

GROUND-BASED AND MICROGRAVITY STUDY OF FLAME QUENCHING DISTANCE IN METAL DUST SUSPENSIONS

Samuel Goroshin[†], Jorin Mamen[†], John Lee[†], and Kurt Sacksteder[‡]

[†]Mechanical Engineering, McGill University, Montreal Quebec, Canada H3A 2K6

[‡]NASA Glenn Research Center, Cleveland, Ohio, USA

samuel.goroshin@mcgill.ca

INTRODUCTION

A fundamental knowledge of heterogeneous combustion mechanisms is required to improve utilization of solid fuels (e.g. coal), safe handling of combustible dusts in industry and solid propulsion systems. The objective of the McGill University research program on dust combustion sponsored jointly by the Canadian Space Agency and NASA is to obtain a reliable set of data on basic combustion parameters of the dust suspensions (i.e. laminar burning velocity, flame structure, quenching distance, flammability limits etc.) over a range of particle sizes, dust concentrations and types of fuel. This set of data then permits theoretical models to be validated and, when necessary, new models to be developed to describe the detailed reaction mechanisms and transport processes.

Microgravity is essential to the generation of a uniform dust suspension of arbitrary particle size and dust concentration [1]. When particles with a characteristic size of the order of tens of microns are suspended, they rapidly settle in the gravitational field. To maintain a particulate in suspension for time duration adequate to carry out combustion experiments invariably requires continuous convective flow in excess of the gravitational settling velocity, which is comparable with and often exceeds laminar burning velocity of the dust suspension. This makes the experiments turbulent in nature and thus renders it impossible to study laminar dust flames. Even for small particle sizes of the order of microns, a stable laminar dust flow at normal gravity conditions can be maintained for relatively low dust concentrations. High dust loading leads to gravitational instability of the dust cloud and to the formation of recirculation cells in the dust suspension in a confined volume, or to the rapid sedimentation of the dense dust cloud, as a whole, in an unconfined volume [2]. Many important solid fuels such as carbon and boron also have low laminar flame speeds (of the order of several centimeters per second [3]). Convection that occurs in combustion products due to buoyancy disrupts the low speed dust flames and makes observation of such flames at normal gravity difficult.

The newly constructed apparatus for the experiments on board the NASA KC-135 parabolic flight aircraft permits the creation of uniform dust clouds for a wide range of particle sizes and dust concentrations. The laminar dust flame propagates in semi-opened tubes permitting free expansion of the combustion products that are continuously vented overboard. The apparatus design, results of its ground-based testing, and results of the first microgravity experimental campaign are presented below.

DUST COMBUSTION 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 flow filtering and venting system. The dust fluidization system is modeled after dust dispersion device that we have used in numerous ground-based experiments [4,5] and which also demonstrated the ability to produce a uniform and well disaggregated dust suspension in the microgravity environment [6].

The dust concentration is monitored directly within the dust supply tube by a laser light extincionimeter. 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 small, even for optically thick dust clouds. A narrow bandwidth interference filter protects the photodetector from ambient light, and the low rate protective gas flows prevent deposition of the dust onto windows of the optical system.

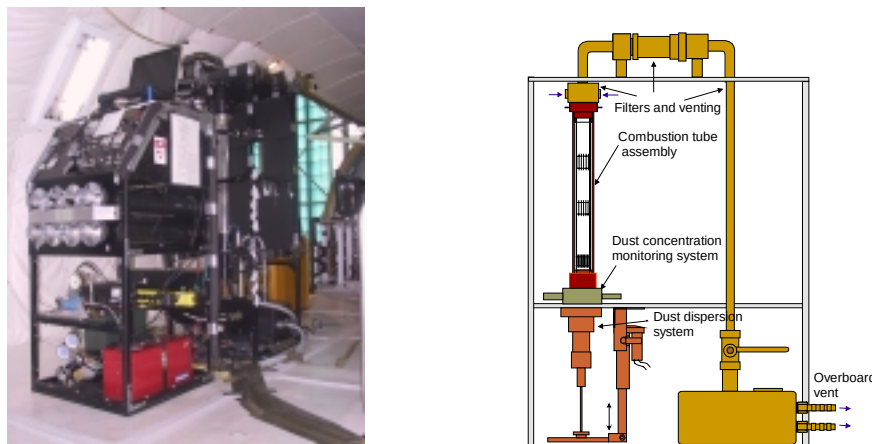


Figure 1 Photograph of the microgravity experimental package on board NASA KC-135 parabolic flight aircraft and schematic of the frame containing dust combustion tube assembly.

The flame propagates in a 70-cm long, 5-cm ID Pyrex glass 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 2 to 15 mm have been prepared. Up to nine combustion tube assemblies that might contain, in total, about 27 quenching assemblies can be used in each flight.

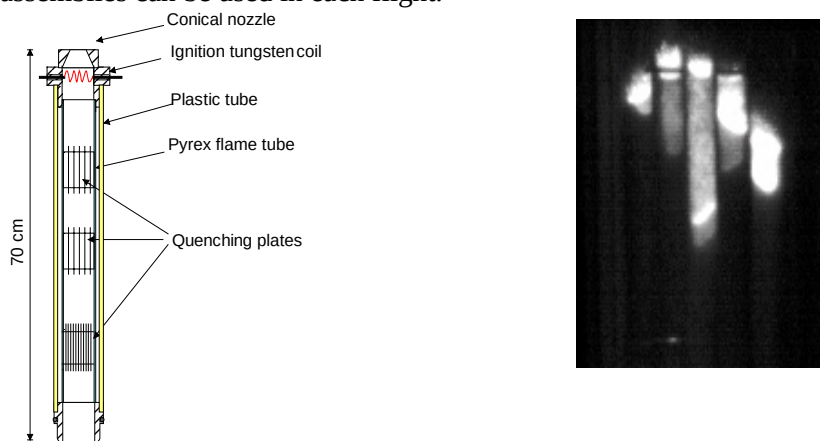


Figure 2 Combustion tube assembly and photograph of the aluminum dust flamelets propagating between quenching plates.

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. A second, standard 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.

GROUND-BASED TESTING: FLAME PROPAGATION AND QUENCHING IN MICRON-SIZE METAL PARTICLE SUSPENSIONS

The microgravity apparatus was extensively tested on the ground using gaseous methane-air mixtures and micron-size ($d_{32} < 5\mu\text{m}$) suspensions of pure powders of Al, Fe, Cr, and Ti. Calibration tests with

stoichiometric methane-air gas mixtures demonstrated flame propagation speeds and quenching distances close to those reported in the literature [7] (see Table 1). Experiments with aluminum and titanium powders revealed the existence of strong acoustically driven flame oscillations that appear almost immediately after 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 oscillatory combustion mode previously observed by one of the authors (SG) in longer tubes [8].

Special experiments were performed to investigate the influence of the intensity of acoustic oscillations on flame quenching distance. 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 speeds than unperturbed ones. Thus, only flame speeds measured in the absence of the acoustic coupling are shown in the table below. Table 1 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 oscillatory combustion was ever observed in Fe and Cr dust suspensions.

Table 1 Summary results of ground-based experiments on quenching distance in metal dust clouds.

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	4	3	8	7	3
Flame quenches, mm	3	2	7	6	2
Flame speed in 5 cm ID tube ($\pm$ 5 cm/s)	55	60	20	30	80

A simplified theory of dust flame quenching in narrow channels [4], predicts that flame quenching distance is proportional to a square root of characteristic combustion time $D_q \sim \tau_c^{0.5}$. The combustion time of heterogeneously reacting metal particles, whose burning rate is controlled by oxygen diffusion towards particle surface, can be considered, as a first approximation, to be proportional to particle density, ρ and inversely proportional to the stoichiometric coefficient of the oxidizer ξ , $\tau_c \sim \rho/\xi$ [9]. Using this criteria, the flame quenching distances in metal suspensions of different metallic dusts normalized by quenching distance in aluminum suspension can be ranked as follows: Al-1; Ti-1.03; Cr-1.5; Fe-1.6. The deviation from this prediction demonstrated by experimental data for aluminum and titanium (Al and Ti switch places in comparison to the theoretical prediction) might be explained by a possible kinetic resistance in aluminum combustion (see below). Thermodynamic calculations of Ti combustion also indicate considerable concentration of the titanium suboxide (TiO) at high temperatures. This might shift the stoichiometric coefficient in the above theoretical prediction in which only formation of Ti₂O₅ was considered.

MICROGRAVITY EXPERIMENTS.

The objectives of microgravity experiments were to obtain quenching distance data in the range of dust parameters where observation of laminar dust flames under normal gravity conditions is difficult. Thus, during ground-based experiments we were unable to observe low speed laminar flames in iron-air suspensions with particle size above 5 microns and aluminum-air suspensions with particle size above 10 microns. Microgravity environment eliminates buoyancy forces and make observation of low speed flames possible.

Spherical iron carbonyl powder from Alfa Aesar with average particle size about $d_{32} \approx 3.1 \mu\text{m}$ and nonspherical iron powder from Atlantic Eng., NJ with particle size about $d_{32} \approx 9.0 \mu\text{m}$ were used in

microgravity experiments. Spherical aluminum powders with particle sizes $d_{32} \approx 5.8 \mu\text{m}$ and $d_{32} \approx 14.7 \mu\text{m}$ that were used in microgravity experiments are manufactured by Valimet Inc., CA.

Microgravity experiments were performed on board the NASA KC-135 parabolic flight aircraft. The obtained results on flame propagation and quenching events inside narrow channels of different diameters are summarized in Fig. 3. Note that in all experiments dust concentrations were close to corresponding stoichiometric values of iron and air (600 g/m^3) and aluminum and air (310 g/m^3). No detectable acoustic excitation was observed for flames in aluminum suspensions of larger particle sizes, though acoustic excitation of the flame in suspension of fine aluminum powder was the same in microgravity as for in ground-based experiments.

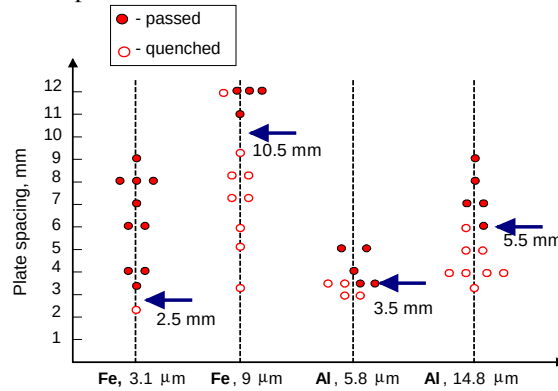


Figure 3 Results of the microgravity quenching distance experiments. Arrows indicate boundary between quenching and propagation events.

The quenching distance, as was mentioned above is proportional to square root of particle size ($D_q \sim \tau_c^{0.5}$). In turn, particle combustion time depends on the particle size as $\tau_c \sim d^2$, if combustion rate is controlled by oxygen diffusion towards flame zone on or near particle surface, or as $\tau_c \sim d$, if particle combustion is controlled by the kinetic of heterogeneous reaction. Correspondingly, the dependence of the flame quenching distance on particle size is stronger for diffusive combustion than for a kinetically controlled one ($D_q \sim d$ versus $D_q \sim d^{0.5}$). Although analysis of the first experimental results shown in Fig. 3 point to possibility that combustion of small aluminum particles might be, at least partially, controlled by reaction kinetics, and combustion of iron particles is controlled by diffusion, the small number of available data points do not permit an unambiguous conclusion. Additional experiments with larger particle sizes in iron and aluminum suspensions will be performed in the coming microgravity flight campaign (February-March, 2005).

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