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## Combustion Science and Technology

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/gcst20>

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Published online: 06 Apr 2007.

To cite this article: Y. Pu, J. Podfilipski & J. Jarosiński (1998) Constant Volume Combustion of Aluminum and Cornstarch Dust in Microgravity, Combustion Science and Technology, 135:1-6, 255-267, DOI: [10.1080/00102209808924160](https://doi.org/10.1080/00102209808924160)

To link to this article: <http://dx.doi.org/10.1080/00102209808924160>

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## Constant Volume Combustion of Aluminum and Cornstarch Dust in Microgravity

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(Received 9 April 1998)

The subject of the present work is to report an experimental comparative study of the effect of dispersion-induced turbulence on dust combustion in constant volume vessel, carried out both in normal gravity and in microgravity environment. Dispersion system with small scale of turbulence, creating uniform homogeneous mixture, was used in experiments. To improve reproducibility of the explosion data an ignitor of small energy, with local soft ignition was developed. Both factors contributed to acquisition of more reproducible experimental data. In experiments under microgravity conditions a dust suspension during combustion remains constant. This makes possible to study dust explosion under stationary dust suspension without influence of turbulence.

**Keywords:** Dust combustion; dust explosion; dust flame

### INTRODUCTION

The fundamental mechanism of the combustion of dust mixtures is still not well understood. In most of the combustion experiments in a constant volume vessel dust is dispersed by a pneumatic dispersion system and is maintained in suspension by means of turbulent mixing. However, turbulence decays very quickly. In normal gravity the decaying turbulence is followed by increasing dust sedimentation, which results in a reduced mean dust concentration. Therefore to carry out the tests with high dust concentration, it is necessary to keep high level of turbulence during

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combustion. The influence of turbulence on the process going inside the flame is manifested by the fact that microscale of turbulence equalizes local nonhomogeneities of dust concentration, while macroscale of turbulence stratifies its concentration, because a particular large-scale vortex structure behaves as a centrifuge. From this point of view a dispersion system with small-scale turbulence should be used to create an uniform homogeneous mixture. The dispersion-induced turbulence affects not only the uniformity of the dust suspension, but also the combustion process, by increasing the dust burning rate. Usually in normal gravity flame propagates through the mixture with decaying turbulent mixing and with decreasing dust concentration (as a result of sedimentation). Both turbulence and concentration depend on a vessel geometry and a dispersion system used and decrease in time. It is rather difficult to distinguish the independent contribution of each factor to the combustion process. In general, for a short ignition delay time there is high influence of the dispersion-induced turbulence and low influence of the dust concentration change on the combustion process. On the contrary, for a long ignition delay time the influence of both factors is inverted.

The ignitor is an additional, very important factor, influencing to a high degree the combustion process. Unfortunately, there are no recommendations what kind of ignitor should be used for ignition of dust mixture. In most of the experiments pyroelectric match-heads or black powder ignitors are used. Most of them contribute to poor reproducibility of the experimental data. The reason for that is volume ignition, usually in different parts of the vessel, because of directed sprinkling of burning particles from bursting ignitor. It happens from time to time, that an exploding ignitor contributes to a secondary dispersion of dust, settling under gravity conditions on the walls, which sometimes can be observed for a long ignition delay time. That is why test to test data variation is observed. That is also why some fundamental parameters determined with help of such technics are not reliable. To improve reproducibility of the explosion data it was necessary to develop an ignitor with local soft ignition.

It is impossible to set up an experimental system under normal gravity conditions to investigate pure laminar combustion of dust mixture with controlled homogeneous concentration. However, the data on laminar combustion in that mixture is essential for the theory of dust combustion process and for understanding of the fundamental mechanism of flame propagation in dust mixture, both laminar and turbulent. It is well known from many experiments with dust combustion that, contrary to gas

combustion, only part of heat is released at the flame front, the remaining part being released behind it, inside the combustion gases.

The microgravity environment in falling assembly of a drop-tower creates an unique situation, where steady uniform dust cloud is maintained during the whole experiment, and the only variable parameter is decaying turbulence.

The objective of the present work is to report an experimental comparative study of the effect of dispersion-induced turbulence on dust combustion in constant volume vessel, carried out both in normal gravity and in microgravity environment.

Systematic studies on constant volume combustion of aluminum dust clouds under microgravity conditions provided by the parabolic flights have been carried out by Peraldi *et al.* (1993). Their data demonstrated that the constant volume explosion pressures were invariant with the ignition delay time between 1 and 15 s. We can conclude from these experiments that ignition delay time equal 1 s is a minimum time to characterize the combustion of uniform dust mixture practically without turbulence.

## EXPERIMENTAL DETAILS

The experiments were carried out in a 7 liter cylindrical closed combustion tube, 0.16 m inside diameter and 0.36 m long ( $L/D = 2.25$ ). The dispersion system, characterized by small-scale turbulence, developed previously was used (Pu, 1988; Pu *et al.*, 1988, 1990). It consists of two independent units, each of them contains a dispersion tube, dust reservoir, magnetic valve, air reservoir and mechanical valve. Two parallel dispersion pipes run along the tube wall and are collocated symmetrically with respect to the central line of the tube. Tens of small holes were bored on each pipe to let the dust to be blown out. In each unit the dispersion process begins with the opening of a solenoid valve causing the dispersion of the dust by an air blast from a 100 cm<sup>3</sup> compressed air reservoir with the initial pressure of 1 MPa. The air passes through the dust reservoir where it entrains the dust which is then dispersed by a perforated pipe located on the wall. Dust distribution along each dispersion tube, divided into several sections, was investigated, and corrections of dispersion holes were made to obtain uniform linear dust dispersion. Dust concentration measurements were carried out under gravity conditions in different sections of the vessel, by a light attenuation method, to prove uniform dust distribution. In microgravity conditions the

nominal dust concentration was based on the mass of dust injected. The duration of the dispersion process is about 100 ms and the mixture introduced causes pressure in the vessel to increase. The system ensures precise control of the whole dispersion process. A black powder match with a calorimetric energy of 2.2 kJ is used for ignition of aluminum dust, and a gas ignitor with an energy of 0.2 kJ for cornstarch dust. The pressure history is measured by transducer FTSV 2100 and sampled and recorded by an AD card installed in a PC computer. The time of combustion is from about 100 ms for a short ignition delay time, to about 300 ms for ignition delay time of 1 s. The apparatus is shown in Figure 1.

The constant volume dust combustion experiments were conducted both under normal gravity and microgravity conditions. Efforts were made to keep the same experimental conditions and procedures for these two sets of experiments, so the only difference was gravity.

Microgravity experiments were conducted in the Institute of Heat Technology and Refrigeration, of the Technical University of Lodz, in a drop-tower which can provide a  $10^{-2}$  g condition for 1.2 seconds.

In microgravity tests the ignition delay time from 200 to 1000 ms was used to examine the effects of turbulence on dust combustion.

Aluminum dust consists of atomized aluminum particles with average diameter of 7.2  $\mu\text{m}$ .

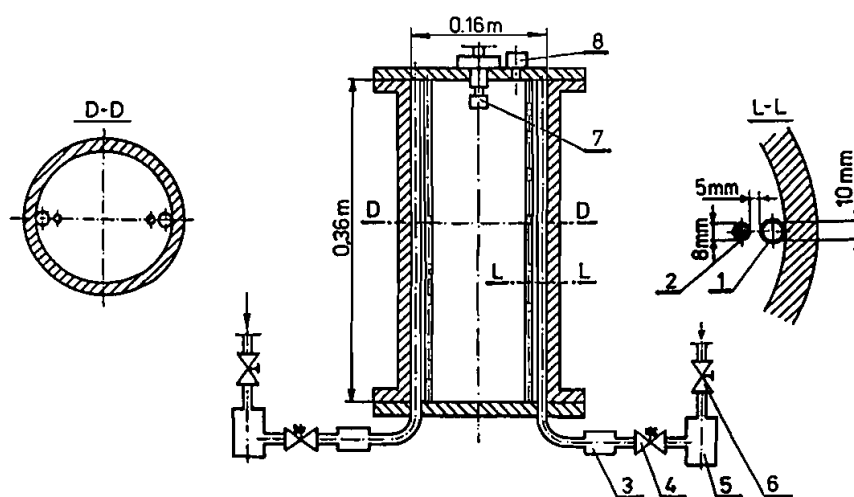


FIGURE 1 Structure of 7 l testing tube (1 – dispersion tube; 2 – bar; 3 – dust vessel; 4 – magnetic valve; 5 – air reservoir; 6 – mechanical valve; 7 – ignitor; 8 – pressure transducer).

Cornstarch ( $C_6H_{10}O_5$ ) consists mostly of volatiles with little fixed carbon or ash. The particles are nearly spherical in shape and are fairly uniform in size with a mean diameter of  $20\mu\text{m}$ . The methods of preparing the cornstarch fuel adopted for the present investigation consist of mixing the cornstarch with 1% by mass of fumed silica gel and storing it in an open jar in an oven at  $50^\circ\text{C}$ .

### Ignition

At the early stage of experiments a typical, commonly used black powder match was adapted to ignition of the dust mixture. As it soon became evident such ignitor was the main source of poor reproducibility of the experimental results. It was necessary to redesign it by minimizing the quantity of black powder and by addition of some kind of mantle around black powder charge. Finally, it contained 0.8 g of black powder with calorimetric energy of 2.2 kJ. The pressure rise from nothing but the ignitor was about 0.05 MPa. The corrected ignitor improved reproducibility of the experimental results and was used for ignition of aluminum dust-air mixture.

For ignition of cornstarch dust-air mixture a new gas ignitor was developed. As an ignitor was used the flame from gas reservoir filled with stoichiometric propane-air mixture. The capacity of the reservoir is  $60\text{ cm}^3$ . The calorimetric energy of such ignitor is 0.2 kJ. It was difficult to distinguish the pressure rise in the vessel from this ignitor. The new ignitor is noticeable by very local, soft ignition and is characterized by very reproducible results of experiments.

### Turbulence

Dispersion-induced turbulence of the vessel was determined. In turbulence measurements two sets of hot-film anemometers were used (TSI and DISA). One probe was kept at the center and at the half-length of the tube. The other one was set at several positions along radial direction. Due to the fact that the nature of the dispersion-induced turbulence is highly transient the measurements had to proceed ensemble average approach. Every measurement was an average over 30 identical experiments, as described in (Pu *et al.*, 1989).

Typical measurements of RMS velocity  $u'$ , instantaneous mean velocity  $U$  and integral scale of dispersion-induced turbulence  $L$  as a function of time  $t$  are shown in Figure 2.

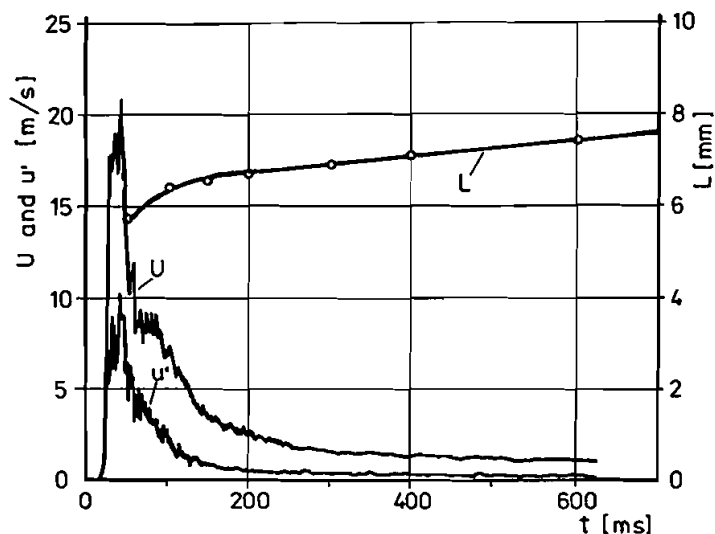


FIGURE 2 The ensemble average instantaneous velocity  $U$ , RMS velocity  $u'$  and integral scale of dispersion-induced turbulence  $L$  as a function of time  $t$  in the closed vessel of 7 l volume.

Velocities of dispersion-induced turbulence reach their maximum values roughly at 30 ms. The maximum value of RMS velocity is as high as 9 m/s. Turbulence decays very fast and at 100 ms value of RMS velocity is only around 2 m/s, and for times greater than 200 ms is less than 0.5 m/s. Though the dispersion system used in experiments is characterized by a small mean scale of turbulence, advantageous for uniformity of dust concentration, there are also larger vortex structures with centrifugal effects of vortices, which may differentiate locally its concentration.

### Combustion of Aluminum Dust-air Mixture

The selected pressure-time curves for the constant volume combustion of aluminum dust at nominal concentration of  $500 \text{ g/m}^3$ , for different ignition delay time, with the superimposed turbulence decay curve are shown in Figure 3.

The curves obtained under normal gravity conditions (dashed lines) decrease their maximum pressure  $\Delta p_{\max}$  and the rate of pressure rise ( $dp/dt$ ) with an increase of ignition delay time. This is due to decrease of the dust concentration as well as the turbulence intensity. It is evident from the presented results that the dust concentration appears to have dominant

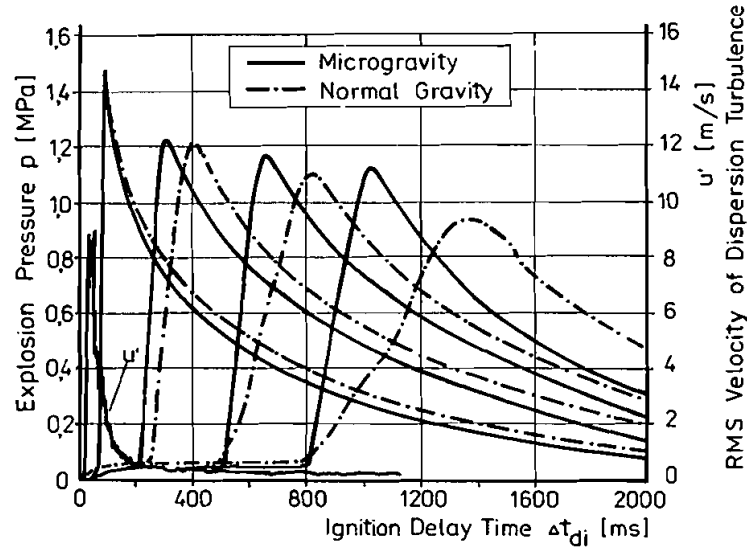


FIGURE 3 Variation of explosion pressure with ignition delay time under microgravity and normal gravity conditions (Al dust,  $d_p = 7.2 \mu\text{m}$ ,  $C_d = 500 \text{ g/m}^3$ , top center ignition).

influence on  $\Delta p_{\text{max}}$  and  $(dp/dt)_{\text{max}}$ , because for ignition delay time longer than 200 ms turbulence intensity varies slightly.

The curves obtained under microgravity conditions (solid curves) indicate much smaller changes to the pressure-time profile. Because dust concentration under microgravity conditions is invariable, small changes of pressure curves one can explain by the decrease in the dispersion induced turbulence.

The maximum explosion pressure of aluminum dust-air-mixture as a function of ignition delay time under microgravity and normal gravity conditions is shown in Figure 4.

High value of the maximum pressure  $\Delta p_{\text{max}}$  at the high level of turbulence intensity indicates very fast combustion process with small heat losses to the wall. As the ignition delay time increases, the combustion process slows down (but not so fast as the turbulence decays) and changes insignificantly. This is the reason why the maximum explosion pressure under microgravity conditions, for ignition delay time more than 200 ms, is almost constant (Fig. 4). The difference between  $\Delta p_{\text{max}}$  values obtained under microgravity and normal gravity conditions can be explained by the variation of dust concentration.

The pressure data were used to calculate the maximum effective burning velocity, as some global parameter, convenient in correlation of the data

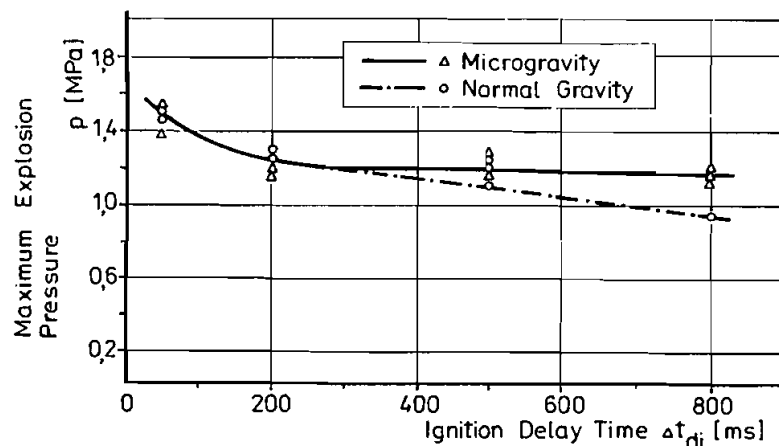


FIGURE 4 Variation of maximum explosion pressure with ignition delay time under microgravity and normal gravity conditions (Al dust,  $d_p = 7.2 \mu\text{m}$ ,  $C_d = 500 \text{ g/m}^3$ , top center ignition).

from different experiments carried out in elongated vessels (Pu *et al.*, 1997). This parameter was first introduced by Lee *et al.*, 1987, and was applied previously (Pu *et al.*, 1988, 1990, 1997) in the form of expression

$$u_{\text{eff}} = \frac{p_0^{1/k}}{\Delta p_{\text{max}}} \cdot \frac{V}{A} \cdot \frac{1}{p^{1/k}} \cdot \frac{dp}{dt}$$

where  $u$  is burning velocity,  $p_0$  initial pressure,  $p$  pressure,  $\Delta p_{\text{max}}$  maximum pressure rise,  $V$  volume of the vessel, and  $A$  area of the flame front.

The maximum value of  $u_{\text{eff}}$  is determined for combustion parameters at  $(dp/dt)_{\text{max}}$ . The calculated maximum effective burning velocity is shown in Figure 5.

For a very short ignition delay time the burning velocity with gravity effect (dashed line), and without it (solid line), have the same values. This reflects the fact that strong turbulence overweigh the gravity settling. As the ignition delay time increases the burning velocity curves drop in a similar way as the curve of turbulence intensity decays. For a given ignition delay time the distance between both burning velocity curves is a measure of difference in dust concentration. Usually, the measurements from experiments obtained under gravity conditions are used to estimate the turbulence effect on explosion parameters. It is clear from Figure 5 that explosion parameters under gravity conditions are influenced both by turbulence and by change of dust concentration.

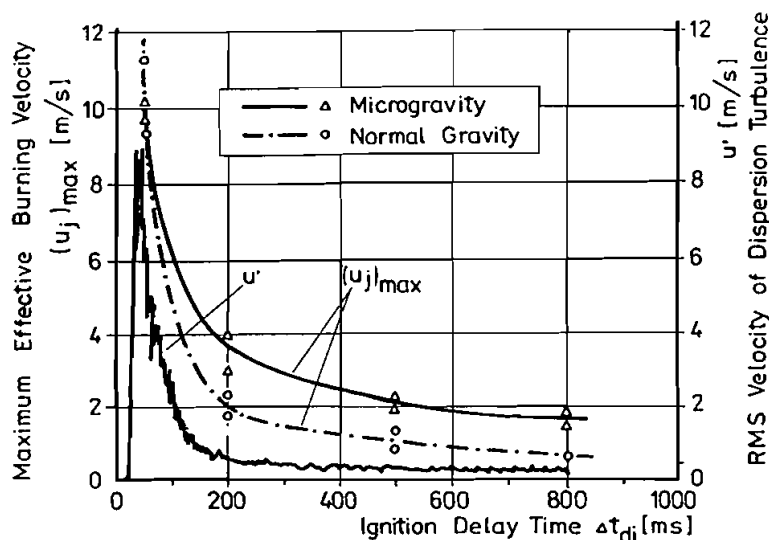


FIGURE 5 Variation of maximum effective burning velocity with ignition delay time under microgravity and normal gravity conditions (Al dust,  $d_p = 7.2 \mu\text{m}$ ,  $C_d = 500 \text{ g/m}^3$ , top center ignition).

### Combustion of Cornstarch Dust-air Mixture

The pressure-time history for constant volume combustion of cornstarch dust-air mixture as a function of ignition delay time, with the superimposed turbulence decay curve, is shown in Figure 6 for experiments under normal gravity and microgravity conditions.

The curves obtained under normal gravity conditions decay in their peak values and in the rate of the pressure rise due to gravity sedimentation. Contribution of decaying turbulence to decrease in the burning rate is manifested by pressure-time curves obtained under microgravity conditions. The variation of the peak overpressure and the peak rate of the pressure rise with the ignition delay time for both normal gravity and microgravity experiments is summarized in Figures 7 and 8.

The calculated maximum effective burning velocity is shown in Figure 9.

For experiments in normal gravity conditions the peak overpressure and the peak rate of the pressure rise drop with increasing ignition delay time due to gravity sedimentation. For the microgravity experiments, the value of peak overpressure is maintained nearly at the same level, while the maximum rate of the pressure rise decreases slightly due to decaying turbulence.

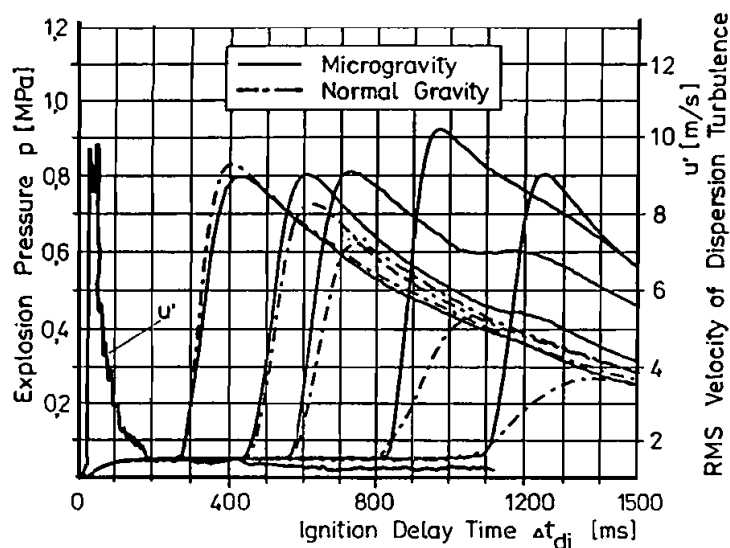


FIGURE 6 Variation of explosion pressure with ignition delay time under microgravity and normal gravity conditions (cornstarch dust,  $d_p = 20 \mu\text{m}$ ,  $C_d = 500 \text{ g/m}^3$ , top center ignitions).

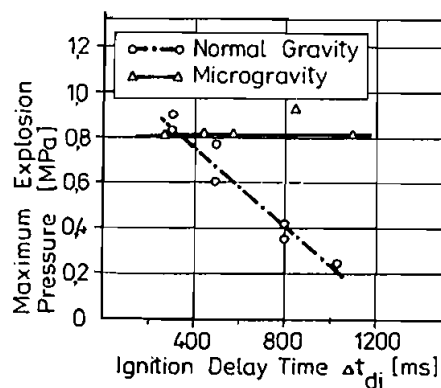


FIGURE 7 Variation of maximum explosion pressure with ignition delay time under microgravity and normal gravity conditions (cornstarch dust,  $d_p = 20 \mu\text{m}$ ,  $C_d = 500 \text{ g/m}^3$ , top center ignition).

### Similarities and Differences in Combustion of Aluminum and Cornstarch Dusts

The main tendencies characterizing the combustion of both dusts are the same. Combustion of aluminum dust as well as cornstarch dust under normal gravity conditions is characterized by a drop in the peak pressure

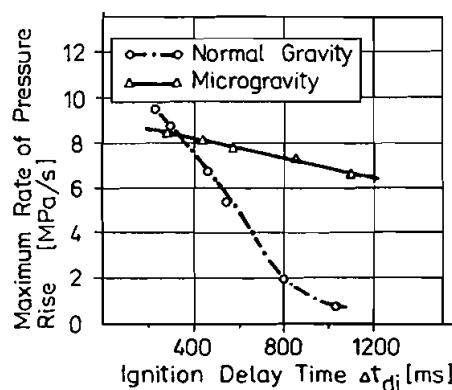


FIGURE 8 Variation of maximum rate of pressure rise with ignition delay time under microgravity and normal gravity conditions (cornstarch dust,  $d_p = 20 \mu\text{m}$ ,  $C_d = 500 \text{ g/m}^3$ , top center ignition).

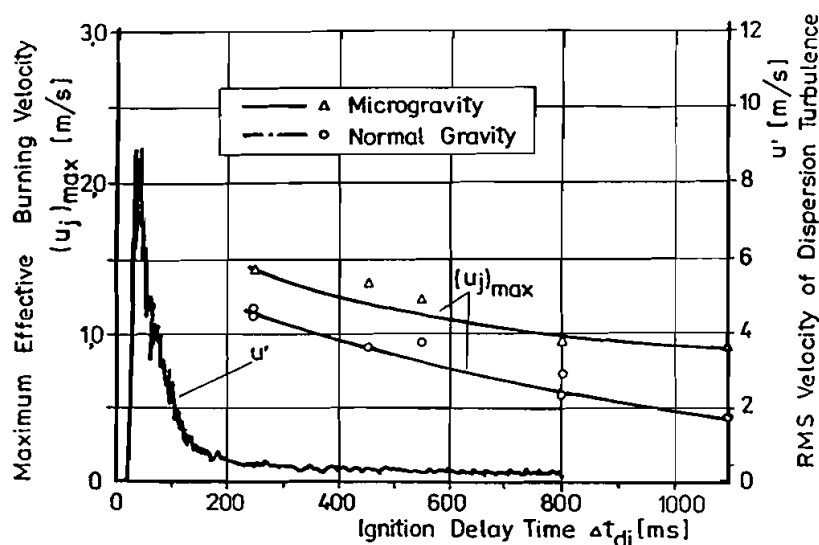


FIGURE 9 Variation of maximum effective burning velocity with ignition delay time under microgravity and normal gravity conditions (cornstarch dust,  $d_p = 20 \mu\text{m}$ ,  $C_d = 500 \text{ g/m}^3$ , top center ignition).

and the peak rate of the pressure rise with an increase of the ignition delay times. The present study indicates that dust concentration appears to have dominant influence on decrease of both measured parameters  $\Delta p_{\max}$  and  $(dp/dt)_{\max}$ . On the other hand, combustion of both dusts under microgravity

conditions revealed tendency to maintain the maximum explosion pressure at almost the same level, for different ignition delay times. At the same time the maximum rate of the pressure rise  $(dp/dt)_{\max}$  during combustion of both dusts decreases insignificantly with ignition delay time, which can be explained by decaying turbulence.

There are also differences in combustion of the two dusts. The maximum explosion pressure  $\Delta p_{\max}$  and the maximum rate of pressure rise  $(dp/dt)_{\max}$  are markedly higher for aluminum dust than for cornstarch. In experiments under gravity conditions both mentioned parameters drop with an increase of ignition delay time much slower for aluminum than for cornstarch.

The most probable reason for that is small particle size of aluminum dust. In this case the vaporizing process is fast and gravity settling is not prominent in comparison with cornstarch or with other dusts. It may be anticipated that coarse and slowly vaporized dust would be a subject of increased sedimentation.

## CONCLUSIONS AND PERSPECTIVES

It is possible to achieve a stationary dust suspension during combustion of dust under microgravity conditions. This makes possible to study dust explosion under stationary dust suspension without influence of turbulence. Further optimization of the various parameters is necessary to improve reproducibility of experimental results. Future experiments in the drop tower will be carried out to study laminar dust flame and the mechanism of its propagation.

## Acknowledgements

This work is sponsored by the Polish State Committee for Scientific Research (KBN), grant No. PB034/T12/96. The authors would like to thank also the Chinese State Committee for Science and Technology and the Polish State Committee for Scientific Research for supporting co-operation in this work.

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