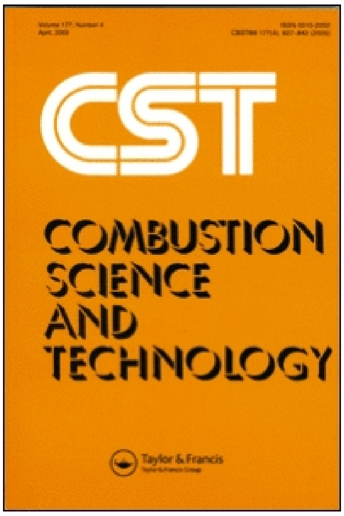

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EXPERIMENTALLY DETERMINED FLAME PROPERTIES NEAR FLAMMABILITY LIMITS UNDER GRAVITY AND MICROGRAVITY CONDITIONS

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Flammability limits for flames propagating in a rich propane/air mixture under gravity conditions appeared to be 6.3% C_3H_8 for downward propagation and 9.2% C_3H_8 for upward propagation. Different limits might be explained by the action of preferential diffusion of the deficient reactant ($Le < 1$) on the limit flames, which are in different states of instability. In one of the previous studies, the flammability limits under microgtravity conditions were found to be between the upward and downward limits obtained in a standard flammability tube under normal gravity conditions. It was found in those experiments that there are two limits under microgravity conditions: one indicated by visible flame propagation and another indicated by an increase of pressure without observed flame propagation. These limits were found to be far behind the limit for downward-propagating flame at 1 g (6.3% C_3H_8) and close to the limit for upward-propagating flame at 1 g (9.2% C_3H_8). It was decided in the present work to apply a special schlieren system and instant temperature measuring system for drop tower experiments to observe combustion development during propagation of the flame front. A small cubic closed vessel (inner side, 9 cm × 9 cm × 9 cm) with schlieren quality glass windows were used to study limit flames under gravity and microgravity conditions. Flame development in rich limit mixtures, not visible in previous experiments under microgravity conditions for strait photography, was identified with the use of the schlieren method and instant temperature measuring system. It was found in experiments in a small vessel that there is practically no difference in flammability limits under gravity and microgravity conditions. In this paper, the mechanism of flame propagation under these different conditions is systematically studied and compared and limit burning velocity is estimated.

Keywords: Flammability limits; Limit burning velocity; Microgravity

INTRODUCTION

Flammability limits identified in a vertical tube under gravity conditions for mixtures with Lewis number of the deficient reactant $Le < 1$ depend on direction of flame propagation, but limits for mixtures with $Le > 1$ are nearly the same. Such limits are determined during flame propagation from the open to the closed end of

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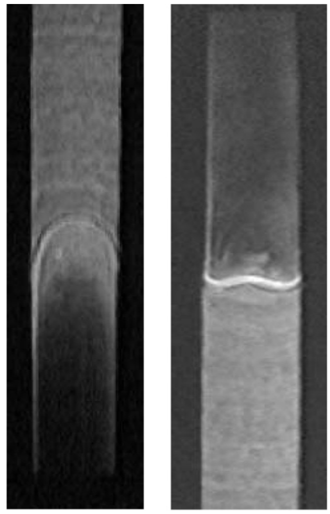


Figure 1 Near limit flames propagation in lean propane/air mixtures from the open to the closed end of the vertical tube: a) upward propagating flame, b) downward propagating flame.

the tube. The upward propagating limit flame is convex and positively stretched, while limit flame propagating in opposite direction is nearly flat (see Figure 1).

The upward propagating limit flame in a mixture with $Le < 1$ is affected by preferential diffusion. The tip of this flame is supplied with additional amount of a deficient reactant. This increases its burning intensity and temperature. Under such conditions, flame extinction limit can be extended in comparison with flammability limit of downward propagating flat flame.

In contrast, the limit flame propagating upward in a mixture with $Le > 1$ decreases its burning intensity under stretch effect. Decreased temperature and laminar burning velocity can lead directly to flame extinction at the same composition as for downward propagating limit flame.

Lewis number $Le < 1$ is characteristic, for example, for lean limit hydrogen/air and methane/air mixtures (fuel as a deficient reactant) and rich limit propane/air and higher hydrocarbon/air mixtures (oxygen as a deficient reactant). Thus, flammability limits for flame propagating in rich propane/air mixture is 6.3% C_3H_8 ($\Phi = 1.600$) for downward propagation and 9.2% C_3H_8 ($\Phi = 2.413$) for upward propagation (Jarosinski et al., 2002). The concentration gap between the two limits is extremely large.

On the other hand, $Le > 1$ is characteristic for rich limit methane/air and lean limit propane/air mixtures. Flammability limits for upward and for downward propagating flames in these mixtures are nearly the same.

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 (Levy, 1965; Lovachev et al., 1973; Krivulin et al., 1980). Understanding of the mechanism of flame propagation and extinction at the flammability limits was extended by microgavity experiments in which flame propagation can be observed with no influence of buoyancy forces. Krivulin et al. (1980) 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 eight seconds in duration. They studied 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. At the same time, Strehlow and Reuss (1980) came to the same conclusion in their drop-tower experiments with flames propagating in lean methane/air mixtures in open flammability tube. Ronney and Wachman (1985) later confirmed these observations. In the next set of experiments carried out under microgravity conditions, Strehlow et al. (1986) studied flame propagation and extinction in lean methane/air and lean propane/air mixtures with the use of very sensitive camera. The experiments were carried out in a shortened (0.71 m long) standard diameter (51 mm) vertical flammability tube with mixture ignition at its open end. They found that the flammability limit for lean methane/air mixture under microgravity conditions was the same as for upward propagating flame under gravity conditions (5.25% CH_4), while for propane/air mixture, it was outside the limit for upward propagating flame under gravity conditions (2.06% C_3H_8 against 2.15% C_3H_8). Jarosinski et al. (2002) observed the behavior of flame propagation in rich propane/air mixtures under microgravity conditions (in the range of concentration between 6.3% 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 history 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 are two limits under microgravity conditions: at concentration 8.75% 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 (Jarosinski et al., 2002). 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 downward-propagating flame (6.3% C_3H_8) and close to the limit for 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 upward-propagating flame at 1 g. 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 1 g, as the flame starting from concentration 8.75% C_3H_8 was not visible but combustion was indicated by pressure rise.

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

EXPERIMENTAL DETAILS

The falling assembly in a form of steel framework of size 800 mm × 800 mm × 1000 mm was used for microgravity experiments. It contained a compact schlieren system (see Figure 2), high-speed video camera, instant temperature and pressure measuring systems, and spark ignition system with large spark gap created by extended electrodes located at two perpendicular each other vessel walls.

A small (0.5 liter) cubic closed vessel with square cross-section (see Figure 3) with schlieren quality glass windows was used to study limit flames under gravity and microgravity conditions.

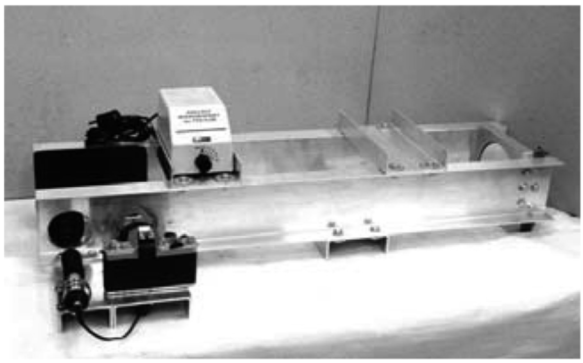


Figure 2 Schlieren system used in microgravity experiments.

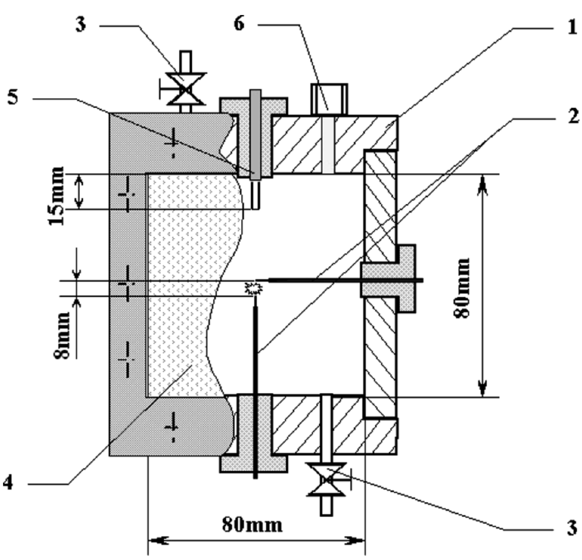


Figure 3 Cubic combustion vessel with central ignition. 1: vessel wall; 2: ignition electrodes; 3: valve; 4: quartz window; 5: temperature probe; 6: pressure transducer.

Propane/air mixtures were prepared by blending of propane and air with flow-meters. The vessel was supplied with the mixture by displacement of at least 50 its volumes. 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 500 mV/MPa.

The flame temperatures were determined by the use of a horizontal positioned resistance thermometer with a 2.2 mm-long unshielded 10 μm Pt-Rd10% wire. The wire time constant was about 5 ms. 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 work of Jarosinski et al. (2002). The temperature probe was located at the center of 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 the signal from the pressure transducer and 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, which provided 10^{-2} g conditions during freefall time of the assembly (1.2 s). The experiments were carried out at the temperature $20 \pm 3°C$.

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 1 g and μg conditions. The microgravity experiments were compared with those conducted under normal gravity conditions.

The experiments began with ignition of the flammable mixture at the center of the vessel. The high-speed video camera registered schlieren image of flame development, while temperature and pressure records indicated the arrival of flame front and changes in combustion pressure under the influence of heat release (see Figure 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, probability of flame development from spark ignition for a limit mixture was similar and close to 50%.

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

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 (Jarosinski et al., 2002), it was found that an increase in near-limit

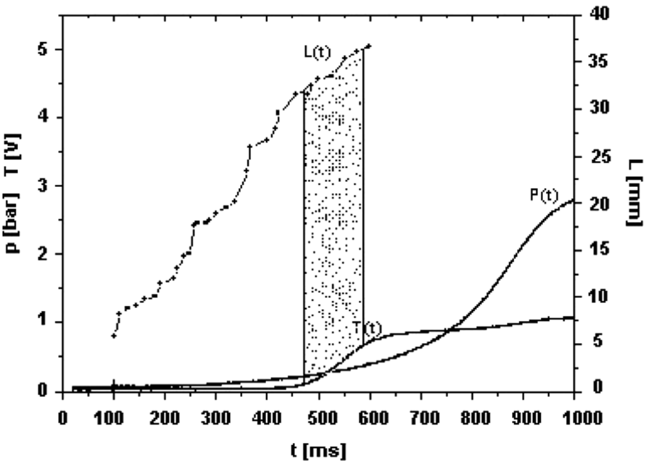


Figure 4 Pressure and temperature records as a function of time for mixture concentration 9.2% C_3H_8 under microgravity conditions. L(t) indicates distance from ignition point to the flame front highest temperature. Central ignition.

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 mixture concentration in flame propagation under the influence of normal gravity acceleration and without this influence. It appeared that flame behavior and burning out of the mixture is practically the same for mixtures with relatively high laminar burning velocity but very different for mixtures characterized by its low value. The closer a concentration is to flammability limit, the more diversified a mixture burning out becomes. The main factor in the differences is most probably the laminar burning velocity. For mixtures distant from the flammability limit, the laminar burning velocity is relatively high, combustion process is fast, and the influence of buoyancy very small. Thus, for instance, flame propagating in a mixture with concentration equal to 6.5% C_3H_8 practically does not show any difference in flame propagation under gravity and microgravity conditions. On the

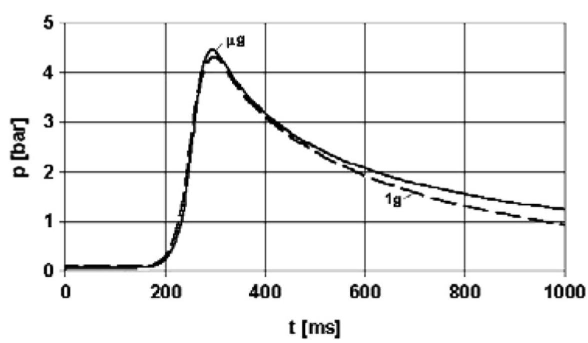
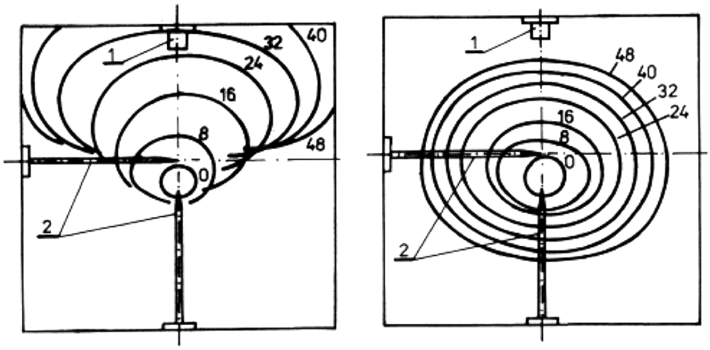


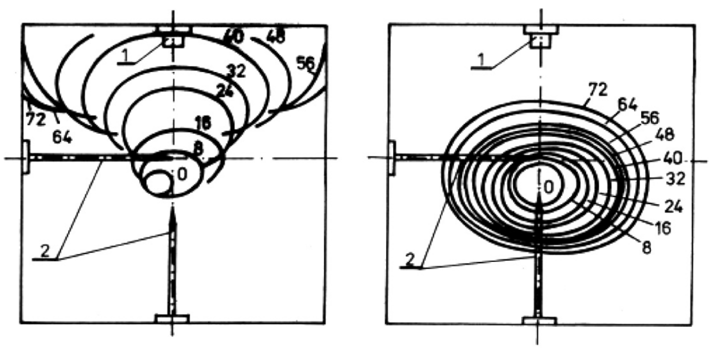
Figure 5 Pressure records as a function of time for mixture concentration 2.2% C_3H_8 under gravity and microgravity conditions. Central ignition.



(A) (B)

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

other hand, flame shape and total flame surface significantly diversifies under the influence of gravity for the richer mixtures approaching this limit (see Figures 6 and 7). As the limit is closer, the role of buoyancy forces in deformation of the flame surface under normal gravity conditions increases. The initial stage of flame propagation in the limit mixture is characterized by much faster development of a volume of combustion gases as well as its surface in gravity than in microgravity conditions. About 140 ms after ignition, the expanding flame touches the top wall of the vessel, and from this instant it starts to be quenched without the ability to propagate downwards (see Figure 7A). Pressure records correspond with propagation velocity and heat losses: at the beginning of the process, the rate of pressure rise is high and the maximum pressure remains low in comparison with microgravity conditions.



(A) (B)

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

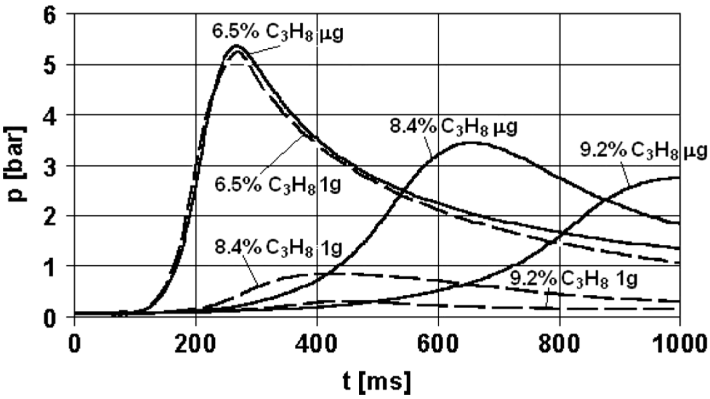


Figure 8 Pressure records as a function of time determined during gravity and microgravity experiments. Flame propagation in propane/air mixture with concentrations 6.5% C_3H_8, 8.4% C_3H_8 and 9.2% C_3H_8. Central ignition.

After that moment, flame propagating under gravity conditions gradually dies, and that propagating under microgravity conditions starts to develop faster than before (see Figure 8).

Thus, in limit mixture, laminar burning velocity is very small in comparison with buoyancy velocity, which it is the main reason why under gravity conditions only a small part of the mixture volume can burn. Change of the maximum combustion pressure Δp_z and the maximum rate of pressure rise $(pd/dt)_{max}$ with near limit mixture concentration is shown in Figure 9. Both parameters are determined during flame propagation from the center of the vessel to its walls under gravity

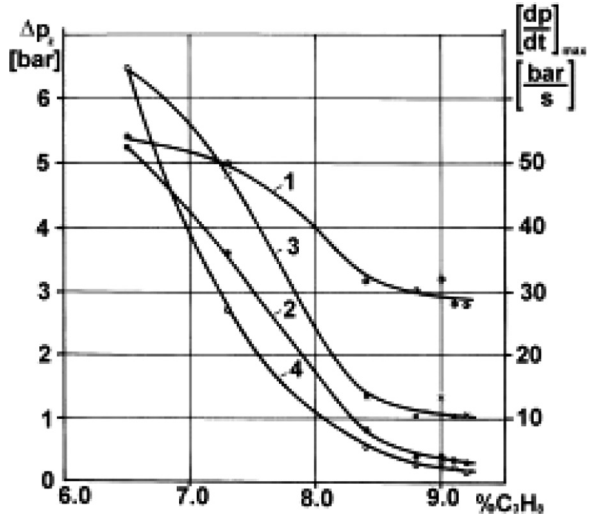


Figure 9 Measured maximum pressure Δp_z and maximum rate of pressure rise $(dp/dt)_{max}$ as a function of propane concentration in a mixture with air determined under normal and microgravity conditions. 1: Δp_z, μg; 2: Δp_z, 1 g; 3: $(dp/dt)_{max}$, μg; 4: $(dp/dt)_{max}$, 1 g.

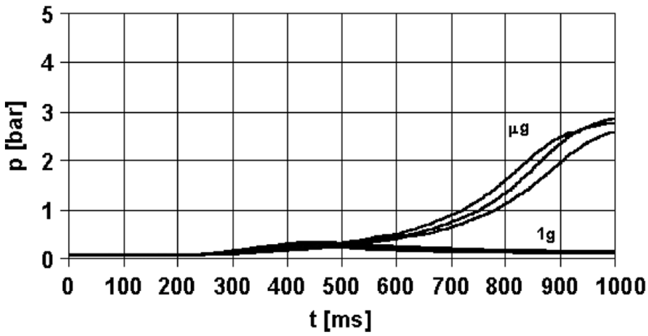


Figure 10 Reproducibility of pressure history during combustion of limit mixture (9.2% C_3H_8) under gravity (five curves) and microgravity conditions (three curves).

and microgravity conditions. They are always higher for microgravity than for gravity conditions. Experiments were highly reproducible (see Figure 10). For experiments with the same mixture concentration, usually such a mixture was prepared in advance in a special vessel. Than a set of tests were made with the use of mixture from this vessel.

Recorded history of flame propagation together with pressure records can be used for calculation of near limit laminar burning velocity. Two equations were adopted from work of Jarosinski et al. (2002) for calculation of its value:

$$u_L = \frac{\frac{dr_b}{dt}}{1 + \left(\frac{p_e}{p} - 1\right)\frac{1}{\gamma_u}} \tag{1}$$

$$u_L = \frac{\rho_b}{\rho_u}\frac{dr_b}{dt} + \frac{r_b}{3\gamma_b p}\frac{\rho_b}{\rho_u}\frac{dp}{dt} \tag{2}$$

Only the initial stage of flame propagation was used in the analysis. A simplified method of calculation was employed. Mean propagation velocity was used for calculation, and a flame thickness correction factor was not taken into account. An example of the calculated laminar burning velocity as a function of time for flame propagating in rich limit propane/air mixture is shown in Figure 11. One can learn from this figure that at the initial stage of combustion, the laminar burning velocity is the order of magnitude of 1 cm/s for both methods of calculation. Experimental data were used for similar calculations of laminar burning velocity for rich propane/air mixtures within the range of mixture concentration between flammability limits for downward and upward propagation limits. Calculated laminar burning velocity as a function of mixture concentration in this transition region is shown in Figure 12.

Microgravity experiments showed that the rich flammability limit in propane/air mixture is nearly identical with flammability limit obtained under normal gravity conditions for upward propagating flames. These results are in contrast to previous microgravity experiments (Jarosinski et al., 2002; Krivulin et al., 1980; Ronney & Wachman, 1985) that reported microgravity flammability limits for mixtures with $Le < 1$ to be in a range between the downward and upward flame, propagating the

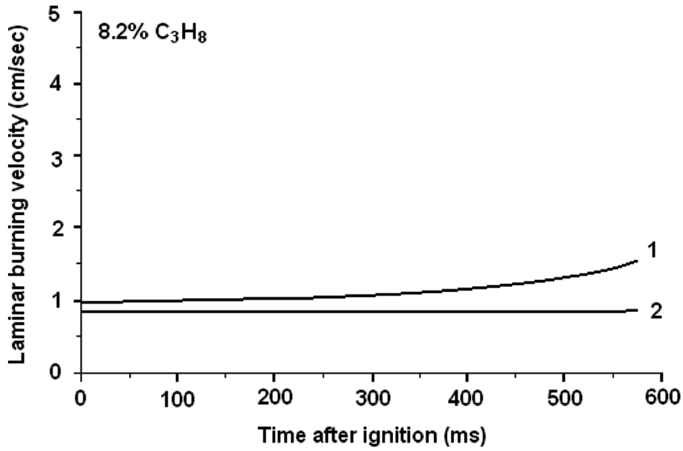


Figure 11 Calculated laminar burning velocity as a function of time after ignition for the rich limit propane/air mixture. 1: Eq. (1); 2: Eq. (2).

results obtained under normal gravity conditions. The previous results were due to insufficiently sensitive measurement techniques. The hardly visible limit flame propagating in its developed shape in a tube is not visible for camera in its initial spherical shape during microgravity experiments. A proper and sensitive instrument should be used to identify the limit.

Flame propagation in propane/air mixture for equivalence ratio higher than $\Phi = 1.60$ is possible thanks to the action of flame stretch and preferential diffusion. The flame stretch rate of the spherically propagating flame is quite low because it is

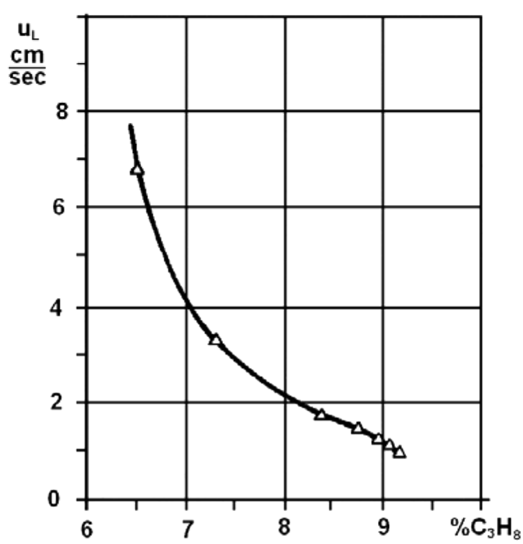


Figure 12 Calculated laminar burning velocity as a function of mixture concentration.

contributed only by flame curvature excluding flow divergence. The flame stretch rate can be calculated as (Law, 1988)

$$k = \frac{2}{r}\frac{dr}{dt},$$

where r is the flame radius.

The flame stretch rate attains its maximum value at the initial stage of flame development (its value is $k \approx 340$ for $\Phi = 1.60$ and $k \approx 12$ for $\Phi = 2.413$). It decreases with a rise of the flame radius and the equivalence ratio. Experiments under microgravity conditions showed that existing flame stretch and preferential diffusion support flame propagation in mixtures with equivalence ratio between $\Phi = 1.60$ and $\Phi = 2.413$.

CONCLUSIONS

Flame propagation in propane/air mixtures was studied in a small, cubic, closed vessel under gravity and microgravity conditions. The following conclusions can be reached:

1. The lean limit was determined to be 2.2% C_3H_8 ($\Phi = 0.535$) both under gravity and microgravity conditions. Under gravity conditions, flammability limits for lean mixture are nearly the same for upward and downward propagating flames.
2. The rich limit was determined to be 9.2% C_3H_8 ($\Phi = 2.413$) both under microgravity and gravity conditions for upward-propagating flame. Limit composition for downward-propagating flame under gravity conditions is 6.3% C_3H_8 ($\Phi = 1.60$).
3. Only a small amount of mixture can burn out for this composition in a closed vessel under gravity conditions (see Figures 8 and 9).
4. Laminar burning velocity determined under microgravity conditions for compositions in a gap between $\Phi = 1.60$ and $\Phi = 2.413$ (corresponding to limit compositions for downward- and upward-propagating flames at normal gravity) dramatically decreases from about $u_L \approx 8$ cm/s to $u_L \approx 1$ cm/s, respectively.
5. All observations made in the present study with the use of the schlieren method and instant temperature measurements can rationally explain the previous results.

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