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Experimentally determined flame properties near flammability limits under gravity and microgravity conditions

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Flammability limits identified in a vertical tube depend on the direction of flame propagation. Usually such limits are determined during flame propagation from the open to the closed end of the tube. A difference between the flammability limits for upward-and downward-propagating flames depends on the Lewis number of considered mixtures. For the Lewis number, defined as the thermal diffusivity of mixture to the mass diffusivity of deficient reactant, which is less than 1 ($Le=a/D<1$), flammability limits, in a gravity field, are always different for flames propagating upwards or downwards. It is the well known fact that a factor responsible for the existence of two different flammability limits is preferential diffusion of deficient reactant. If the Lewis number for a given mixture is less than 1 and the flame in relation to a fresh mixture is convex, then preferential diffusion supplies the reaction zone with additional molecules of deficient reactant. In rich mixtures of higher hydrocarbons such a role is played by oxygen. For example, ethylene and propane are characterized by $Le < 1$ for rich mixtures. Thus, the flammability limits for flame propagating in a rich propane/air mixture is 6.3% C_3H_8 (ϕ=1.60) for downward propagation and 9.2% C_3H_8 (ϕ=2.42) for upward propagation [1]. The concentration gap between two limits is extremely large.

The fact that the experimentally measured flammability limits are dependent not only on the apparatus and experimental technique, but also on the gravity has been well known for a long time [2-4]. The understanding of the mechanism of flame propagation and extinction at the flammability limits was broadened by microgavity experiments in which flame propagation can be observed with no influence of buoyancy forces. Krivulin et al. [5] were some of the first to study near limit phenomena under microgravity conditions. Their observations were made during zero g trajectory flights of up to 8 seconds duration. They studied zero g rich limit propane/air and lean limit hydrogen/air flames using central ignition in a 20-liter cylindrical closed vessel of equal length and diameter. During the experiments they measured pressure in the cylinder and recorded flame propagation by a camera. They found that the flammability limits determined under microgravity conditions were between those obtained under normal gravity conditions for the upward and downward propagating flame in a standard flammability tube. Nearly at the same time Strechlow and Reuss [6] came to the same conclusion in their drop-tower experiments with flames propagating in lean methane/air mixtures in an open flammability tube. Some time later Roney and Wachman [7] confirmed these observations. In the next set of experiments carried out under microgravity conditions Strechlow et al. [8] studied flame propagation and extinction in lean methane/air and lean propane/air mixtures with the use of a very sensitive camera. The experiments were carried out in a shortened (0.71 m long) standard diameter (51mm) vertical flammability tube with mixture ignition at its open end. They found that the flammability limit for a lean methane/air mixture under microgravity conditions was the same as for the upward propagating flame under gravity conditions (5.25% CH_4), while for a propane/air mixture it was outside the limit for the upward propagating flame under gravity conditions (2.06% C_3H_8 against 2.15% C_3H_8). Jarosinski et al. [1] observed in their study the behavior of flame propagation in rich propane/air mixtures under microgravity conditions (in the range of concentration between 6.4% C_3H_8 and 9.5% C_3H_8). Their experiments were carried out in a cylindrical closed vessel of 8.5-L capacity. Pressure and flame propagation histories were recorded. The flammability limits under microgravity conditions were found to be between the upward and downward limits obtained in a standard flammability tube under normal gravity conditions. It was also found that there were two limits under microgravity conditions: at a concentration of 8.75% of C_3H_8 when indicated by visible flame propagation and 9.0% C_3H_8 when indicated by an increase of pressure without observed flame propagation [1]. These limits, as compared with the flammability limits determined in a vertical tube under gravity conditions, were found to be far behind the limit for the downward-propagating flame (6.3% C_3H_8) and close to the limit for the upward-propagating flame (9.2% C_3H_8). The experimental results demonstrated that the flammability limit under microgravity conditions was close to the limit for the upward-propagating flame at 1g. It was shown that under microgravity conditions the behavior of flame propagation and pressure history near the flammability limit was completely different from that at 1g, since the flame starting from a concentration of 8.75% of C_3H_8 was not visible but combustion was indicated by pressure rise.

It was decided in the present work to study in detail the flame behavior in a propane/air mixture near lean and rich flammability limits under gravity and microgravity conditions. To explore effectively not visible in the previous study reaction region a special schlieren system was designed for a drop tower and an instant temperature measuring system was installed to observe the temperature history during propagation of the flame front.

Experimental details

The falling assembly in a form of steel framework of 800mm × 800mm × 1000mm size was used for microgravity experiments. It contained a compact schlieren system (Fig.1), a high-speed video camera, instant temperature and pressure measuring systems and a spark ignition system with a large spark gap created by extended electrodes located at two perpendicular each other vessel walls.

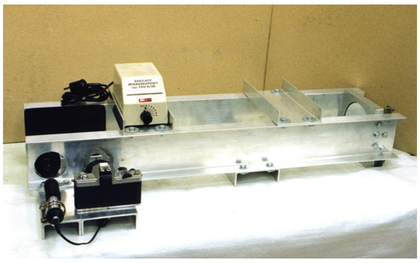

Fig. 1. Schlieren system used in microgravity experiments.

A small (0.5 liter) cubic closed vessel with square cross-section (Fig. 2) and a shortened standard flammability open tube (Fig. 3), both with schlieren quality glass windows, were used to study limit flames under gravity and microgravity conditions.

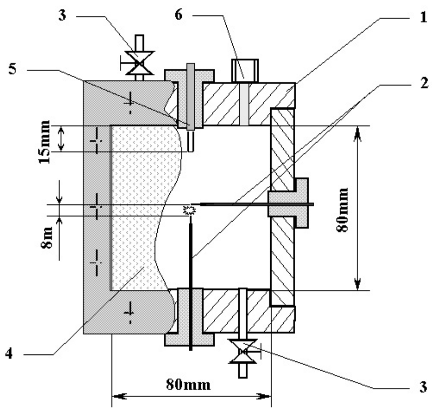

Fig. 2. Cubic combustion vessel with central ignition. 1-vessel wall, 2-ignition electrodes, 3-valve, 4-quartz window, 5-temperature probe, 6-pressure transducer.

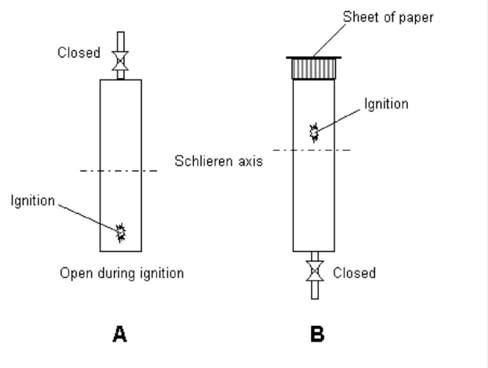

Fig. 3. Flammability open tube (0.7 m long) with 5cm×5cm cross-section. A-tube position during gravity experiments, B-tube position during microgravity experiments.

Propane/air mixtures were prepared by blending propane and air using flow-meters. The vessel was filled with the mixture by displacement. Rich propane/air mixtures were used in experiments with seven different concentrations: 6.5%, 7.3%, 8.4%, 8.8%, 9.0%, 9.1% and 9.2% C_3H_8. Special attention was devoted to observation of flame behavior at the flammability limit. The purity of propane was 96.4%. The remaining 3.6% consisted of ethane, butane, and butylenes. Compressed air was used directly from the air compressor.

A membrane-type strain-gauge transducer, located at the bottom part of the vessel, measured the vessel pressure history with a sensitivity of 500mV/MPa.

The flame temperatures were determined by the use of a horizontally positioned resistance thermometer with a 2.2 mm long unshielded 10μm Pt-Rd10% wire. The wire time constant was about 5ms. The response time of this probe during measurements of laminar flame temperature profile was sufficiently fast to follow the local gas temperature. No corrections for heat losses were made. The thermometer was calibrated by using the method and data from [1]. The temperature probe was located at the center of the top wall of the vessel with its sensor 15 mm apart. It measured the temperature history during propagation of the flame front.

A computer recorded a signal from the pressure transducer and the temperature probe after amplification. A high-speed video camera supplied by Redlake Co. was used to record by the schlieren system the history of flame propagation.

The microgravity tests were performed at the drop tower located in the Combustion Laboratory of the Technical University of Lodz. The free-fall time of the falling assembly was 1.2 s.

The experiments were carried out at the temperature 20±5° C.

Experimental results and discussion

In the present study of flame development in a closed cubic vessel a history of pressure, temperature and flame propagation was recorded under 1g and μg conditions. In similar experiments with open tube only subsequent pictures of propagating flame was recorded. The microgravity experiments were compared with those conducted under normal gravity conditions.

Closed vessel

The experiment began with ignition of the flammable mixture at the center of the vessel. A high speed video camera registered a schlieren image of flame development, while temperature and pressure records indicated the arrival of the flame front and changes in combustion pressure under the influence of heat release (Fig. 4). It was found for the technical propane used in experiments that the lean and the rich flammability limits were 2.2% C_3H_8 and 9.2% C_3H_8, respectively, for an upward-propagating flame under gravity conditions. The same results were obtained for flame propagation under microgravity conditions. In both sets of experiments the probability of flame development from spark ignition for a limit mixture was similar and close to 50%.

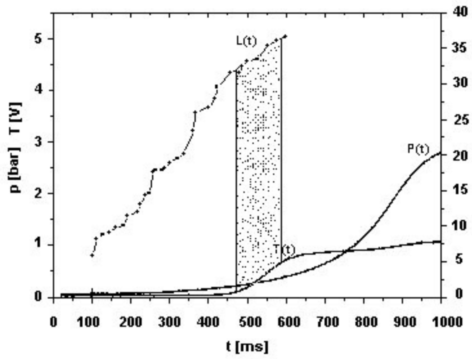

Fig. 4. Pressure and temperature records as a function of time for mixture concentration 9.2% C_3H_8 under microgravity conditions. L(t) indicates the distance from the ignition point to the flame front highest temperature. Central ignition.

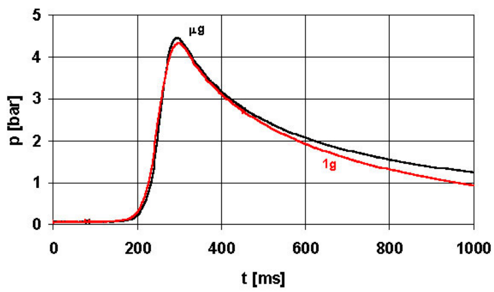

Fig. 5. Pressure records as a function of time for mixture concentration 2.2% C_3H_8 under gravity and microgravity conditions. Central ignition.

At the lean flammability limit practically no difference was found in flame propagation from the point of view of gravity acceleration (see Fig. 5).

A detailed experimental study was devoted to flames propagating in rich mixtures between the limit concentrations 6.3% C_3H_8 and 9.2% C_3H_8. In a former rich limit study [1] it was found that an increase in near-limit mixture concentration was followed by an increase of flame thickness and by a significant decrease of flame propagation velocity. It was decided in the present study to estimate the role played by the mixture concentration in flame propagation under the influence of normal gravity acceleration and without this influence. It appeared that the flame behavior and burning out of the mixture are practically the same for mixtures with a relatively high laminar burning velocity and very different for mixtures characterized by its low value. The closer the concentration to the flammability limit, the more diversified is mixture burning out. The main factor creating differences is most probably the laminar burning velocity. For mixtures distant from the flammability limit the laminar burning velocity is relatively high, the combustion process is fast and the influence of buoyancy is very small. Thus, for instance, a flame propagating in a mixture with a concentration equal to 6.5% C_3H_8 practically does not show any difference in flame propagation under gravity and microgravity conditions. On the other hand, the flame shape and the related to it total flame surface significantly diversify under the influence of gravity for the richer mixtures approaching this limit (Figs. 6 and 7).

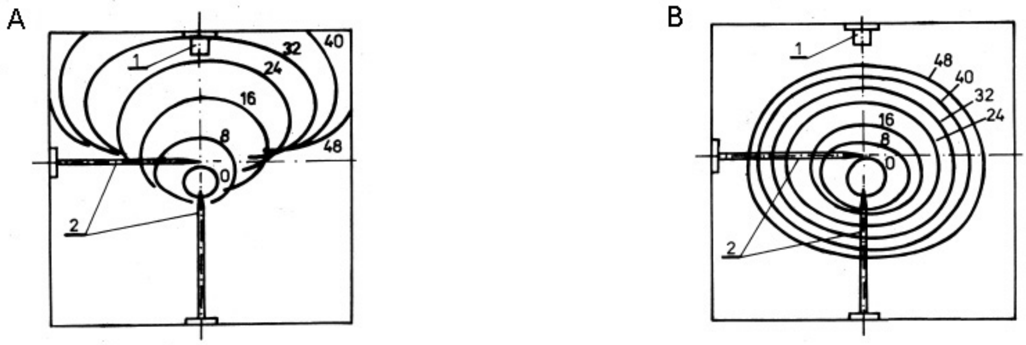

Fig. 6. History of flame propagation in the propane/air mixture with a concentration of 8.4% C_3H_8 under conditions of normal gravity (A) and microgravity (B). Ignition at the center of the cubic vessel. 1-temperature probe, 2- electrodes. Flame propagation is indicated in the form of its successive contours. Numbers mark subsequent frames. Frame rate: 250 frames/s

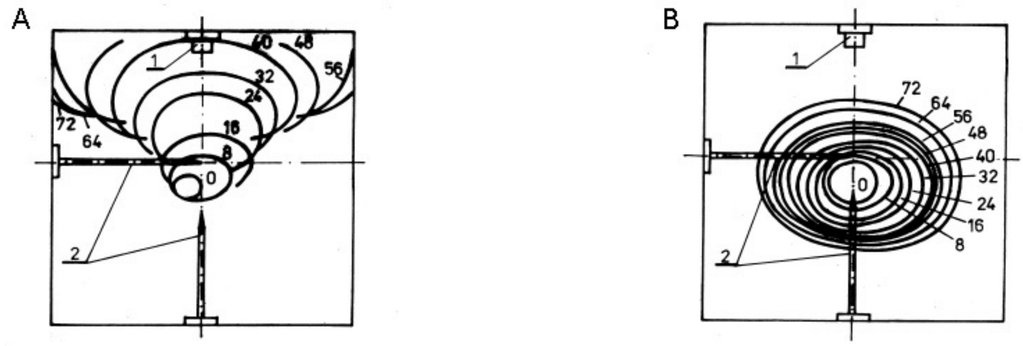

Fig. 7. History of flame propagation in the propane/air mixture with a concentration of 9.2% C_3H_8 under conditions of normal gravity (A) and microgravity (B). Ignition at the center of the cubic vessel. 1-temperature probe, 2- electrodes. Flame propagation is indicated in the form of its successive contours. Numbers mark subsequent frames. Frame rate: 250 frames/s

Buoyancy forces influenced flame propagation in the limit mixture under normal gravity conditions. In such a mixture the volume of hot combustion gases as well as the flame surface grew slower than in microgravity. About 140 ms after ignition the expanding flame touched the top wall of the vessel and from this instant it started to be quenched without ability to propagate downwards (see Fig. 7A). Pressure records corresponded with the lower propagation velocity and heat losses: The rate of pressure rise and the maximum pressure remained lower and the time of combustion was shorter in comparison with microgravity conditions. Thus the near rich flammability limit the flame propagating through the same mixture develops much faster under microgravity than under gravity conditions (see Fig. 8).

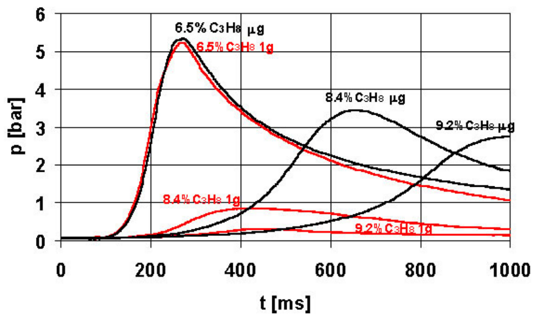

Fig. 8. Pressure records as a function of time determined during gravity and microgravity experiments. Flame propagation in the propane/air mixture with concentrations of 6.5% C_3H_8, 8.4% C_3H_8 and 9.2% C_3H_8. Central ignition.

In the limit mixture the laminar burning velocity is very small in comparison with the buoyancy velocity and it is the reason why under gravity conditions only a small part of the mixture volume can burn. Change of the combustion pressure Δp_z and the maximum rate of pressure rise $(pd/dt)_{max}$ with near limit mixture concentration is shown in Fig. 9. Both parameters are determined during flame propagation from the center of the vessel to its walls under gravity and microgravity conditions. Experiments were highly reproducible (Fig. 10). For experiments with the same mixture concentration usually such a mixture was prepared in advance in a special vessel. Then a set of tests were made with the use of the mixture from this vessel.

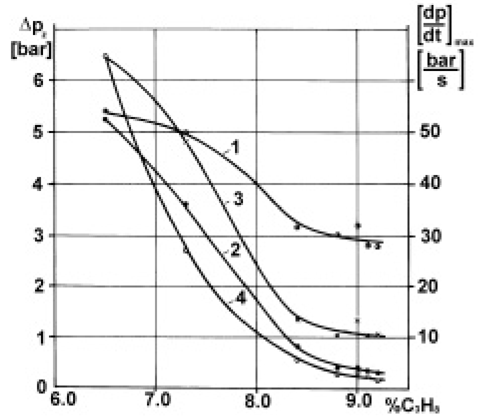

Fig. 9. Measured pressure Δp_z and measured maximum rate of pressure rise $(dp/dt)_{max}$ as a function of propane concentration in a mixture with air determined under normal and microgravity conditions. 1-Δp_z, μg, 2-Δp_z, 1g, 3-$(dp/dt)_{max}$, μg, 4-$(dp/dt)_{max}$, 1g.

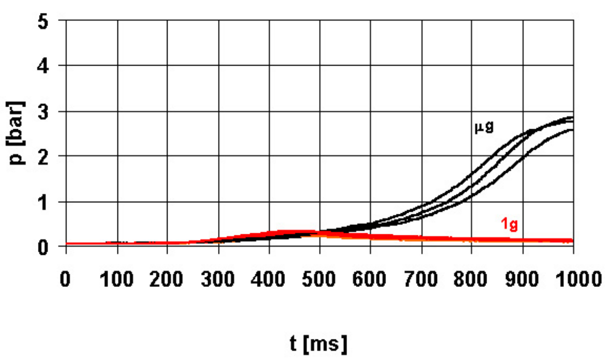

Fig. 10. Reproducibility of pressure history during combustion of the limit mixture (9.2% C_3H_8) under gravity (5 curves) and microgravity conditions (3 curves).

Open tube

Experiments with upward propagating flames under normal gravity conditions in a shortened open flammability tube confirmed the results obtained before in a standard flammability tube [9] for the lean and rich limits (2.25% C_3H_8 and 9.2% C_3H_8, respectively). Similar experiments carried out under microgravity conditions required some changes in the exit part of the tube to prevent the sucking effect caused during falling down of the drop-tower cage (see Fig. 3B). It was found that flammability limits under microgravity conditions were very close to those determined under gravity conditions: the lean limit was the same (2.25% C_3H_8), but the rich limit appeared to be slightly less (9.1% C_3H_8).

Fig. 11. History of flame propagation in the propane/air mixture with a concentration of 2.25% C_3H_8 under normal gravity (A) and microgravity (B) conditions. Points of ignition shown in Fig. 3. Flame propagation is indicated in the form of its successive contours. Distance between subsequent contours equal to 8 frames. Frame rate: 250 frames/s

In Fig. 11 the flame propagating upward under gravity conditions is compared with the flame propagating under microgravity conditions at the same near limit mixture concentration equal to 2.25% C_3H_8. Under gravity conditions flame propagation is controlled by buoyancy forces, while under microgravity conditions this role is played only by the laminar burning velocity. Extinction of the upward propagating flames is initiated by excessive flame stretch at the tip, while extinction of flames propagating under microgravity conditions is caused by heat loss to the walls [8]. The cooling effect of the walls on flame propagation can be observed in Fig. 11B: the flame surface decreases and becomes less convex. At limit mixture the cooling effect of the walls initiates flame extinction.

Conclusions

1. Flame propagation and extinction were studied in lean and rich propane/air mixtures in a small, cubic, closed vessel and a shortened, open, flammability tube under gravity and microgravity conditions.

2. The lean limit was determined to be 2.2% C_3H_8 in closed vessel and 2.25% C_3H_8 in an open tube both under gravity and microgravity conditions.

3. The rich limit was determined to be 9.2% C_3H_8 in a closed vessel both under gravity and microgravity conditions. This limit was also found to be 9.2% C_3H_8 in an open tube for upward propagation under gravity conditions and 9.1% C_3H_8 under microgravity conditions. In a closed vessel only a small amount of limit mixture composition can burn out under gravity conditions.

4. All observations made in the present study with the use of the schlieren method and instant temperature measurements can rationally explain the previous results.

Acknowledgements

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