Influence of tube diameter on lean limit flame propagating upward in methane/air mixture

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1 Introduction

It is known that flammability limits of premixed flame are influenced by coupled effect of flame stretch and preferential diffusion [1]. Preferential diffusion depends on Lewis number for the deficient reactant (Le=a/D). Positively stretched flames are characterized by increased flame temperature and extended flammability limits for mixtures with Le<1, and reduced flame temperature and narrowed down flammability limits for mixtures with Le>1.

Flammability limits of different combustible mixture are usually determined in 51mm diameter and 1.8m long standard flammability tube introduced by Coward and Jones [2]. Mixture is consider to be flammable if a flame can be formed and propagate all the way to the top. However, if the flame is extinguished on the way up the tube, the mixture is considered to be nonflammable.

It was found that limit methane flame propagating upward in a standard flammability tube is strongly affected by buoyancy forces of hot combustion products [3]. The visible speed is much higher than normal burning velocity of limit mixture, and the shape of the flame closely resembles shape of rising air bubble in a tube filled with water, when bottom end of tube is opened. The flame has a nearly spherical cap with a long skirt attached to it. Numerical calculations of the gas flow ahead of the flame, based on experimentally determined flame shape, visible flame speed, and burning velocity of limit flames in tube (which was assumed to be constant along the flame front), predicted that positive stretch rate attains its maximum value at the leading point of limit methane/air flame [4].

Asymptotic analytical models of adiabatic weakly stretched flames predict that response of flame front parameters should depend on the sign of the expression $w = k(1\text{-Le})$ [5, 6]. When w is positive, flame temperature and flame velocity are expected to increase and extinction of such flame is not expected-unless flame is affected by a real or virtual stagnation surface.

Lean methane/air flames propagating upward in a tube are characterized by Le<1 and they are positively stretched, therefore w>1, and these flames, near the top region, seemingly are not affected by any boundary, real or virtual one. At the same time, according to the experimental observations the extinction of the limit methane/air flame propagating upward in a tube starts from the flame leading point, where stretch rate is predicted to be maximum. To understand the mechanism of the extinction of limit methane/air flame further experimental investigations are necessary. Tube diameter also can influence this mechanism. In the present work hydrodynamic structure of limit methane/air flame was experimentally studied in tubes of different diameters using PIV method. Stretch rate along the flame

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was experimentally determined and the prediction of maximum stretch rate at the flame top was verified. The local burning velocities along the flame front flame were determined.

2 Experimental procedure

Three transparent plastic tubes 1.8m long with inner diameters 24mm, 50mm and 80mm were used in experiments. Tubes were filled with mixture from their top ends by the displacement method. Mixture was prepared by partial pressures method. Before entering the tube the mixture passed through a fluidized bed seeding system. The flow was stopped after the displacement of ~8 tube volumes. Then, after about1min delay, the bottom end of the tube was opened and mixture ignited.
Velocity distributions were masured in the central plane of 60x50mm tube segment located in the middle of the tube. For these measurements Particle Image Velocimetry sytem FlowMap by DANTEC Measurement Technology® was used. The setup included two doubled frequency Q-switched Nd: YAG lasers with maximum 50 mJ pulse energy output, and 1.3 mega pixel PIV camera. The operation rate of the PIV setup was 4 measurements (double PIV images) per second.
To determine the visible flame speed flame was recorded with the use of a digital video camera at frame rate 25 s^{-1}

3 Results and discussion

Experimentally determined flammability limits were 4.90%, 5.15% and 5.50% CH_4 by volume, for inner diameter tubes 24mm, 50mm and 80mm, respectively. Measured visible flame speeds in these tubes were 14.3±0.2cm/s, 21.5±0.7cm/s and 28.0±0.3cm/s, which is in good agreement with theoretical prediction for the speed of a rising hot bubble [3].
Flame behavior in 24mm tube was very specific and unique in comparison with other tubes: its extinction at intermediate tube location has never been observed. Flame either did not start propagating in this tube or propagated through its entire length. Figure 1 compares experimental flame shapes in studied tubes at their lean limit concentrations. The observed shape of the limit flame in 24mm tube is qualitatively different from shapes in the other tubes. The skirt of this flame is nearly cylindrical near the flame cap and becomes convergent downstream. The dead space between the flame and tube wall is very wide (~5 mm). The flame flow structure in the tube 24mm is also different from flames in larger tubes. It was found that no seeding particles penetrate into the combustion products inside flame skirt. In a special set of experiments a torus-like structure was identified inside a bubble-shaped flame near its cap. Numerical simulations confirmed experimental observations and demonstrated presence of negative flame speed at the flame edge [7]. The calculated stretch rate with its maximum value at the leading point $k \sim 48s^{-1}$ is distinctly higher from those in larger tubes ($k \sim 33s^{-1}$ in the same point of 50mm tube). Higher stretch rate compared to the ones measured in larger tubes suggest that the observed extension of flammability limit is probably generated by this parameter (coupled effect of flame stretch and preferential diffusion).
Flames in larger tubes are characterized by a different flow structure. In their flame coordinate system a stagnation zone of combustion products is observed near flame cap. Experimentally investigated qualitative thermal structure field of lean limit methane/air flame in 50mm tube with the use of SiC filament pyrometry showed that the flame temperature has a local minimum at the flame tip. The measured local burning velocity also revealed its minimum value at the same place (Fig. 2). Both these observations are in agreement with extinction behavior of this flame. Based on these observations, a mechanism responsible for cooling of flame leading point is suggested. According to this mechanism, the positive strain rate reduces the rate of outflow of the combustion products from the reaction zone. As a consequence, combustion products at the flame location with higher stretch rate are cooled by radiation to lower temperatures. Radiation heat losses are predominant in this flame region. Flame extinction occurs, when local temperature attains critical low value.
Figure 3 shows an example of the global velocity field in a form of vector map (in 40cm long 50mm diameter tube section) for lean limit methane/air flame. Two bubbles of stagnant combustion products

are seen: one enclosed with flame front and second one located ~270mm below it. Experiments showed that after flame extinction the rising bubble of hot combustion gases still travels some distance without any significant change with the same velocity as the flame [3, 8]. The evolution of the flow structure during this process is illustrated in Fig. 4. The gradually shrinking flame surface produces gradually less and less hot combustion products at the top of the hot gas bubble. Heat deficit in this region initially is compensated by the reaction products flow from the reaction zone located in the region of the flame skirts (recirculation). After complete flame extinction, heat comes from the central core, located some way below. As the flame surface shrinks, the hot gases accelerate upward. After complete flame extinction, their velocity exceeds 1m/s.

In contrast with limit flame in 24mm tube the skirts of the limit flames in 50mm and 80mm tubes are divergent and the dead space between the lower part of the flame skirt and tube wall are relatively narrow (2-3mm).

Experiments demonstrated that tube diameter exerts significant influence on flammability limits, limit flame flow and thermal structure, flame parameters at the limits and even on the mechanism of its propagation and extinction. It would be interesting to identify a limit tube diameter separating different limit flame structures (it should be somewhere between 24mm and 50mm).

24mm 4.90% CH_4 | 50mm 5.15% CH_4 | 80mm 5.50% CH_4

Figure 1. Images of lean methane/air flames propagating in 24mm, 50mm and 80mm diameter tubes at their limit concentrations (the same diameter scale).

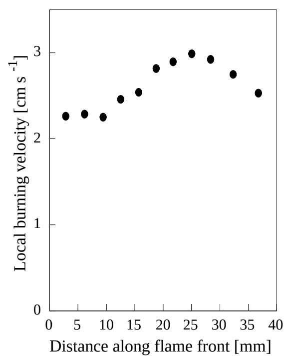

Fig. 2. Burning velocitiy along 5.15% methane flame in a standard flammability tube (starting from the flame leading point).

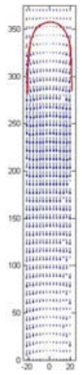

Fig. 3. Global velocity distribution behind flame front in a standard flammability tube.

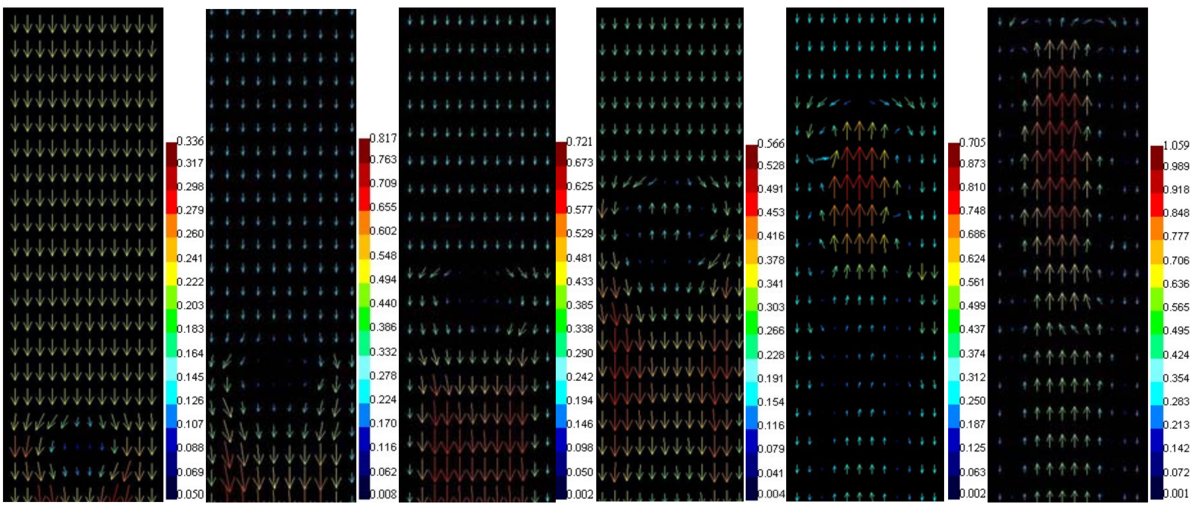

Fig. 4. Evolution of flow velocity field in flame coordinate system during extinction of upward propagating lean limit methane flame in a standard flammability tube. Framing rate: 4 frames/s.

4 Conclusions

Flammability limits, flame structure, stretch rate, flame speed and some other parameters have been measured at the lean limit methane flames propagating upward in 1.8m long tubes with inner diameters 24mm, 50mm and 80mm opened at their bottom end.

Significant differences between shapes of the lean limit methane flames in small 24mm diameter and large diameter tubes were observed both in experiments and numerical simulations.

In 24mm diameter tube a torus-like structure inside a bubble-shaped flame near it cap was identified. The flame had a converging skirt separated from the tube wall by a wide dead space (~5mm).

In large diameter tubes a stagnation zone of combustion products inside a bubble-shaped lean limit methane flame near its tip was observed. Such flames contained diverging skirts separated from the tube wall by a narrow dead space (~2-3mm).

Observed extension of the flammability limits in 24mm diameter tube suggests that this extension is due to high stretch rate influenced flame in this tube (coupled effect of flame stretch and preferential diffusion). Lean limit methane flames propagating in 50mm and 80mm diameter tubes influenced by smaller stretch rates have markedly narrower flammability limits.

It was found that flame speeds of limit flames in all tubes are in good agreement with theoretical prediction for the speed of a rising hot bubble in such tubes.

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