Burning Velocity of Premixed Flame Tips: Experimental and Numerical Study

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1 Introduction

The Bunsen flame is a classical example of an axisymmetric concave flame configuration displaying an increase of local burning velocity due to flame compression (negative stretch), specially at the flame tip. The curvature of the flame and the strain rate of the flow, which exist at any point along the flame, cause separate changes of the local burning velocity of the flame with respect to the burning velocity of a planar flame. By assuming that these changes are proportional to the magnitudes of curvature and strain rate, the reactive mixture is characterized by two proportionality factors, which are known as Markstein lengths. In quasi planar configurations, the two Markstein lengths are equal and the two effects add up into a single term: the so-called flame stretch [1, 2]. The Markstein lengths can be determined experimentally by simultaneously measuring the curvature of the flame, the strain rate of the flow and the local burning velocity of the flame. To achieve this goal, we have set up a laminar jet burner and used a PIV system to measure the gas flow velocity in a vertical cross-section through the axis of a methane-air Bunsen-like flame. The PIV system is composed by a double Nd-YAG pulse laser (New Wave 120XT) with light sheet forming emission optics, a double-shuttered camera (PCO, 1392 × 1040 pixels), and a pulse generator (ILA). To track the flow, the fresh gas is seeded with oil droplets formed by evaporation-condensation in a seeding chamber inserted in the air line. The laser light dispersed by the oil droplets before they evaporate in the flame preheating region is captured by the camera at two closely spaced instants of time, and the velocity of the gas is determined from these images using the ViDPIV cross-correlation software. In addition, the long exposure picture of each PIV couple receives enough radiation from the flame, in the laser wavelength that goes through the narrow band filter set in front of the camera, to clearly display the outline of the reactive front, which allows to measure its position and curvature.

2 Results and discussion

The stretch at the tip of a Bunsen flame is

$$S = U_L \mathcal{C} + \frac{\partial u}{\partial x} \ , \tag{1}$$

where $\mathcal{C} = 2/R$ is the curvature of the reaction layer at the tip. Here R is the radius of curvature of the meridional section of the reaction layer, U_L is the velocity of the planar flame, and x and u are the vertical distance and the velocity of the fresh gas on the axis of the burner. Markstein's proposal is that the velocity U_n of the flame at the tip, defined as the velocity of the fresh gas extrapolated to the reaction layer, should satisfy

$$U_n = U_L + \mathscr{L} S \ , \tag{2}$$

where $\mathscr{L}$ is the Markstein length of the flame.

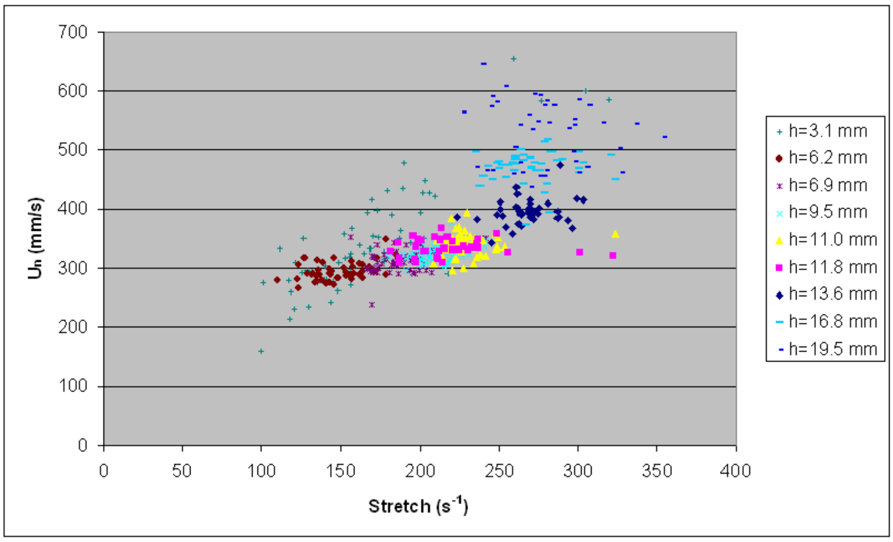

Figure 1. Velocity of the flame at the tip versus flame stretch for $\phi = 1.49$ and different flame heights.

Values of the three magnitudes U_n, R and $\partial u / \partial x$ have been measured for different flames with an equivalence ratio $\phi = 1.49$ and different values of the height h of the tip above the burner's nozzle, which amount to different values of the injection velocity U_0. Figure 1 shows U_n *vs.* S computed from these experimental data and the planar flame velocity $U_L \cong 222$ mm/s, determined as explained below.

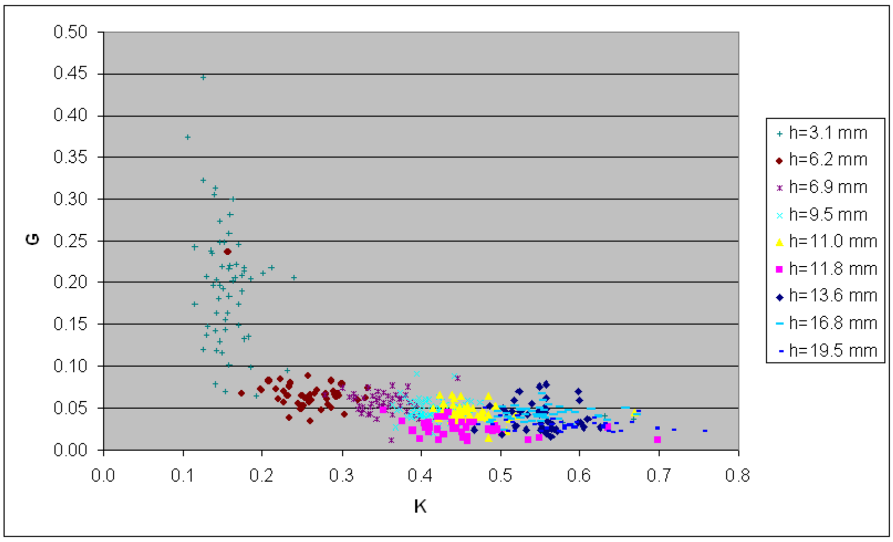

Figure 2. Contributions of the curvature (K) and the strain rate (G) to the dimensionless stretch σ in Eq. (3).

According to Eq. (1), the dimensionless stretch $\sigma \equiv \mathscr{L} S/U_L$ can be split into two terms, a curvature contribution (K) and a flow strain rate contribution (G), as follows

$$\sigma \equiv \frac{\mathscr{L} S}{U_L} = \frac{2\mathscr{L}}{R} + \frac{\mathscr{L}}{U_L}\frac{\partial u}{\partial x} \equiv K + G \ , \qquad (3)$$

Figure 2 shows that the curvature contribution is large compared to the strain rate one for all but the shortest flames, with h = 3.1 mm. Data for these flames show considerable scatter and suggest trends different from those of other flames in our experiments. They will not be discussed in what follows.

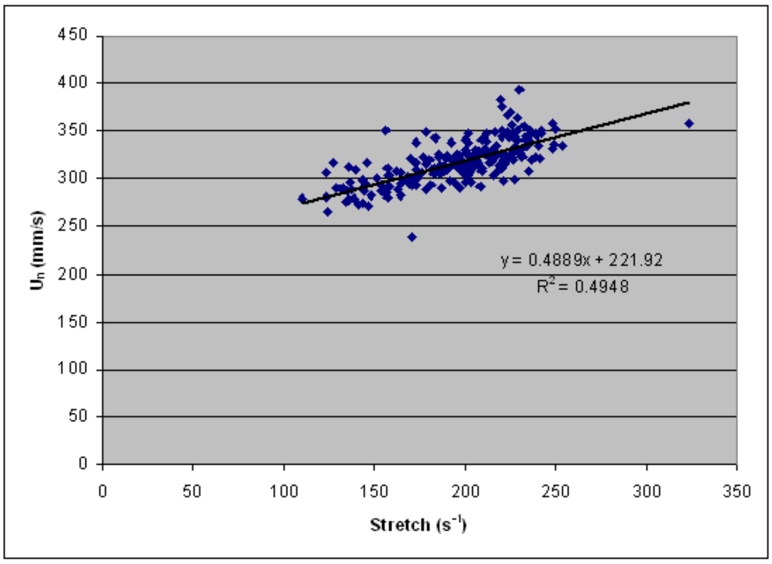

Figure 3. Determination of the planar flame velocity U_L and the Markstein length $\mathscr{L}$ by fitting a straight line to the experimental data for four different flame heights.

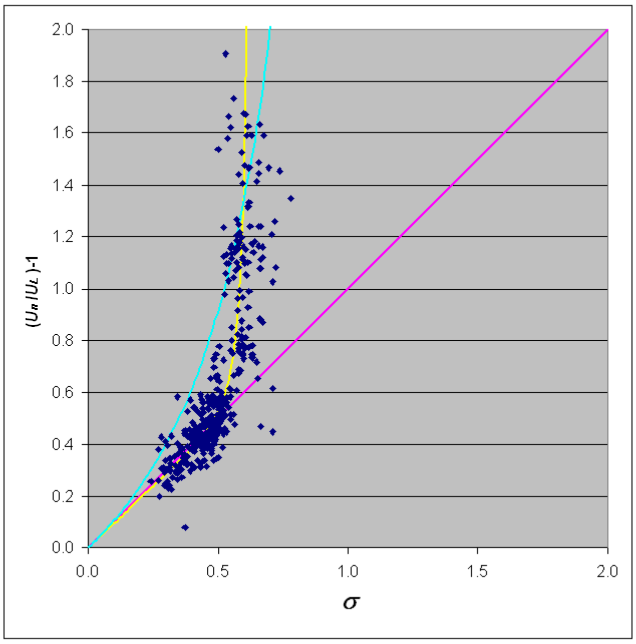

Figure 4. Left- and right-hand sides of Markstein's relation $U_n / U_L - 1 = \sigma$ evaluated with the experimental data for different flame heights. The blue curve shows Mungal's modified relation (4) whereas the yellow curve is a nonlinear fit to the experimental results.

According to Eq. (2), the velocity of the planar flame and the Markstein length can be determined from the experimental data by fitting a straight line to the data in the (S, U_L) plane. This is illustrated in Fig. 3, where only data for four heights h = 6.2, 6.9, 9.5, and 11 mm have been used. It should be noted that the fitting process requires iteration, because the stretch in Eq. (1) depends on U_L. The Markstein length determined from this fitting is $\mathscr{L}$ = 0.489 mm, which is in reasonable agreement with other experimental values and with the theoretical value of Ref. [3]. The velocity of the planar flame, given by the intercept of the straight line in Fig. 3, is U_L = 222 mm/s, as was advanced before.

Figure 4 shows that the data for all the available flame heights collapse reasonably well in the plane of the dimensionless variables σ and $(U_n/U_L - 1)$ when the values of U_L and $\mathscr{L}$ obtained above are used. According to Markstein's linear relation (2) and (3), the data should fall on the diagonal of this figure $U_n/U_L - 1 = \sigma$. The results in Fig. 4 reveal that (a) the linear relation between flame velocity and stretch is accurate up to remarkably high values of $U_n/U_L - 1$, of the order of 0.5, and (b) the velocity of the curved flame shows an apparent divergence for a value of the dimensionless stretch σ which is about 0.6 – 0 7.

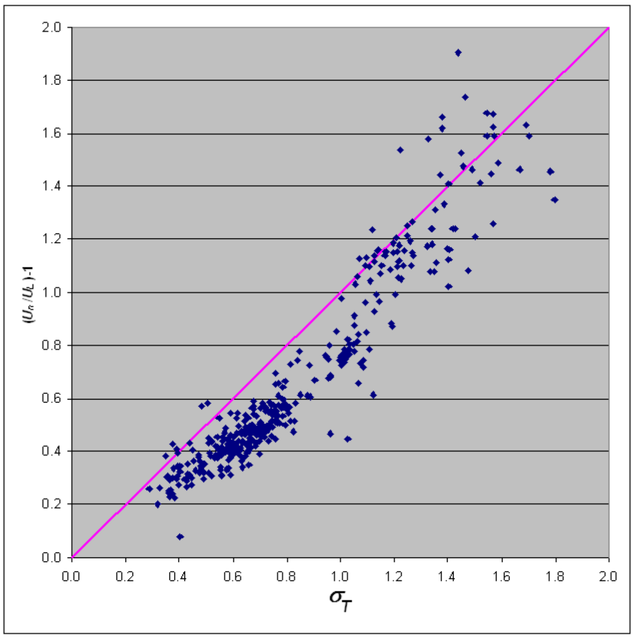

Figure 5. Left- and right-hand sides of the modified velocity-stretch relation (4) evaluated with the experimental data for different flame heights.

Mungal and coworkers [4, 5] have argued that a modified definition of stretch should be used, with the local velocity of the curved and strained flame U_n replacing U_L in (1), and have proposed the modified velocity-stretch relation

$$\frac{U_n}{U_L} - 1 = \sigma_T \tag{4}$$

with

$$\sigma_T \equiv \frac{\mathscr{L}}{U_L} S_T \quad \text{and} \quad S_T \equiv U_n \mathscr{C} + \frac{\partial u}{\partial x} \ , \tag{5}$$

which amounts to $U_n/U_L - 1 = \sigma/(1 - \sigma + G)$. Figure 5 shows our experimental data replotted in terms of the modified variables (see also the blue curve in Fig. 4). As can be seen, the data do not fully agree with the modified relation (4), but undeniably they follow it better than the original Markstein relation $U_n/U_L - 1 = \sigma$ for moderate and large values of the stretch.

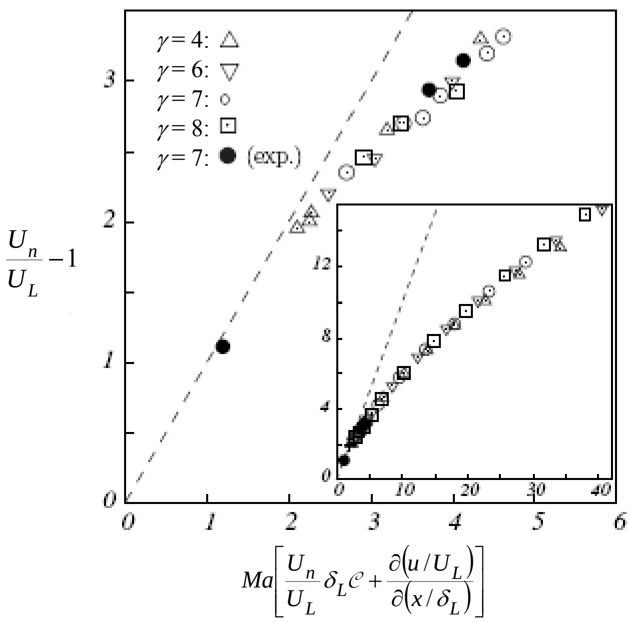

Figure 6. Left- and right-hand sides of Eq. (4) evaluated with the numerical data for $\gamma = 4$ (△), 6 (▽), 7 (○), and 8 (□), and with the experimental data for $\phi = 1.49$ ($\gamma \approx 7$, ●).

Some comparisons with numerical results are shown in Fig. 6, where the computed and measured fractional change of the flame velocity relative to the planar flame velocity is plotted as a function of the modified stretch (in brackets in the horizontal axis), for an equivalence ratio $\phi = 1.49$ and different dilutions, measured by the ratio of the adiabatic flame temperature to the temperature of the fresh gas. Here $\delta_L = \alpha_u / U_L$ is a reference flame thickness, with α_u the thermal diffusivity of the fresh gas, and $Ma = \mathscr{L} / \delta_L$ is the Markstein number, evaluated from the theoretical results of Clavin and Garcia-Ybarra [3] as a function of γ for Lewis number equal to the unity. The factor U_n / U_L multiplying the curvature of the front is the modification of the flame stretch introduced by Mungal and coworkers. This factor tends to the unity in the limit of zero stretch, in which the data tend to the diagonal of the figure, in agreement with asymptotic theory. The data stay near the diagonal for moderately large values of the stretch when the factor U_n / U_L is included, which again shows the usefulness of the phenomenological modification, but they finally depart from the diagonal and approach a square root relation between flame velocity and modified stretch for large values of the latter. The numerical results show that this transition is connected to a transition between rounded tips, with curvature radii of the order of the thickness of the preheated region of the flame, and slender tips, with curvature radii small compared to the thickness of the preheated region.

Asymptotic analysis for large values of the thermal expansion γ and of the velocity ratio $U \equiv U_n / U_L$ shows that the results of Buckmaster and Crowley [6] for slender flames are applicable when $U >> \gamma$, leading to a curvature radius of the reaction layer at the tip smaller than the thickness of a planar fame by a factor of $O(\gamma / U)$. When $1 << U << \gamma$, the flame consists of two slender regions followed by a rounded cap, where the curvature radius of the reaction layer (r_b) is effectively of the order of the thickness of a planar flame. The cold gas enters this cap as a narrow stream tube of radius of

$O\left(r_b / U^{1/2}\right)$ and expands and deflects significantly upon being heated. More details can be found in Refs. [7, 8].

3 Conclusions

The flow and the shape of the reaction layer around the tip of a methane-air Bunsen flame have been measured using PIV and photographic records. The results compare well with numerical simulations carried out with an infinite activation energy reaction. When the injection velocity of the fresh gas increases, the tip is predicted to evolve from a rounded cap, with a curvature radius of the order of the thickness of the preheating region of the flame, to a slender structure with larger curvature. The numerical and experimental results confirm that the modified definition of flame stretch introduced by Echekki and Mungal and Poinsot *et al*. allows to extend the linear relation between flame velocity and stretch to non-small values of the stretch. However, the linear relation becomes less accurate when the stretch is very large, and it is predicted to break down when the tip becomes slender.

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