis, B. and von Elbe. G., *Combustion, Flames, and Explosions of Gases,* Ac. Press, NY, 1961
9. Goroshin, S., Shevchuk, V., Ageyev, N. *Comb., Expl., and Shock Waves,*, V.17, 595- 600, 1982