

## MICROGRAVITY COMBUSTION OF DUST CLOUDS. QUENCHING DISTANCE MEASUREMENTS.

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### Introduction

The bulk of current energy production in the industrialized world comes from the burning of fossil fuels, a large part of which is in the form of a solid (e.g., coal) or a heavy liquid (e.g., diesel oil). Such fuels are invariably burnt in an atomized form. Efficient and environmentally clean combustion necessitates a fundamental understanding of the underlying mechanisms of heterogeneous combustion. There is also an inherent danger of dust explosion when combustible dusts are handled in industry. Dust explosions occur in coal mines, in agricultural handling and processing facilities, and in the wood, sugar, metal, paper, chemical, and rubber industries. Processing of ultra-fine and ultra-pure ceramic monosized particles (metal oxides, silicon oxide, carbides) via dust combustion processes (ref. 1) is another example of an important modern technological application of dust combustion.

The current level of physical understanding of dust combustion phenomena is still in a rudimentary state compared with the understanding of gas combustion processes. The reason for such a lack of fundamental understanding is partially based on the complexity of multiphase combustion and the enormous diversity of chemical-physical properties of heterogeneous combustible mixtures but is largely due to difficulties in the experimental investigation of dust combustion. The influence of gravity on a dust suspension is the main reason. First of all, when particulates (either solid particles or liquid droplets) with a characteristic size of the order of tens of microns are suspended, they rapidly settle in the gravitational field. To maintain a particulate suspension for a time duration adequate to carry out combustion experiments invariably requires continuous convection of particulates at or in excess of the gravitational settling velocity. Of necessity, this makes the experiments turbulent in character and makes it impossible to study laminar dust flames. For particle sizes of the order of microns a stable laminar dust flow can be maintained only for relatively small dust concentrations (e.g., for low fuel equivalence ratios) at normal gravity conditions. High dust loading leads to gravitational instability of the dust cloud and to the formation of recirculation cells in a dust suspension in a confined volume (ref. 2 and 3), or to the rapid sedimentation of the dense dust cloud as a whole in an unconfined volume (ref. 4). In addition, many important solid fuels such as low volatile coal, carbon, and boron have low laminar flame speeds (of the order of several centimeters per second). Gravitational convection that occurs in combustion products due to the buoyancy forces disrupts low speed dust flames and, therefore, makes observation of such flames at normal gravity impossible.

The only way to carry out "clean" fundamental experiments in dust combustion over a wide range of dust cloud parameters is in a gravity-free environment. Access to the microgravity environment provided by the use of large-scale drop towers, parabolic flights of aircraft and rockets, and shuttle and space station orbits has permitted now to proceed with a systematic program of dust combustion microgravity research. For example, the NASA-Lewis drop tower and a Lear jet parabolic flight aircraft were used by Ross et al. (ref. 5) and by Berlad and Tangirala (ref. 6) for experiments with lycopodium/air mixtures. The Japan Microgravity Center drop shaft (JAMIC) where a microgravity condition of  $10^{-4}$  g for 10 s is available, was recently used by Kobayashi, Niioka et al. for measuring flame propagation velocities in Polymethyl methacrylate dust/air suspensions (ref. 7).

Microgravity dust combustion experiments were started at McGill University in the early 90's under the sponsorship of the Canadian Space Agency. Several generations of dust combustion platforms permitting dust combustion microgravity experiments to be carried out on board a parabolic flight aircraft (KC-135, NASA) have been designed and tested (ref. 8). The experimental data and experience gained from this research allowed us to design and build in a current phase of this program the microgravity apparatus for the visual observation of freely propagating constant pressure laminar dust flames. Quenching distances in aluminum dust suspensions have been measured in a wide range of dust cloud parameters in ground-based experiments and in recent microgravity experiments (KC-135 parabolic flights, Houston, February 1995).

### **Microgravity Experimental Set-Up**

The microgravity experimental package (see Fig. 1) is assembled in a frame (26"×46"×50") which contains the dust combustion set-up along with flow visualization equipment. The frame is built from standard 1" steel pipe and mounted on a 1/2" thick base aluminum plate which is bolted to the aircraft floor. The dust combustion set-up consists of four major components: the dust dispersion system, the combustion tube assembly, the venting system and optical diagnostics with video and high speed framing cameras.

The dust dispersion system also consists of two parts: a dust feeder and a disperser (Fig. 2). The dust is fed via a syringe-type device which has an internal diameter of 0.5" and a maximum piston stroke of 3". The rate at which the dust is supplied to the flow (and hence the dust concentration in the suspension) is controlled by varying the piston speed with the help of a special electromechanical system (Linear Actuator, Thomson Saginaw, MI). The dust is dispersed at the base of conical chamber through the impact of a high velocity cylindrical jet issuing from an adjustable (20-40  $\mu\text{m}$ ) circular slot. A Pyrex flame tube (2" ID) where combustion experiments are performed is connected to the dispersion chamber through an 8° conical diffuser. The diffuser provides expansion and laminarization of the dust flow which is initially turbulent in the dust disperser.

The combustion tube assembly is shown in Fig. 3. The design allows for safe observation of the dust flame as well as for measurement of the quenching distance. This design also allows one to replace the flame tube quickly and store it safely during the flight. A conical nozzle with an opening of about 1" is installed in the upper part of the tube to prevent the appearance of acoustic flame oscillations. An ignition coil made from 0.25 mm tungsten wire is installed in the upper ring of the tube. The lower ring is threaded for fast connection of the tube assembly with the dispersion system. In order to determine the quenching distance a set of thin evenly spaced steel plates (thickness 0.25 mm, L = 50 mm) was installed in the upper section of the flame tube to form a grid aligned with the flow direction. The plates in the set are connected by four thin needles and soldered to form a rigid structure. A second similar set of quenching plates with a smaller gap between the plates of about 3.5 mm is also installed upstream in the lower third of the tube. This set serves as a flame arrester to prevent flashback into the dispersion system and also helps to laminarize the dust flow after it exits the dust disperser.

The venting system provides venting and filtration of the dust flow and combustion products from the combustion tube to the outside of the airplane through the overboard vent. In flight it uses the natural pressure difference between the cabin and the high altitude atmosphere. The venting duct is connected with the combustion tube by a sliding O-ring seal. Four one-way silicon diaphragm valves are installed in the upper ring on top of the tube assembly to prevent the dust flowing into the cabin in case of failure of the venting system. It also provides free access for cabin air in the venting duct at normal conditions, thus ensuring constant-pressure conditions within the combustion tube. A check-flow valve is also installed in the venting duct to prevent ignition and dispersion in the case of a venting system failure.

The filtration system is composed from a two-inch layer of 1/4" stainless-steel balls to provide sufficient cooling of the combustion products and is followed by a 2"-thick glass-wool filter. The filtration system is replaced after each second shot (5 filters are prepared for each flight). The process of flame propagation was monitored by a video camcorder as well as by a high-speed 16 mm camera at a framing rate of about 1,000 frames per second.

## **Ground-based Experiments**

Atomized aluminum powder Ampal-637 (Ampal Inc., NJ), which was used in the ground-based experiments, has an aluminum content of not less than 99.5%. The particles have a spheroidal or nodular shape, and the particle size is found to be  $5.4 \mu\text{m}$  (Sauter mean diameter,  $d_{32}$ ). The dust concentration is monitored by a light extinction meter using an expanded parallel He-Ne laser beam ( $d = 8 \text{ mm}$ ) passing through the dust mixture along the tube diameter near its upper rim. The light extinction meter was calibrated by the complete aspiration of the dust from the total flow through a set of filters with a vacuum pump. The dust concentration is then determined by dividing the total mass of the collected dust by the volume of gas that flowed through the dispersion system during the same time interval.

The high speed films show that when the flame with a parabolic shape approaches the quenching plates it becomes almost flat. Far from the quenching limit the flame penetrates into all the channels of the quenching section and propagates with almost the same speed in each channel. Sometimes several cycles of flame pulsation can be seen inside the quenching plates with a frequency close to the basic acoustic mode of the tube. If the fuel concentration is close to the quenching limit the flame usually propagates only through the central channel of the quenching section near the tube axis. The quenching distance as a function of dust concentration in dust-air mixtures is shown in Fig. 6. The measured lean limit of the flame propagation in the tube was found to be about  $150 \text{ g/m}^3$ . This result is consistent with the value of  $160 \text{ g/m}^3$  measured by Ballal for  $10 \mu\text{m}$  atomized aluminum powder in tubes (ref. 9). The minimum quenching distance is found to be about  $5 \text{ mm}$ , which is close to the value of  $4 \text{ mm}$  estimated by Ballal from dust ignition experiments (ref. 10), but considerably lower than the value of  $10 \text{ mm}$  found by Jarosinski for  $7.5\text{-}9 \mu\text{m}$  atomized aluminum powder (ref. 11).

## **Motivation for Microgravity Experiments**

The experimental ground-based results show that the weak dependencies of flame speed and quenching distance on concentration in rich dust mixtures are the most distinguishing features of the dust flame propagation in comparison with premixed homogeneous gas flames. So far it is unknown how far this plateau extends and what the value of the rich limit of dust flame propagation is. This poses one of the most intriguing questions in dust combustion. Obviously, dust clouds with much higher dust concentration than those obtained in ground-based experiments should be produced in order to approach the rich concentration limit. However, in normal gravity this is extremely difficult to achieve experimentally. The results reported by Mason and Wilson (ref. 3) and Green and O'Donnel (ref. 2), as well as our own experiments show that the difficulties of producing laminar dust flows or quiescent dust clouds with high dust concentrations are largely due to the instability of the dust cloud at normal gravity conditions. Green and O'Donnel observed the formation of a chain of large scale vortices in highly loaded dust flows in tubes even at very moderate flow Reynolds numbers and small particle sizes. The tendency towards the formation of large scale vortices at the bottom of the combustion tube was also observed in the present work during attempts to produce flows with dust concentrations higher than  $500 \text{ g/m}^3$ . The formation of vortices leads to intensive particle agglomeration and dust deposition on the walls of the combustion tube and the conical diffuser and eventually to the depletion of dust concentration. Only dust combustion experiments in a microgravity environment can alleviate the problem of the gravitational dust cloud instability at high concentrations as well as for large particle sizes.

## **Microgravity Experiments**

The application of the laser light attenuation technique which is used for the dust concentration monitoring in our ground-based experiments is restricted to dusts with relatively small concentrations. We have found that at concentrations higher than  $500 \text{ g/m}^3$ , the dust cloud (with a particle size  $5.4 \mu\text{m}$ ) is almost opaque and the noise from multiple scattering of light decreases the accuracy of the measurements below an acceptable level. In addition, the light absorption technique requires calibration with the same dust and at the same level of dust concentration as in the actual measurements. This inevitably requires that the calibration has to be carried out in the microgravity environment for the high dust concentration and large particle sizes. The dust dispersion system

was calibrated in microgravity conditions to determine the range of attainable dust concentrations. Two flights were reserved for calibration of the dust dispersion system with the 5.4 $\mu\text{m}$  aluminum dust and one flight for calibration with 18  $\mu\text{m}$  aluminum dust (Ampal-611). The calibration was provided by collecting the dust with the help of a stack of fine dust filters. Dust concentration was then determined by dividing the total mass of the collected dust by the known volume of gas which flowed through the dispersion system during the same time interval. The variable parameter was the speed of the piston in the dust feeding system which is proportional to the DC voltage applied to the linear actuator motor. The results of the calibration (see Fig. 4) show that the dust concentration is fairly reproducible and in microgravity the maximum value is more than double the value attainable at normal gravity conditions.

The quenching distance data obtained in microgravity for the 5.4  $\mu\text{m}$  dust (Fig. 6) are in good agreement with the ground-based data for dust concentrations  $\leq 600 \text{ g/m}^3$ . The microgravity results show that for dust concentrations larger than  $600 \text{ g/m}^3$ , the quenching distance continues to decrease and it is probably well below 4 mm (the flame regularly passes through 4 mm quenching plates at concentrations larger than  $750 \text{ g/m}^3$ ). This means that at extremely high concentrations, the quenching distance in dust clouds approaches values that are characteristic of homogeneous gas mixtures. For the first time, quenching distance was also measured for dust clouds formed with comparatively large 18  $\mu\text{m}$  particles - Fig. 6.

### Theoretical Analysis

A simple analytical model of a quasi one-dimensional dust flame with heat losses has been developed (details will be published elsewhere). It was assumed that radiative heat transfer in a flame front is negligible, that the aluminum particles are burning heterogeneously and that the particle burning rate in the flame front is controlled by the process of oxygen diffusion. Algebraic equations defining flame speed were obtained in two limiting cases: lean and rich mixtures. The model predicts wide plateaus in the flame speed and quenching distance versus dust concentration plots for rich mixtures - Fig. 5. These plateaus are observed experimentally and calculated values of quenching distances are also in good agreement with experimental data.

The mechanism of flame quenching in a dust-air mixture is similar to that in homogeneous mixtures, i.e., a feedback between flame speed and conductive heat losses. However, because of the diffusive mechanism of particle combustion, a number of significant differences exist. For example, the maximum temperature drop in a homogeneous gas flame before extinction due to the heat loss is known to be not greater than  $RT_{\text{ad}}^2/E$ , (ref. 12) (i.e., of the order of a few hundreds degrees). In the present case, due to the diffusive particle combustion, the reaction rate is not controlled by Arrhenius kinetics, and the drop of the average gas temperature in a dust flame before extinction is restricted only by the particle ignition temperature. Thus the temperature drop can easily reach more than a thousand degrees. The weak dependence of the particle diffusive combustion rate on temperature can also explain the phenomenon of the weak dependence of the flame speed on dust concentration in rich mixtures. The increase in the dust concentration above stoichiometric only intensifies, due to the larger specific dust surface area, the consumption of oxygen (burning rate). This can compensate for the drop in flame temperature in a broad region of dust concentrations and hence account for wide plateaus in the dependence of the flame speed and quenching distance on the fuel equivalence ratio (dust concentration) in rich mixtures.

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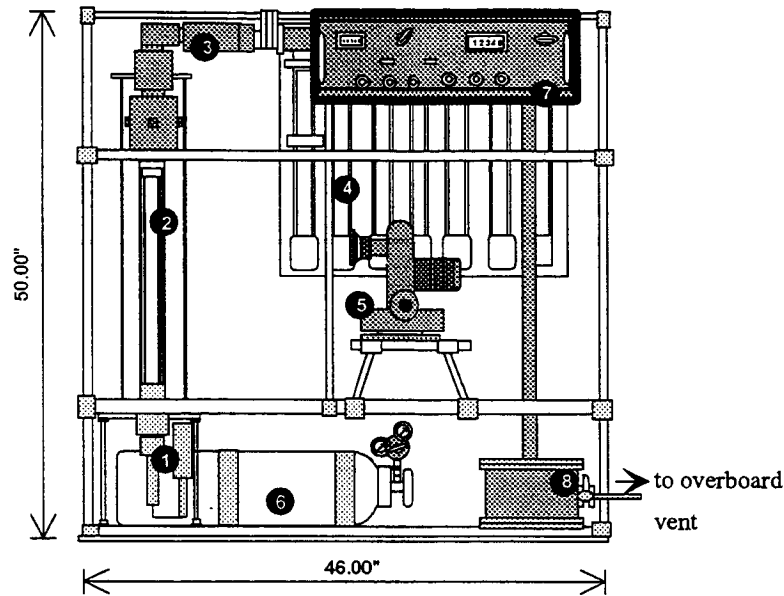


Fig. 1 Microgravity Experimental Package

- 1- dispersion system, 2 - combustion tube assembly, 3 - flame arrester and filter,
- 4 - combustion tube stock, 5 - high speed camera, 6 - compressed air bottle,
- 7 - control panel, 8 - vacuum tank.

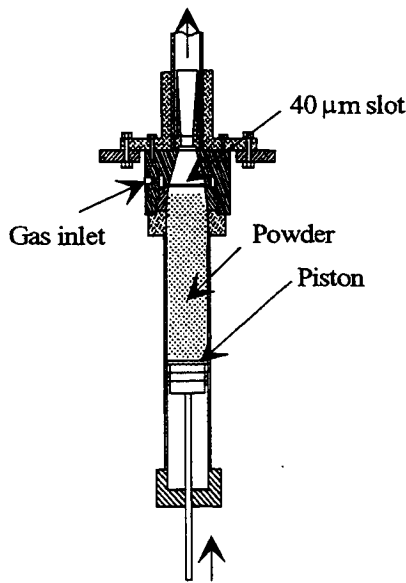


Fig. 2 Dust dispersion system

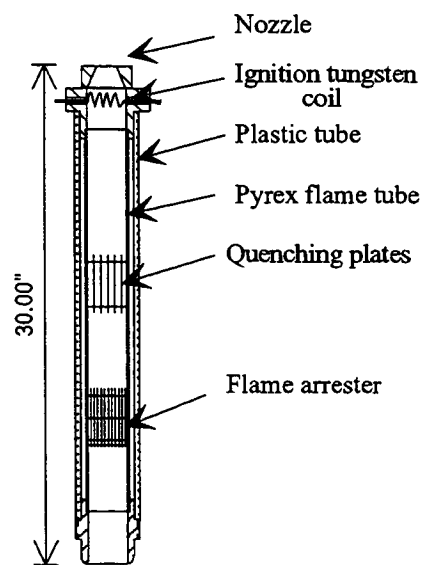


Fig. 3 Combustion tube assembly

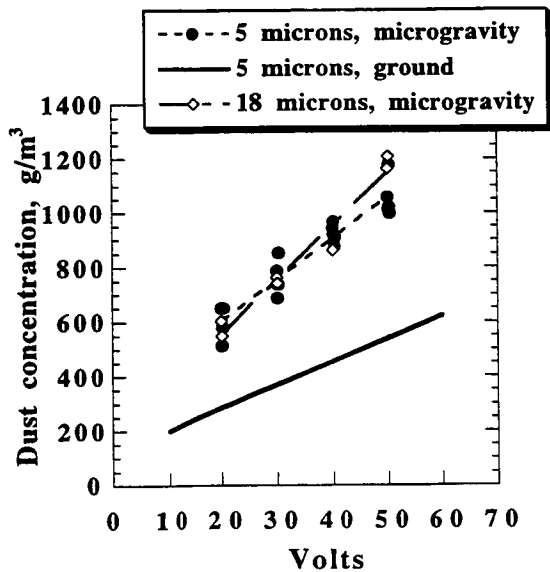


Fig. 4 Results of the dust dispersion system calibration on the ground and in microgravity.

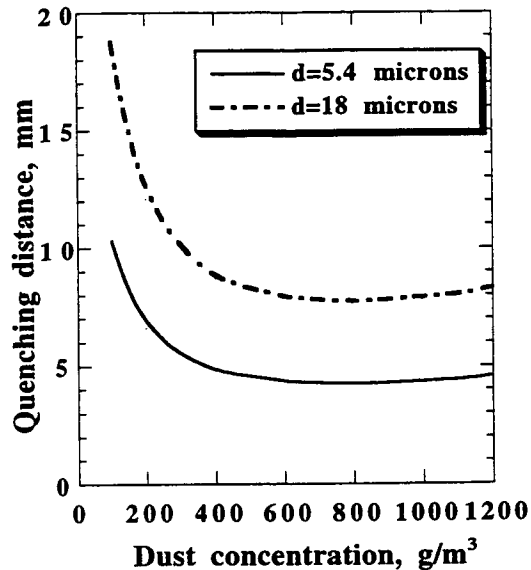


Fig. 5 Effect of aluminum dust concentration on quenching distance (theoretical results).

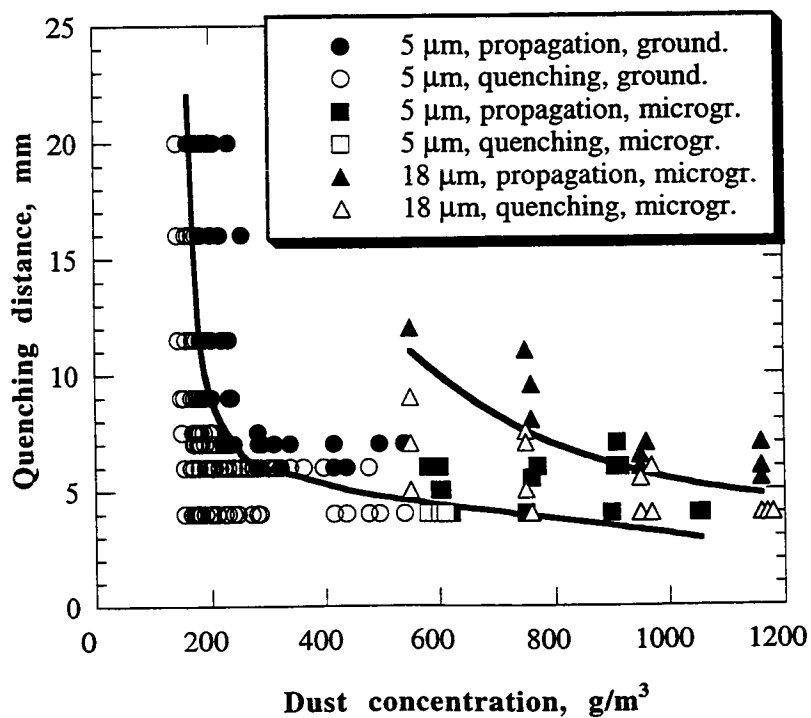


Fig. 6 Quenching distance as function of aluminum dust concentration . Ground-based and microgravity results.