

MICROGRAVITY COMBUSTION OF DUST SUSPENSIONS

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Introduction

Unlike the combustion of homogeneous gas mixtures, there are practically no reliable fundamental data (i.e., laminar burning velocity, flammability limits, quenching distance, minimum ignition energy) for the combustion of heterogeneous dust suspensions. Even the equilibrium thermodynamic data such as the constant pressure volume combustion pressure and the constant pressure adiabatic flame temperature are not accurately known for dust mixtures. This is mainly due to the problem of gravity sedimentation. In normal gravity, turbulence, convective flow, electric and acoustic fields are required to maintain a dust in suspension. These external influences have a dominating effect on the combustion processes. Microgravity offers a unique environment where a quiescent dust cloud can in principle be maintained for a sufficiently long duration for almost all combustion experiments (dust suspensions are inherently unstable due to Brownian motion and particle aggregation). Thus, the microgravity duration provided by drop towers, parabolic flights, and the space shuttle, can all be exploited for different kinds of dust combustion experiments. The present paper describes some recent studies on microgravity combustion of dust suspension carried out on the KC-135 and the Caravelle aircraft. The results reported are obtained from three parabolic flight campaigns; NASA KC-135 (March and July 1992) and ESA Caravelle (April 1992).

General Considerations

Pioneering studies of microgravity combustion of lycopodium dust clouds have been carried out by Berlad, Ross and co-workers at NASA LeRC [1,2]. Acoustic waves from a speaker at one end of a $5\text{ cm} \times 30\text{ cm}$ flame tube was used to lift a uniform layer of dust initially placed along the horizontal tube. An inflatable balloon at the other end of the tube maintains more or less constant pressure combustion. Chattering or pulsating flames were observed which were credited to the non-uniform stratified distribution of the dust by the acoustic field [3]. However, vibrating flames are typical for flame propagation in tubes due to flame-pressure wave interactions. Laminar burning velocities

were deduced based on an estimate of the complex flame shapes. Adhesion of the dust to the tube wall was found to be a problem.

Although the laminar burning velocity and the temperature profile in the reaction zone provide more important information on the flame propagation mechanism, we consider it important to first obtain some thermodynamic data on dust combustion in microgravity. The standard combustion experiment for dust suspension is constant volume burning where the peak pressure and the maximum rate of pressure rise are determined. Standard apparatus and procedures have been developed (e.g., the Hartmann bomb, the spherical 20 liter bomb of Siwert, the 1 m³ vessel of Bartknecht) by the dust explosion community. In all these apparatus, a given sample of dust is first dispersed by a strong turbulent jet and the subsequent suspension is then introduced into the partially evacuated combustion chamber. A key parameter is the so-called dispersion turbulence which decays rapidly with time. However, in normal gravity, dust sedimentation occurs when the dispersion turbulence decays and it is necessary to carry out the burning at a high level of turbulence in the dust suspension. Strong turbulence tends to stratify the dust in the eddies beside having a quenching effect on the combustion processes (especially for the slower burning rates of heterogeneous dust mixtures). Furthermore, turbulence also strongly influences the transport and hence burning rate. Therefore, the rate of pressure rise is strongly influenced by the dispersion turbulence and perhaps more so than by the chemical and physical properties of the dust cloud itself. Thus far, it has not been possible to obtain accurate data even on the thermodynamic combustion parameters for dust suspensions. In microgravity, where sedimentation is absent, it is then possible to wait till the dispersion turbulence has decayed prior to ignition. In this manner, more fundamental information can be obtained that is characteristic of the dust cloud and not the apparatus and procedure. We judge that this is an appropriate first step towards the understanding of dust cloud combustion.

Apparatus

Experiments were carried out during the nominal 20 sec duration of μg of parabolic flights of the NASA KC-135 and ESA's Caravelle. The spherical combustion chamber used is 5.4 liters in volume (~ 20 cm diameter) and is essentially a 1/4-scaled down version of the standard 20 liter spherical bomb of Siwert [4]. The dust sample is placed inside a small cylindrical dust cup which is connected to a small pressure vessel of about 0.2 liter in volume via an electrically operated solenoid valve. When the valve is activated, the high pressure air from the 0.2 liter chamber discharges into the dust cup and disperses the dust sample. The resulting dust suspension then flows into the spherical combustion chamber through numerous small jets (~ 1 mm diameter) spaced about 1 cm apart around the inner radius of a tubular ring inside the spherical vessel. The spherical vessel is initially evacuated to some sub-atmospheric pressure so that after the dust dispersion, the final pressure in the chamber is atmospheric. Ignition is via a small pyroelectric match-head and the time delay between dispersion (activation of the

solenoid valve) and ignition is controlled by a time delay generator. A schematic of the apparatus is shown in Fig. 1. To carry out the experiments on board the KC-135, a self-contained system comprising the vacuum and compressed gas supply, data acquisition system and the various electrical equipment, and control valves is required. This system is shown schematically in Fig. 2. The dust used is aluminum and two mean particle sizes are used (AMPAL 637 ($d_{32} = 5 \mu m$) and AMPAL 615 ($d_{32} = 20 \mu m$). Electron micrograph analysis of these dusts indicate a far from spherical morphology. Instead, the geometries of the particles are highly irregular. Two pressure transducers (PCB 113A24) with heat shields are used as the main diagnostics and a matrix of light absorption probes are used to monitor the dust concentration inside the vessel. The concentration-time measurements are taken without combustion in the vessel. After each experiment, the burnt products are evacuated to outside the aircraft and the bomb is opened to clean the residual deposits.

Results and Discussion

Figure 3 compares the pressure-time curves (for the $5 \mu m$ dust) for both the normal and μg experiments. For short delay times (i.e., $0.2 m/s$), the normal and μg results are practically identical, indicating that the dispersion turbulence dominates the early time combustion processes inside the chamber. As the turbulence decays both the peak overpressure as well as the rate of the pressure rise decreases for the normal gravity experiments. The decrease in peak overpressure with delay time for the initial period can be credited to both turbulent quenching and wall deposits as the dust jets impact on the wall. It should be noted that the duration of the dispersion process (i.e., pressurized air discharging from the 0.2 liter vessel) is about $500 ms$. Thus, the turbulence level is still fairly intense for the first few seconds after the start of the dispersion process. The slower decrease of the peak pressure (as well as the rate of pressure rise) for the longer delays of $10 sec$ and $15 sec$ could be due to gravity sedimentation. For the microgravity case, we note that the pressure-time profile appears to reach an asymptotic limit without the gravity sedimentation. The rate of pressure rise remains the same for different delay times, indicating that the influence of the dispersion turbulence is essentially negligible after about the first $5 sec$. For both the normal and the μg experiments, the optimum peak overpressures (corresponding to a time delay of $200 ms$) is about $6.2 atm$. as compared to the theoretically computed constant volume explosion overpressure for aluminum of $11.6 atm$. Incomplete voiding of the dust from the dust dispersion system into the vessel, adhesion of the dust to the wall, as well as heat losses and quenching as the flame reaches the copper wall of the spherical vessel could account for this. From the microgravity gravity results, an asymptotic value of the peak overpressure of about $4 atm$ is obtained, corresponding to only about 10% of the dust that is actually burnt in terms of energetics. Hence, instead of the global nominal dust concentration, of $500 gm/m^3$ based on the total account of dust divided by the volume of the bomb, only about 10% remains in suspension after the dynamic process has subsided. The actual amount of dust may be higher since heat losses to the wall and the dispersion ring may

be significant. Assuming a thin spherical flame, one can also deduce the laminar burning velocity from the pressure-time curve [5]. The laminar burning velocity corresponding to the asymptotic pressure-time history from the microgravity experiment is found to be about 0.25 *ms* based on the peak overpressure of 4 *atm* observed experimentally. This is quite a reasonable value.

The peak overpressure versus time delays for the 5 μm and 20 μm dusts are shown in Fig. 4. The continuous decrease in the peak overpressure with time in normal gravity after the dynamic dispersion processes have subsided can be attributed to gravity sedimentation. The microgravity results show an asymptotic limit of about 4 *bars* after a delay time of about 5 *sec* where most of the initial dispersion turbulence processes have decayed. However, for the large particle size case, both the microgravity and normal gravity experiments are similar, i.e., the initial dynamic processes completely control the combustion. An optimum peak overpressure (at 200 *ms* delay) of only 4 *bars* (as compared to 7 *bars* for the 5 μm dust) indicating that substantial amounts of dust are not discharged from the dispersion ring. When dispersed, the larger particles also do not follow the recirculation turbulent flow and hence more losses to the wall occur due to particle impact result. For large particles, the standard method of dispersion is not suitable and perhaps the simpler (but perhaps less uniform) method as used in the Hartmann bomb may give better results.

Conclusion

The preliminary experiments so far have demonstrated the feasibility of obtaining a quiescent dust cloud for fundamental flame propagation studies in microgravity. The major problem that has been identified is the initial generation of the dust suspension and its introduction into the combustion chamber. Higher shear rates from an intense turbulent jet is found necessary to break up an agglomerated dust sample, yet a low velocity laminar flow is needed to introduce the suspension into the combustion chamber to avoid turbulent stratification and high speed impact and subsequent adhesion of the dust to the chamber wall. These are technical problems that can best be resolved by more manned experiments on the KC-135 (or equivalent). Once the dust dispersion problem has been resolved, fundamental experiments on flame propagation, structure, quenching distance and flammability limits, minimum ignition energy can readily be designed. Theoretical modelling is considered to be of vital importance in design of the experiments due to the large number of variables involved in dust combustion. The limited diagnostic that can be effectively used for optically thick dust flame in the restricted space lab environment also necessitates the use of theoretical models for interpretation of the experimental results obtained.

Acknowledgement

This work is supported by the Canadian Space Agency through contract #9F007-1-

8022/01-SW. Technical assistance by Champlain Landry, Pedro Gregorio, Debbie Soriano are gratefully acknowledged.

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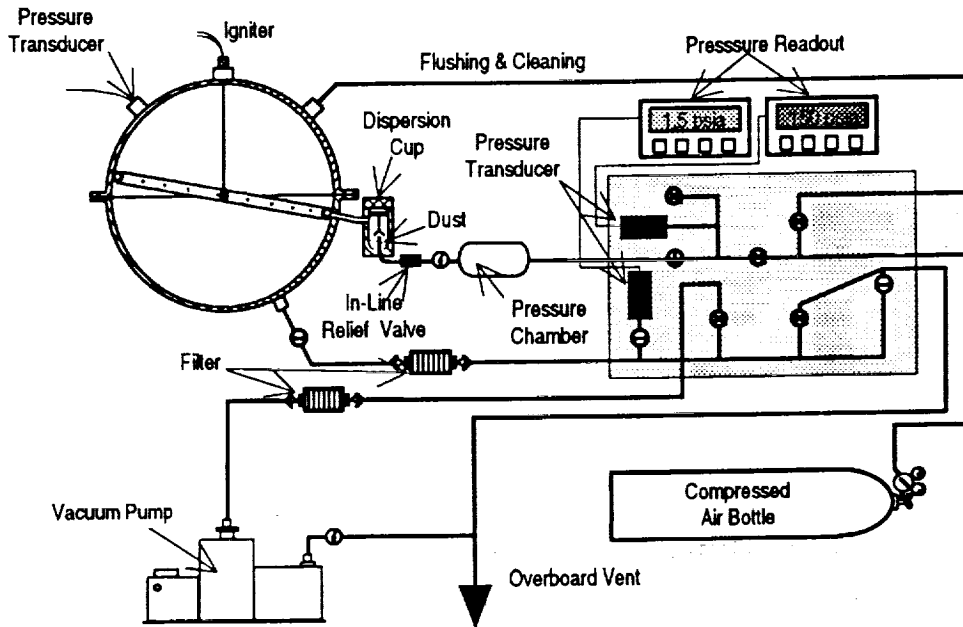


Figure 1 : Schematic diagram of the experimental apparatus.

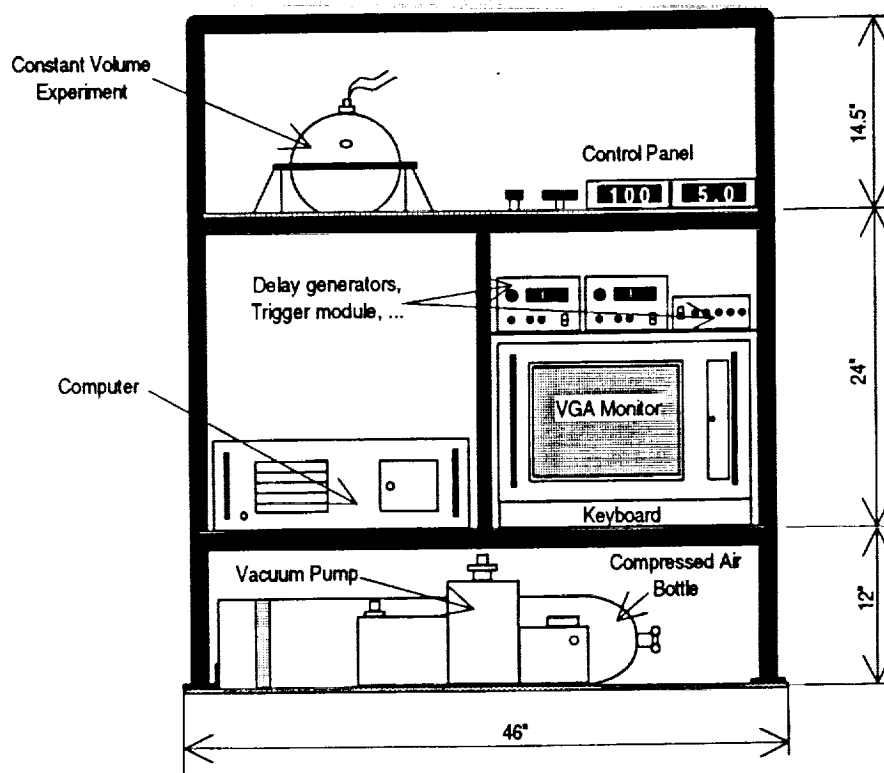


Figure 2 : Microgravity Experimental Package.

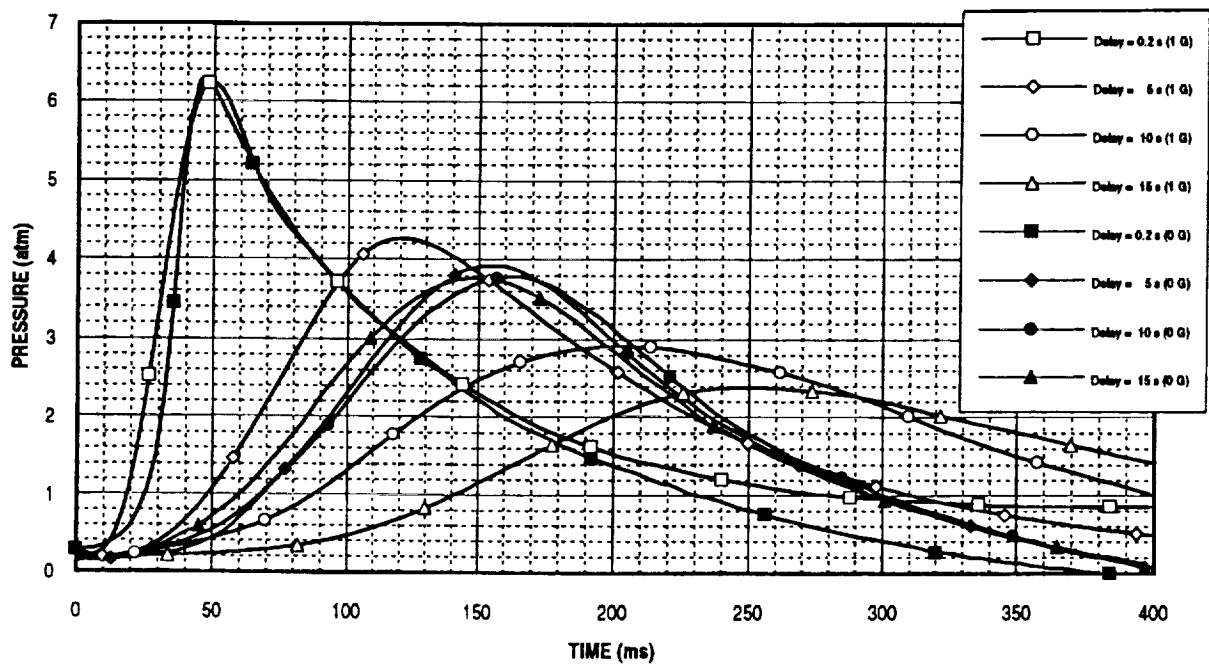


Figure 3 : Pressure rises for different delay times between dispersion and ignition in 1-g and μ -g.

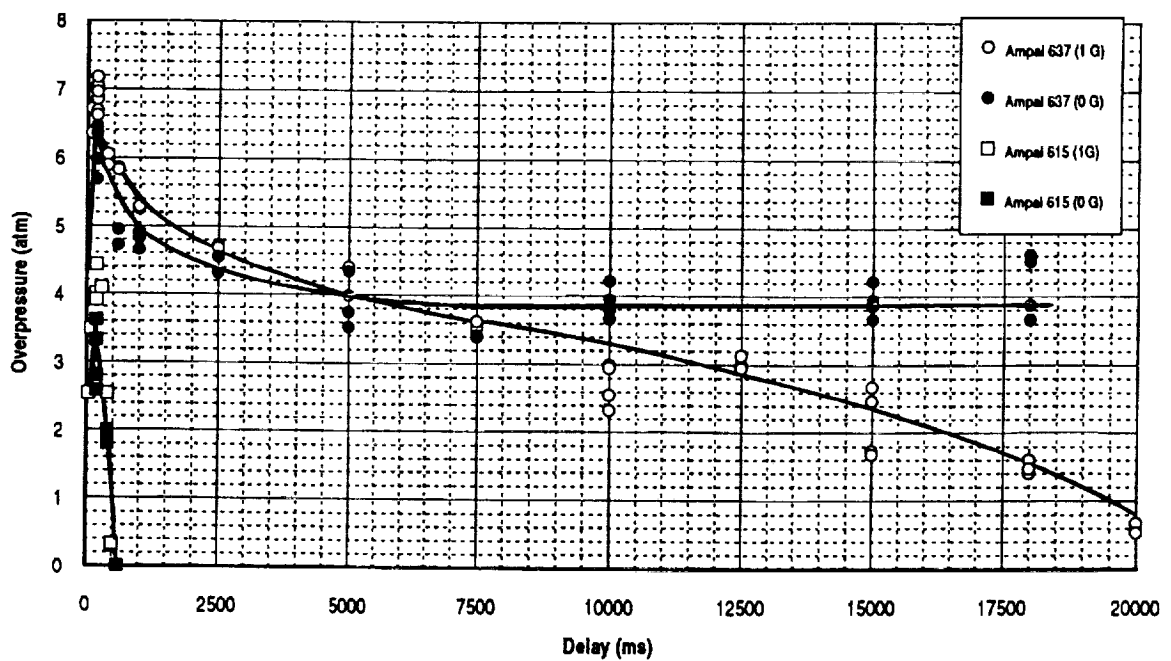


Figure 4 : Variation of peak constant volume explosion pressure with delay time between dispersion and ignition in 1-g and μ -g.

