Stretch Rates and Local Burning Velocities Measured along Limit Methane-Air Flame Propagating Upward in Half-Opened Tube

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Introduction

During last two decades significant advances have been made in theoretical interpretation and experimental investigation of premixed gas flame extinction at the flammability limits. One of the key conceptions used to describe theoretically flame extinction is stretch rate, a generalized definition of which was first introduced by Karlovitz [1]. The value of the local stretch rate along with the ratio of gas mixture conductivity to limiting agent diffusivity (Lewis number, Le = a/D) are considered to be parameters allowing generalized description of stretched flames propagation and extinction phenomena [2,3].

It is known that limit methane flame propagating upward in a standard flammability tube is strongly affected by buoyancy forces of hot combustion products [4]. 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 modeling of the gas flow from the mixture side, based on experimentally determined flame shape, visible flame speed, and burning velocity (which was assumed to be constant along the flame front) of limit flames in tube, 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 $w = k(1\text{-Le})$ [2,3]. 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.

Upwardly propagating lean methane/air flames in tube are characterized by Le < 1 and they are positively stretched, therefore $w > 1$ for such flames, and these flames, near the top region, seemingly are not affected by some 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. In this work hydrodynamic structure of limit methane-air flame was experimentally studied using PIV method. Stretch rate along the flame 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.

Experimental setup and treatment of results

A transparent plastic tube of 1.8m length and 50mm inner diameter was used in the experiments. Tube was filled with mixture from its top by the displacement method. The mixtures were 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 6 tube volumes. Then after ~1min 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 the middle of the tube. For these measurements Particle Image Velocimetry sytem FlowMap by DANTEC Measurement Technology® was used. To determine the visible flame speed flame was filmed with a digital video camera at frame rate 25 s^{-1}.

The raw velocity maps were produced by Flowmanager® software. Most of post-processing of the PIV data was done using Matlab software. The measured by PIV radial coordinate and radial component of velocity were corrected for optical distortions introduced by the cylindrical wall of the tube. The visible flame speed was subtracted from measured velocities and thereby velocity distributions in the coordinate system moving together with the flame were produced and further used to determine stretch rate and burning velocities along the flame front.

To establish flame front location the divergence of the measured velocity field was calculated and local maxima of velocity divergence along radial and axial coordinates were plotted. The obtained plot was fitted with smooth line using beta-spines and axial and radial velocity components were interpolated the fitting line. The stretch rate along the flame front was then determined using the equation derived for stationary cylindrical flames [4]:

$$k = \frac{dv_t}{dL} + \frac{v_t \cos\phi}{\xi}, \quad (1)$$

where v_t is the tangential component of the gas velocity to the flame front, L is the distance measured along the flame front, ξ is the radial distance from the flame front to the flame symmetry axis, and φ is the angle between the symmetry axis and the second main radius of curvature of the flame front surface (first main radius of curvature being defined as radius of curvature of front line in the tube center plane).

To determine local burning velocities streamlines starting from equidistant radial position in cold mixture region were calculated. The burning velocities were determined at the locations of intersection of coaxial flow tubes confined between neighbor streamlines with flame front surface, using the equation:

$$s_u = v_0 \frac{S_0}{S_f}, \quad (2)$$

where v_0 is the visible flame speed (equal to the upstream velocity of the fresh mixture in the flame system), S_0 is the area of normal cross section of a selected flow tube in the cold mixture region, and S_f is the area of the flame front segment cut by this flow tube.

Results and discussion

The extinction of flame was observed at methane concentrations ranging from 5.12% to 5.15%. It was not possible to establish extinction at fixed repeatable location even for the same mixture. To observe changes in gas dynamic flame structure when methane concentration approaches its limit value, the PIV measurements were carried out for set of methane concentrations within the range of 5.15%-5.85%.

Figs.1,2 illustrate measured velocity distributions (in the flame system) and streamline patterns for limit 5.15% methane mixture and for well removed from the limit 5.62% methane mixture in the flame cap region. It is seen from the Fig.1 that at limit methane concentration a region within the flame cup exists in which combustion products have nearly zero velocity. In this zone combustion products are stagnant and move together with the flame. An additional evidence of the formation of stagnation core in products zone in limit flame was accumulation of seeding particles in this region, which formed a small cloud observed on PIV images. Such a cloud was never observed in mixtures with higher methane concentration than the limit value. The streamlines near the top of limit flame are strongly divergent. For some experiments part of streamlines ended in the stagnation core region because combustion products moved there with a very small negative velocity.

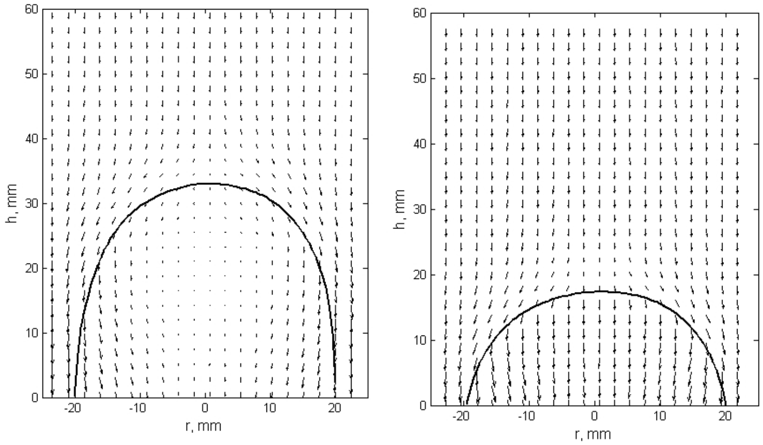

Fig.1. Experimental velocity vector fields in the flame system for 5.15% methane (**a**)- and 5.62% methane (**b**) flame in standard tube. Solid line – fitted line for location of maxumum divergence of velocity.

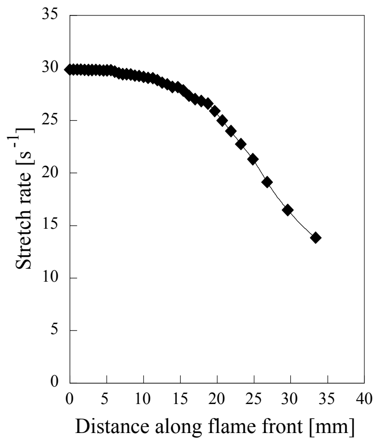

Fig.3. Stretch rate along the 5.15% methane flame (starting from the flame leading point)

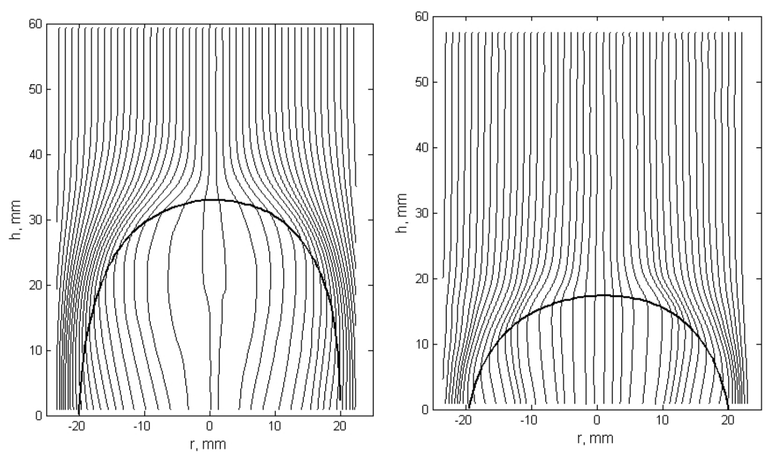

Fig.2. Streamlines recovered from velocity fields shwn in Fig.1.
a – 5.15% methane flame, **b** – 5.62% methane flame

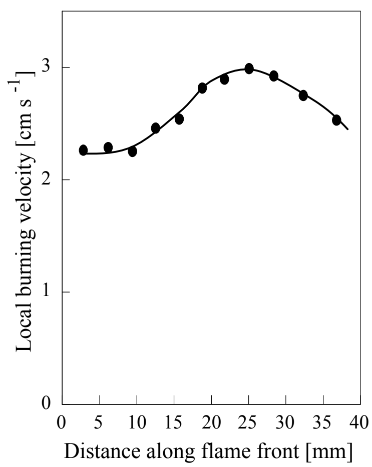

Fig.4. Burning velocities along 5.15% methane flame (starting from the flame leading point)

In the 5.62% methane mixture, fast downward motion of combustion products is observed everywhere behind the flame front. The streamlines are convergent in the flame top region, so that products formed near the flame top flow close to the tube centerline.

Measured stretch rate and local burning velocity along the flame front of 5.15% methane flame are shown in Fig.3 and 4. The maximum stretch rate is attained at the flame top which is in agreement with the prediction [4]. At the same time the qualitative shape of stretch rate distribution along the flame is somewhat different from the predicted one. First, there are no additional local maxima on the measured stretch rate distribution, while predicted distributions showed additional maxima on the periphery of the flame cap. Second difference is that stretch rate in the flame skirt region decreases much slower than it was predicted in [4].

The measured local burning velocity reaches its minimum value (2.25 $cm{\cdot}s^{-1}$) at the flame top, which in agreement with experimental observations of the extinction behavior of limit methane-air flame. At the same time obtained results contradict to asymptotic theory of stretched flames [2,3], which predicts increase of burning velocity for lean methane-air flame with increasing stretch rate.

Two possible explanations of low burning velocity at maximally stretched top region of the flame can be suggested. First one is that the flame top is affected by radiation loss from combustion products more than the skirt region. Indeed, the combustion products are nearly stagnant near the flame top and thermal energy is transported to the stagnation core mainly by slow diffusion mechanism, while near the flame periphery fast convection energy transfer takes place. The same conclusion can also be drawn from consideration of a single-front flame in terms of local stretch rate: Normal to the flame front component of the velocity of combustion products decreases faster in regions with higher stretch rate. Therefore average "residence" time of combustion products near the reaction zone is longer in the regions with higher stretch rate, and radiation cooling of combustion products should produce stronger negative temperature gradients in more stretched flame regions.

Second possible explanation is based on the differential diffusion effect in stretched flames. It was theoretically predicted [5] that the reactant which is initially in excess in fresh mixture may become a deficit one in the reaction zone of stretched flame. Such situation is possible for example in positively stretched flame if Lewis number is less then unity for deficit reactant and more than unity for the initially excessive reactant - the condition being satisfied for lean methane air flames. Though the analysis carried in [5] was only for near-stichiometric flames, authors pointed out that such situation is possible also for mixtures far from stoichiometry at high stretch rates. Should this be the case for limit methane-air flame, the excess methane would leak through the flame front at the flame top region whereas excess oxygen would flow though the front at the flame periphery. Upon diffusion mixing in product zone the methane and oxygen would react and increase the combustion products temperature near the flame skirt. This effect could make flame stable in the skirt region, despite the revealed decrease of burning velocity in this region (Fig. 4).

Conclusions

Stretch rates and local burning velocities have been measured along the flame front of lean limit methane-air flame propagating upward in a standard flammability tube opened from its bottom end. Measured stretch rate attains its maximum value at the flame top, which agrees with earlier semi-empirical numerical model [4]. Similar to previous observations, extinction of the limit flame was observed to start from the flame top. The measured local burning velocity has a local minimum at the flame top where stretch rate is maximum. The obtained results could not be explained in terms of local stretch rates in the framework of existing theory.

Two hypothetical mechanisms for the limit methane-air flame extinction behavior were suggested. First hypothesis is stronger effect of radiation loss from combustion products near the flame top. Second hypothesis is depletion of oxygen near reaction zone at the flame top due to combined effect of stretch and differential diffusion. Both mechanisms, acting separately or together, could reduce burning velocity and lead to extinction at the flame top.

Aknowledgements

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