Negativly streched premixed flames

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Abstract. An experimental study of gravity effect on the blow-off and flash-back borders of the conical methane–air flame (normal and ring-stabilized) was performed. The influence of the preferential diffusion on the flame behavior in vicinity of flash-back boundaries was observed. Under conditions at Lewis number $\text{Le} > 1$, the radius of curvature of the flame tip increased gradually approaching flash-back boundaries while for the lean methane–air flames ($\text{Le} < 1$) the radius decreased abruptly. It was shown that the burning velocity for lean flames is less than that for reach ones, so the flash-back occurs at higher strains.

1. Introduction
Almost all the flames are subjected to the stretching, as a result it brings to the burning velocity changes, and correspondingly stable flame boundaries (flash-back and blow-off limits) vary. In general, the stretching is represented as

$$k = \frac{d \ln(\delta A)}{dT} = \frac{1}{A} \frac{d(\delta A)}{dt}, \quad (1)$$

where $\delta A$ is the area of the flame surface element [1–4]. Stretching of the flame surface is often considered as dimensionless, normalized by the characteristic residence time of the unstretched one-dimensional flame $V_{n,0}/\delta_0$. Here, $V_{n,0}$ is the burning velocity of unstretched flame, $\delta_0$ is the thickness of unstretched flame. It represents well-known dimensionless Karlovic number

$$\text{Ka} = \frac{k}{V_{n,0}/\delta_0} = \frac{k}{V_{n,0}^2/\alpha}, \quad (2)$$

where $\alpha$ is the thermal diffusivity. Stretching of the conical premixed flames is determined by the front curvature, which is maximum at the cone tip (respectively to the entire length of the flame front). In such flames $k \sim \overline{U}/R$, where $\overline{U}$ is the mean flow rate, and $R$ is the radius of the flame tip curvature [4, 5].

Also, the preferential diffusion of heat and mass is an important effect influencing the basic characteristics of a flame, in practice it is estimated by Lewis number (Le), which is the ratio of the mixture thermal diffusivity coefficient to the mass diffusivity coefficient of the stoichiometrically-deficient reactant. Flames can exhibit opposite properties depending upon the combustible mixture components, stretching and the flame geometry, thus forward stagnation and counterflow flames are stretched positively, conical ones—negatively (compressed); for the rich methane–air mixture and lean propane–air Le > 1, and for the lean methane–air and rich propane–air Le < 1 [6, 7].
Previously [8], we had studied the issue of a stable conical flames parameters extension by an external body-stabilizer was studied. It was shown that the major stabilization mechanism is the formation of a toroidal-shaped vortex near the ring, which holds the flame at the nozzle edge. The optimal parameters are determined by occurrence of the co-flow between nozzle wall and ring in range of 45–80% of the main flow for the whole velocity range [8]. In the present work, we have measured the conical flame tip curvature under the approaching blow-off limits. Also we study the effect of gravity on the flame curvature and the change of the stable-flame limits (blow-off and flash-back).

2. Experimental details

The experimental setup was described in detail in previous work [8, 9]. The main parameters were the following: a conical nozzle was used as a burner (outlet diameter \( d = 15 \text{ mm} \)) for flame stabilization a ring next to the nozzle edge was settled, the inner diameter of the ring was \( d_{\text{r in}} = 10 \text{ mm} \), the outlet diameter of the ring \( d_{\text{r out}} = 13 \text{ mm} \). During the experiments, the nozzle was settled in such way that the flow rate was directed towards vector of gravity (−1g conditions) and opposite (+1g conditions). Some features of the behavior of the flame under microgravity conditions (\( \mu g \)) are also presented. As a diagnostic high-speed flame chemoluminescence video-recording, particle image velocimetry (PIV) system, and constant temperature anemometry (CTA) were used. As the result the boundaries of the blow-off and flash-back conditions, the velocity flow-fields of isothermal and reacting jets (PIV method), the mean and pulsation velocity components of isothermal flow (CTA method) were measured. The radii of curvature of the flame tips also were obtained, further the method of theirs determination will be described in detail.

For the conical axisymmetric flame, the stretching rate and Karlovice number are determined as follows:

\[
\begin{align*}
  k &= \frac{2U}{R}, \\
  Ka &= \frac{2U\alpha}{RV_{n,0}^2},
\end{align*}
\]  

(3)

since the nozzle geometry provided flat velocity profile at outlet. As far as coefficient \( V_{n,0}^2/\alpha \) is constant for fixed equivalence ratio, for simplicity it was possible to consider the ratio of value \( U/R \) instead of \( Ka \).

Velocity characteristics that was formed in the conical nozzle are shown in figures 1–3 (mean velocity and pulsations along the nozzle axis were measured by CTA, see figure 1, velocity profiles along nozzle axis and along radius at the nozzle outlet were obtained by PIV measurements, see figures 2 and 3 respectively).

The method of determination of the flame tip curvature radius is represented in figure 4. Flame front image was taken by means of high-speed camera, see figure 4(a). Then the image was treated and the flame front boundaries were extracted as the area with maximum brightness, see figure 4(b).

Data were approximated by the parabolic function:

\[
f(x) = a_2x^2 + a_1x + a_0.
\]  

(4)

Figure 4(c) shows the approximation. Curvature radius at the point \( x = x_0 \) was determined as follows:

\[
R = \left( \frac{1 + |y'(x_0)|^2}{|y''(x_0)|} \right)^{3/2}.
\]  

(5)

At parabola vertex \( R = (1/2)|a_2| \). It is convenient to use the local Karlovice number:

\[
Ka_L = \frac{k}{(V_n/\delta)} = \frac{k}{(V_n^2/\alpha)},
\]  

(6)
Figure 1. Distance along the nozzle axis as a function of mean flow velocity (a) and pulsations (b) from CTA measurements for $\overline{U} = 0.5$ (A), 1.0 (B), 1.5 (C), and 2.0 m/s (D).

Figure 2. Mean axis flow velocity along the nozzle axis for $Re = 750$ (a) and 1000 (b) from PIV measurements: $\varphi = 1.0$ (A), 1.3 (B) and 0.8 (C).

Figure 3. Mean velocity of axial flow as a function of the radial coordinate at the nozzle outlet section measured by PIV method for $Re = 1000$ (A), 750 (B), and 1500 (C).

where $V_n$ is the real flame (stretched) burning velocity. The discrepancy, described in [10, 11], is that the stretching of the flame surface is normalized by the characteristic residence time of the stretched flame. At the flame tip the burning velocity is equal to the flow velocity, thus

$$K_aL = \frac{k}{\left(V_n^2/\alpha\right)} = \frac{2\alpha}{UR}, \quad \text{so} \quad K_aL \propto \frac{1}{UR}.$$  

(7)
Figure 4. The flame photo analysis: (a) the source flame photo; (b) the flame front boundary, $1024 \times 1024$ px$^2$; (c) the flame tip approximations: (A) the whole flame-front line (100% length); (B–E) results of approximation with a portion of the length $\alpha = 80$ (B), 60 (C), 40 (D) and 20% (E).

3. Results and discussions

In figure 5, two diagrams of blow-off and flash-back for both conical normal and conical stabilized flame under normal and “reversed” gravity are shown. Blow-off limits are extended in $-1g$ conditions while flash-back occurs under the higher velocities for the fixed equivalence ratio compared to the normal gravity conditions, see figure 5(b). Before the flash-back under $+1g$ conditions, the flame turns to the flat one, as discussed somewhere [12], and then the tip bends toward the fresh mixture, while under $-1g$, stable flat flame configuration in conical nozzle does not exist (the flash-back occurs abruptly without any pre-requisites). In figure 6, instantaneous photos of lean, stoichiometric and rich flames are shown for the flow rates, those are corresponded to $Re = 750$ (middle row) and 1000 (down row), in the bottom row flames just before flash-back are shown. One can see that under the constant flow rate equivalence ratio, the growth leads to the radius curvature increase, while under the constant equivalence ratio, the radius curvature decreases with flow velocity growth.

Quantitative data are shown in figures 9 and 10. For the lean nearstoichiometric flames in vicinity of the flash-back limits, flame tip curvature radius reduces abruptly but, for the reach flames, it is gradually increase until the flash-back occurs. Instantaneous photos of flames in $-1g$ conditions (“reversed” gravity) are shown in figure 7. Curvature radius behavior in general is the same, but radii and $UR$ (quantity proportional to $Ka$) are bigger, and curvature—smaller, results are shown in figures 9(b) and 10(b). Analogic results for the $\mu g$ conditions are shown in figure 9(b), but results show that graphs are not parallel, that clearly shows significant gravity influence on the flame curvature.

According to the laminar stretched flames theories [13–16] which usually include global one-step reactions, the rates of reactions are controlled by the stoichiometric-deficient reactants: the fuel for lean flames and the oxidant for rich ones. Hence the reaction rates are connected with Le number of a mixture: in reach methane–air mixtures (Le > 1) flame temperature and reaction rate decrease and flash-back occurs under maximum radius curvature, in lean and near stoichiometric mixtures (Le < 1), temperature increases and flash-back occurs under smaller radius curvature. For mixtures with Le > 1, flame flash-back occurs at lower flow rate than for Le > 1. Flame temperature changes bring to the reaction rate decrease or increase, which was observed experimentally. But gravity also influences the burning rate, through the flame flickering. The flame flickering is connected with Kelvin–Helmholtz vortices, occurring on the interface products in motion and still surrounding air. Such kind of instability influences the flame burning velocity and the stretching. Velocity fields of the conical methane–air flames are shown in figure 11, black lines show the flame front. For the stoichiometric mixture on the nozzle axis, velocity is constant, in the vicinity of the flame front it increases and after crossing flame
Figure 5. Blow-off (solid markers) and flash-back (open markers) limits: (A, E) +1g conditions, without ring; (B, F) −1g, without ring; (C, G) +1g, $d_{\text{out}} = 13 \text{ mm}$; (D, H) −1g, $d_{\text{out}} = 13 \text{ mm}$; (a) all data; (b) flash-back data connected by lines as a guide for eyes.

$\phi = 0.9, \ Re = 560$  
$\phi = 1.0, \ Re = 630$  
$\phi = 1.2, \ Re = 500$  
$\phi = 1.3, \ Re = 310$

$\phi = 0.9, \ Re = 750$  
$\phi = 1.0, \ Re = 750$  
$\phi = 1.2, \ Re = 750$  
$\phi = 1.3, \ Re = 750$

$\phi = 0.9, \ Re = 1000$  
$\phi = 1.0, \ Re = 1000$  
$\phi = 1.2, \ Re = 1000$  
$\phi = 1.3, \ Re = 1000$

Figure 6. Flame photos for +1g conditions.

front decreases abruptly because of the gas expansion. In case of reach combustible mixture, as in figure 11(b), velocity shift in the vicinity of the flame front is not so high, because of the burning velocity decreasing, as was discussed earlier.
Figure 7. Flame photos for −1g conditions: Re = 750 (top line) and 1000 (bottom line).

Figure 8. Flame photos for µg conditions.

Figure 9. Flame tip curvature radius versus flow velocity: (a) without ring, +1g conditions: \( \varphi = 0.9 \) (A), 1.0 (B), 1.2 (C), 0.9 (D), 1.0 (E), 1.2 (F); (D–F) flash-back conditions; (b) ring-stabilized flames, \( d_{\text{out}} = 13 \text{ mm} \), solid markers and lines correspond to +1g conditions, open markers and dashed lines—to −1g: \( \varphi = 1.0 \) (A, B), 1.3 (C, D), 0.8 (E, F) and 1.0 under µg conditions (G).
Figure 10. Quantity $\overline{UR}$ versus mixture equivalence ratio. (a) without ring, +1g conditions: Re = 500 (A), 1000 (B). (b) ring-stabilized flames $d_{r\text{out}} = 13$ mm, solid markers and lines +1g conditions, open markers and dashed lines −1g: Re = 600 (A, B), 2000 (C, D).

Figure 11. Mean velocity fields; PIV measurements, +1g conditions: (a) $\phi = 1$; (b) $\phi = 1.3$. 
Spatial measure of the velocity increase under conditions of $\varphi = 1$ is about 1 mm, which corresponds to the mean flame front width. For increase flame front, the width broadens because of the expansion of flame preheating zone.

4. Conclusions
Thus, the flame tip curvature and the local Karlovic numbers were investigated for methane–air flames of conical shape. The experiments were carried out in flame flash-back vicinity. Also the influence of gravity on the flame stretching was studied. It was shown that gravitational forces influence stable burning limits (blow-off and flash-back). It was found the different behavior of rich, lean and stoichiometric flames in blow-off and flash-back limits vicinity. In first case, curvature radius increases gradually with velocity decreasing and it gains maximum value before the flash-back. In other cases, also the curvature radius increase with decreasing flow velocity was observed, but before the flash-back radius reduced abruptly. It was shown for the $-1g$ conditions curvature radiuses in general are bigger than for normal $+1g$ conditions, but has the same tendency. For microgravity conditions the increase of stoichiometric flames curvature radius with velocity decrease is much slower. That fact could assume the increase of flash-back boundaries under zero-gravity conditions at least for the stoichiometric mixtures.

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