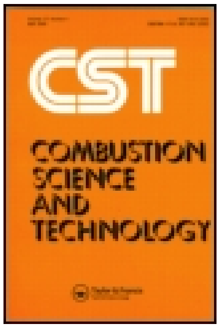

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Visualization of Dust Explosion Under Microgravity Conditions

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The objective of this work was to apply visualization methods to the experimental study of cornstarch dust-air mixture combustion in a closed vessel volume under microgravity conditions. A dispersion system with a small scale of turbulence was used in the experiments. A gas igniter initiated combustion of the dust-air mixture in the central or top part of the vessel. Flame propagation through the quiescent mixture was recorded by a high-speed video camera. Experiments showed a very irregular flame front and irregular distribution of the regions with local reactions of re-burning behind the flame front, at a later stage of combustion. Heat transfer from the hot combustion products to the walls is shown to have an important role in the combustion development. The maximum pressure and maximum rate of pressure rise were higher for flame propagation from the vessel center than for flame developed from the top part of the vessel. The reason for smaller increase of the rate of pressure rise, for the flame developed from the top of the vessel, in comparison with that developed from the vessel center, was much faster increase of the contact surface of the combustion gases with the vessel walls. It was found that in dust flames only small part of heat was released at the flame front, the remaining part being released far behind it.

Keywords: dust explosion, visualization, microgravity

INTRODUCTION

Combustion of suspended solid particles in air is important from the point of view of explosion hazards regarding several areas of modern combustion technology. However, the physical mechanism of flame propagation in dust-air mixtures is still not well understood in comparison with the mechanism related to homogeneous gas flames. For dust-air mixtures, it is difficult to determine such fundamental quantities as laminar burning velocity, flame thickness, quenching

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distance etc. This is due to experimental difficulties in generation of a uniform, quiescent, laminar dust suspension with reproducible dust concentrations, especially in large vessels. Dispersion-induced turbulence commonly used for generation of dust-air mixture decays very fast. Its influence on flame propagation decreases rapidly with increased ignition delay time. Unfortunately, at the same time, dust concentration also decreases due to gravity-induced settlement of dust particles. In experiments carried out under normal gravity conditions, the flame propagates through the mixture with decreasing dust concentration. As a consequence, the experimental results may not be reliable and are usually apparatus-dependent. In recent years, more and more experiments with dust combustion in closed vessels have been carried out under microgravity conditions. The microgravity environment creates a unique opportunity to investigate combustion practically without the influence of turbulence. In microgravity conditions it is also possible to keep the dust in suspension during the entire experiment.

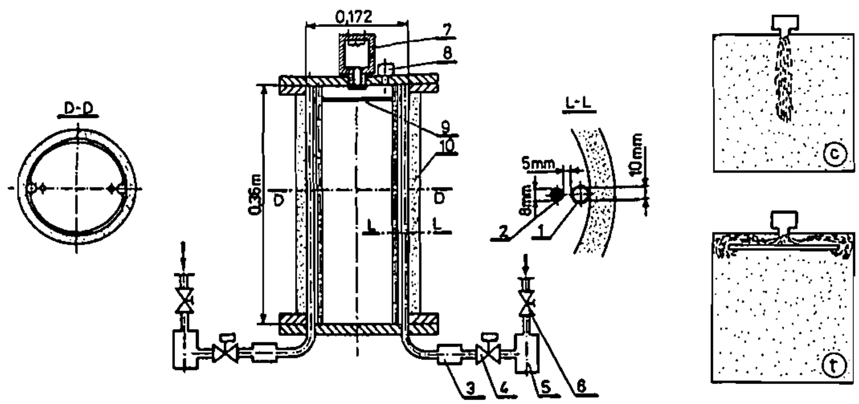

FIGURE 1 Structure of 8.4 l testing vessel (1-dispersion tube; 2-bar; 3-dust vessel; 4-magnetic valve; 5-air reservoir; 6-mechanical valve; 7-igniter; 8-pressure transducer; 9-disc; 10-transparent wall; c-center ignition; t-top ignition

Limitations of closed vessel experiments in gravity conditions also apply to premixed laminar, steady, flat-flame dust-air mixture experiments. Part of these experiments is conducted in microgravity environment [Ballal, 1983, Goroshin *et al.*, 1996a, Goroshin *et al.*, 1996b]. Laminar dust flames, in comparison with laminar gas flames, are dependent on a greater number of parameters. They depend not only on dust concentration and conditions of heat transfer, but also on the size of the particles, the content of volatiles and moisture percentage in the solid fuel. The following phenomena also play an important role in dust combustion: dust concentration, uniformity of the dust suspension, dust sedimentation in a gravity field and the ignition energy and type of the ignition system.

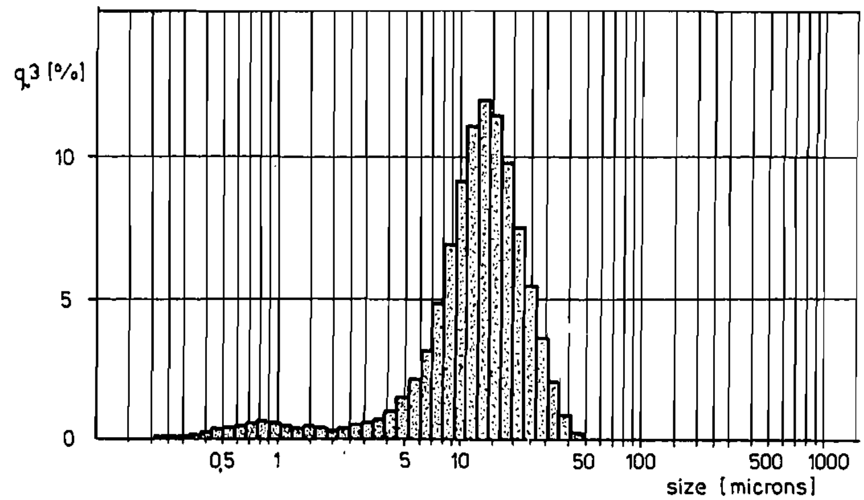

FIGURE 2 Volume distribution of cornstarch particles

Dust-air mixtures can be produced by means of turbulent mixing [Pu *et al.*, 1998], fluidized bed techniques [Proust and Veyssiere, 1988], dust feed assembly [Ballal, 1983], acoustic field [Berlad, 1981], or electrical field [Peraldi *et al.*, 1993]. All these methods have visible effects on the combustion process.

Most of the ground-based experiments on dust combustion have been carried out in constant volume vessels with pneumatic dispersion systems. It was decided to use this system in the present experiments. A dispersion system with a very small scale of turbulence (about 7 mm) was used to produce dust-air mixtures with approximately uniform concentration. In the present study, it was assumed that ignition delay times higher than 0.5 s initiates the combustion process of the dust-air mixture practically with no influence of turbulence. Laminarization of dust combustion occurring in such experiments much better represents real conditions, than does laminar dust combustion carried out in special, usually very small, burners with artificial methods of mixture formation.

The present work applies visualization methods to the experimental study of flame propagation in cornstarch dust-air mixtures, in a closed vessel volume, without influence of turbulence. From the results, a better understanding of the fundamental mechanism of dust-air mixture combustion, based on similarities and differences between gas and dust flames has been sought. The dust combustion experiments in a constant volume vessel with transparent walls were carried

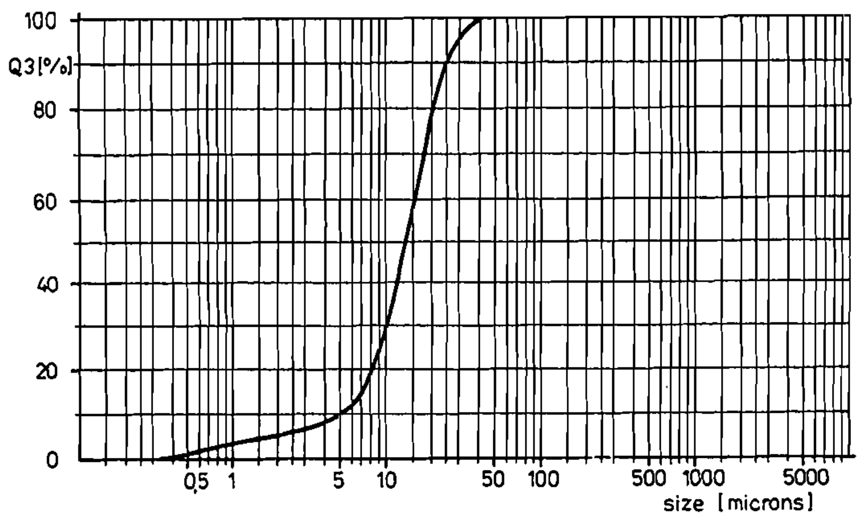

FIGURE 3 Integral curve of the cornstarch particle volume distribution

out in a microgravity environment created by a falling assembly in the drop-tower.

EXPERIMENTAL

The experiments were conducted in a 8.4 liter, cylindrical, closed combustion tube of 0.172 m inner diameter and 0.36 m length (L/D=2.1), made of organic glass (Fig. 1). The dispersion system, characterized by small integral scale of turbulence was used [Pu *et al.*, 1998]. The duration of the dispersion process was about 100 ms and the mixture introduced caused pressure in the vessel to increase (to about 0.04 MPa). The ignition delay time of 500 ms was used in the microgravity experiments to eliminate the effect of turbulence level on the development of combustion process. A gas igniter with small ignition energy of 0.2 kJ was used. It ignited the dust-air mixture by a stream of combustion gases flowing from the igniter reservoir of capacity 60 cu. cm. The igniter could initiate combustion of dust-air mixture in the central (Fig. 1,c) or top part (Fig. 1,t, surface ignition – the stream flowed over the surface of a disc located perpendicular to the jet flow, not far from the igniter) of the vessel. The pressure history was measured by transducer FTSV 2100 and sampled and recorded by an AD card installed in a PC computer. The photographic records of flame propagation were made by Redlake high-speed video camera of the Motion Scope Company with the framing rate of 250 frames/s.

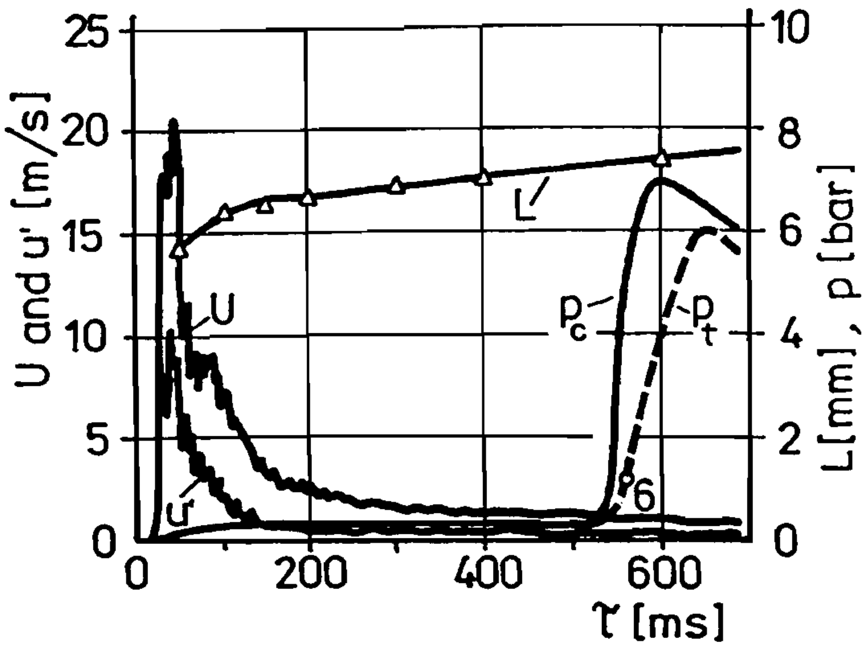

FIGURE 4 Variation of the ensemble instantaneous velocity, U, RMS velocity, u, integral scale of dispersion-induced turbulence, L, measured in similar vessel [Pu *et al.*, 1998] and explosion pressure in present experiments (p_c-center ignition, p_t-top ignition) – as functions of time for cornstarch (d_p=14 μm, c_d=500 g/m^3, t_i=500 ms)

Cornstarch ($C_6H_{10}O_5$) was used as the fuel. The particles were almost spherical with the mass mean diameter of 14 μm. Volumetric distribution of the particles as a function of diameter is shown in Figs. 2 and 3. Particles smaller than 10 μm occupied 30% of the volume while those with diameter 10–20 μm occupied 50% of it. The remaining 20% of the volume were occupied by particles with diameters between 20 μm and 50 μm.

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

RESULTS

The measurements of RMS turbulent velocity u′, instantaneous mean velocity U and integral scale of dispersion-induced turbulence L as a function of time are shown in Fig. 4. The velocities of dispersion-induced turbulence reach their max-

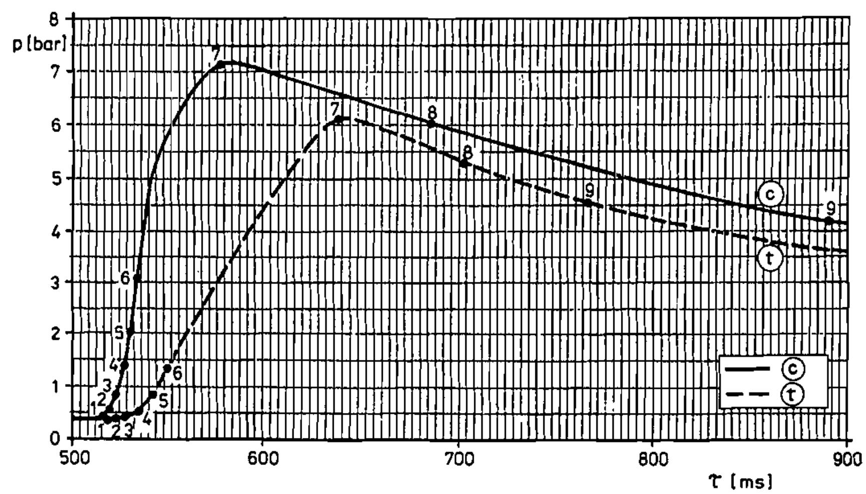

FIGURE 5 Variation of explosion pressure as a function of time. Ignition delay time 500 ms. Microgravity conditions (c-ignition in the center of the vessel; t-ignition at the edge of the disc located in the upper part of the vessel; t6-at this point the flame passed the distance from the top to the bottom of the vessel)

imum values roughly at 30 ms. The maximum value of RMS velocity is as high as 9 m/s. The integral scale of dispersion-induced turbulence is approximately 7 mm. Turbulence decays very fast and at 500 ms value of RMS velocity is less than 0.2 m/s.

A test program of the present study was similar to that made before [Pu *et al.*, 1998]. The experiments were carried out under normal gravity and microgravity conditions. The pressure curves obtained under normal gravity conditions, in comparison with the microgravity curves, decrease in their peak values and in the rate of pressure rise due to gravity sedimentation. Quantitative comparisons of the experimental results, for the same dust-air mixtures, obtained both in normal gravity and in microgravity environment, were made in the previous study [Pu *et al.*, 1998]. In the present study, the same tests data were analyzed from the point of view of visualization method. Special attention was focused on the tests carried out under microgravity conditions, with almost stationary dust suspensions [Pu *et al.*, 1998]. Such conditions made it possible, for a long ignition delay time, to study dust explosion, practically without influence of turbulence. Analysis of the video-camera pictures showed that the combustion process with central ignition resembled volumetric combustion. In search of the pure laminar flame propagation, ignition at the top end of the cylindrical combustion chamber was applied. The character of flame propagation and the pressure curve representing

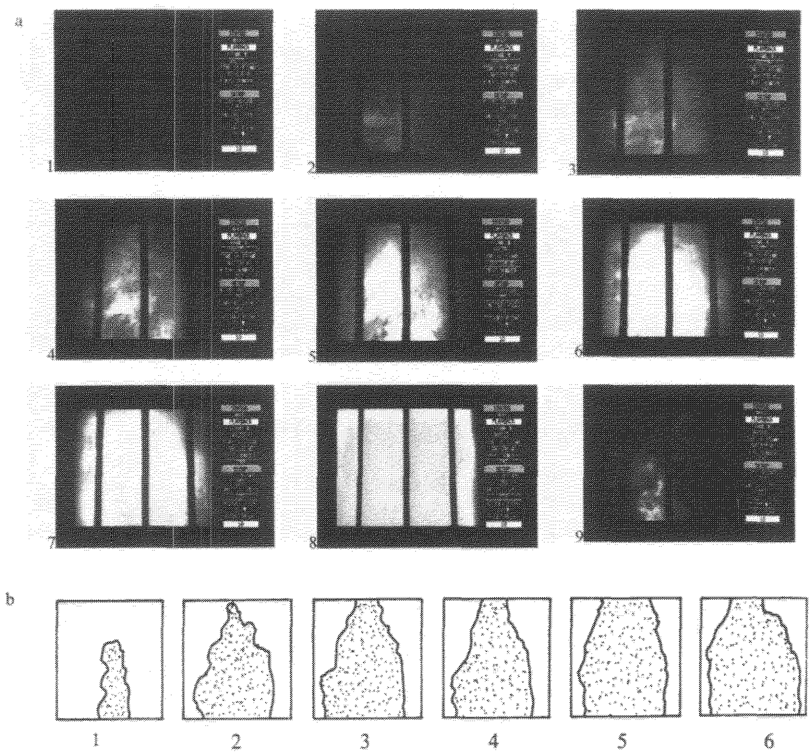

FIGURE 6 History of flame propagation and combustion on selected frames 1–9, corresponding to appropriate points on pressure curve c in Fig. 5., a) direct photographs; b) the most probable position of the flame front. Center ignition. Framing rate: 250 frames/s (See color Plate XII at the back of this issue)

combustion with top ignition appeared different from that with central ignition. The pressure-time history, for the constant volume combustion of cornstarch dust-air mixture, with central or top ignition, in microgravity conditions, is shown in Fig. 5.

Flame visualization appeared to be a serious problem. It was difficult to record combustion development because luminosity of the flame front and the combustion area considerably changed in time. At the beginning of combustion a pale-blue front was poorly visible, while after that the combustion zone became very bright. Selection of camera parameters to record, with great sensitivity, the initial phase of combustion made overexposed the remaining phases of the process. On the other hand, adaptation of the camera to the advanced phases of combustion made the beginning of combustion process not visible. It was decided to use the intermediate parameters of the camera to record the entire combustion

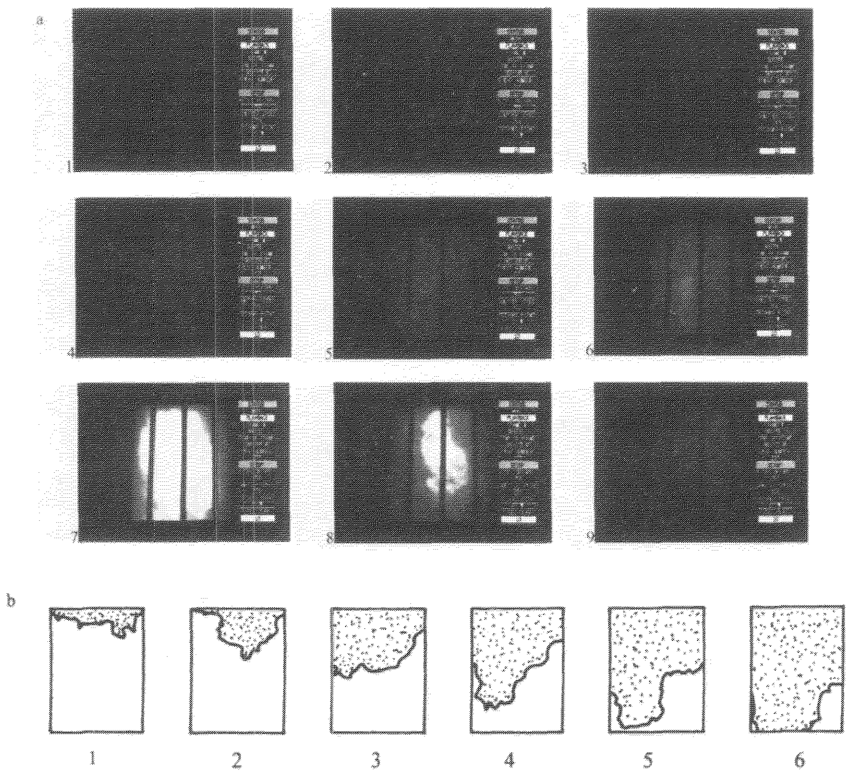

FIGURE 7 History of flame propagation and combustion on selected frames 1–9, corresponding to appropriate points on pressure curve t in Fig. 5., a) direct photographs; b) the most probable position of the flame front. Top ignition. Framing rate: 250 frames/s (See Color Plate XIII at the back of this issue)

process, even if quality of the beginning phase of combustion phase was poor (Figs. 6a and 7a). Every reproduction of the picture additionally reduced its quality. Contrast treatment of the primary picture made it possible to determine the outline of the flame front. This technique was used to determine approximate position of the flame front. The outline of the flame front at the initial frames of a film is shown in Figs. 6b and 7b. The visualization of dust combustion in the closed vessel under microgravity conditions showed, for ignition delay time 500 ms, a very irregular flame front and irregular distribution of the regions with local reactions at a later stage of combustion (Figs. 6 and 7). The continuous flame front was never observed. It is evident from these experiments, that the dispersion system selected with great care does not secure a uniform distribution of dust in the dust-air mixture.

The mixture ignited by a stream of hot gases flowing along the axis burns faster than that ignited in the upper part of the vessel. The maximum pressure is also higher for central ignition.

The irregular dust concentration stationary suspended in the vessel does not change much during combustion – bright regions, representing fast reactions, are quiescent. During flame propagation from the top to the bottom of the vessel, only small part of heat is released, the other parts being released far behind the flame front.

At the final stage of combustion the hot regions generate turbulent motion.

DISCUSSION

For a long time various closed vessel bombs were used to study combustion of dust mixtures, mainly by simulating the explosion conditions in accidents and by classifying the relative level of hazards of different dusts. Most of these experiments are carried out in vessels with pneumatic dispersion systems, where turbulent mixing creates a dust-air mixture. Cognitive value of closed vessel bomb experiments was very limited and resolved itself into collection of various empirical coefficients and indexes. Empirical knowledge from this type of experiments was compiled in a number of monographs (e.g. Barknecht, 1980). Apart from closed vessel bomb experiments, parallel investigations were carried out in search of reliable fundamental data on dust combustion. These data imitated parameters typical for homogenous gas flames, such as laminar burning velocity [Cassel *et al.*, 1949, Smoot *et al.*, 1984, Goroshin *et al.*, 1996a], minimum ignition energy [Eckhof, 1975, Hertzberg *et al.*, 1984], quenching distance [Jarosinski *et al.*, 1986, Proust and Veyssiere, 1988, Goroshin *et al.*, 1996b], flame thickness [Smoot *et al.*, 1984, Mazurkiewicz *et al.*, 1990, Mazurkiewicz and Jarosinski, 1993, Mazurkiewicz and Jarosinski, 1994, Goroshin *et al.*, 1996b]. The most reliable data are quenching distance and laminar burning velocity. Flame thickness, defined by the flame front temperature rise, measured directly for coal dust-air mixture [Smoot *et al.*, 1984] and for cornstarch dust-air mixture [Mazurkiewicz *et al.*, 1990, Mazurkiewicz and Jarosinski, 1993, Mazurkiewicz and Jarosinski, 1994] was found to be 10 mm and 2÷4 mm, respectively. Flame thickness can be also estimated as a half value of a measured quenching distance [Jarosinski, 1983]. For flames propagating in fine coal dust-air clouds and in cornstarch dust-air clouds the quenching distance was 25 mm and 6 mm, respectively [Jarosinski *et al.*, 1986]. On the other hand for aluminum dust-air clouds (with particle size d_{32}=5.4 μm) the quenching distance was found to be about 5 mm (Goroshin *et al.*, 1996b) and laminar burning velocity about 22 cm/s

(Goroshin *et al.*, 1996a), for nearly a whole range of investigated dust concentrations. For flames propagating in methane-air mixtures the quenching distance was found to be 2 mm for stoichiometry and 9.2 mm for lean limit flames [Jarosinski, 1983] and laminar burning velocity 43 cm/s and 15 cm/s, respectively [Andrews and Bradley, 1972]. Also all other values of measured parameters for fine dust flames were comparable with experimental data for gas flames. Because the order of magnitude of measured dust flame parameters was the same as in gas flames the processes controlling flame propagation in these flames should be similar. All these data support the opinion of Smoot and co-workers, who reported a series parametric predictions to identify the controlling processes in premixed fine coal dust-air flame [Smoot *et al.*, 1984]. It has been found as a result of these predictions, that the rate of flame propagation is controlled by the rate of streamwise molecular diffusion of oxygen and volatiles, together with heat conduction from the hot gas to the particles. It can be concluded, as a result of all these works that the most important processes controlling flame propagation in gas and dust cloud flames are similar. This indicates that all necessary information about dust flame propagation is contained in a relatively thin flame front.

On the other hand dust flames are very different from gas flames propagating in homogenous mixtures. Basic differences between combustion of dust clouds and homogenous gas mixtures are due to differences in properties of those mixtures. A dust cloud is a heterogeneous mixture. No single method of dust formation can secure uniform dust concentration. Turbulence usually present in dust cloud combustion differentiates local dust concentration. It is true that a very small scale of dispersion-induced turbulence promotes production of a dust-air mixture with uniform concentration, but at the same time vortical structures of large scale turbulence always present during dust dispersion process make dust concentration nonuniform, due to centrifugal effects. It can be observed in experiments that, finally, the large-scale turbulence plays a crucial role. In the experiments carried out in microgravity conditions turbulent pulsations decay very fast (in Fig. 4 RMS velocity decreased from 10 m/s to 0.5 m/s in 0.2 s), while dust particles continue to be in suspension. In such conditions flame propagates in the quiescent mixture with very different local concentrations. This would result in different local burning velocities and in diffusion combustion behind the flame front.

CONCLUSIONS

Visualization method was used to interpret flame propagation in cornstarch dust-air mixtures in a microgravity environment without turbulence influences.

Flame propagation through the quiescent mixture was recorded by a high-speed video camera. Analysis of the combustion process observed on the video-camera pictures showed that a dispersion system used in the experiments has not secured a uniform distribution of the dust-air mixture. Experiments showed irregular distribution of the regions with local reactions. It was also found that the maximum pressure and the maximum rate of pressure rise were influenced by heat transfer from the hot combustion products to the vessel walls. Central ignition delays a contact of the combustion gases with the walls in comparison with a top ignition, and this secures higher pressure and higher rate of pressure rise. Analysis of the frames in Fig. 7 and the curve t in Fig. 5 shows, that contrary to gas flames, the dust flame propagation from the top to the bottom of the vessel is not explicit with heat release. In gas flames the entire heat is released at the flame front. In dust flames, only small part of heat is released at the flame front, the remaining part being released far behind it. In other words, propagation of the flame front through the dust-air mixture is not equivalent to release of the entire heat contained in the dust fuel.

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