Measurements of the burning velocity of strongly curved methane-air flames

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Abstract

An experimental and numerical study has been carried out of the region around the tip of a methane-air premixed flame attached to a circular laminar jet burner. On the experimental side, photographic records and PIV have been used to measure the shape of the reaction layer and the velocity of the gas around the tip of the flame. The numerical part of the study includes simulations of stationary axisymmetric flames with infinitely high activation energy reactions. The experimental and numerical results compare well with each other and allow to determine the curvature of the reaction layer at the tip and the velocity and strain rate of the fresh gas flow along the axis of the burner. These data, together with the planar flame velocity determined by extrapolating the velocity of the flame at the tip to the limit of zero stretch, are used to assess the well-known linear flame-velocity/flame-stretch relationship originally proposed by Markstein and later derived in the asymptotic limit of weakly curved and strained flames [1, 2], as well as the phenomenological modification proposed more recently by Mungal and coworkers [3, 4].

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. 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

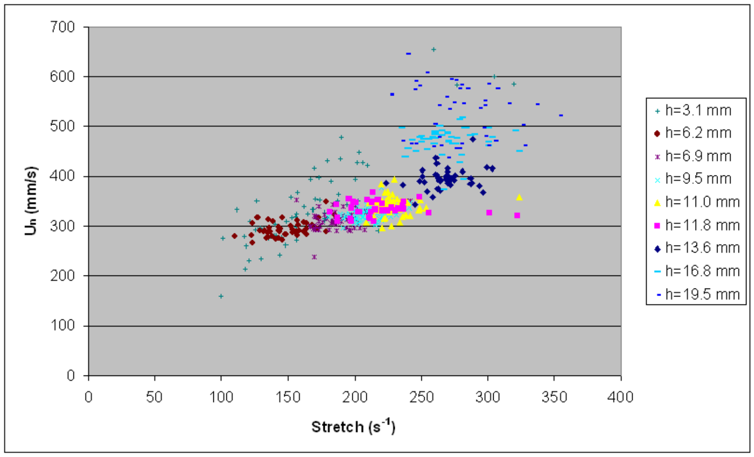

Figure 1: Velocity of the flame at the tip versus flame stretch for $\phi = 1.49$ and different flame heights.

a vertical cross-section through the axis of a methane-air Bunsen flame. The PIV system is composed by a double Nd-YAG pulse laser (New Wave 120XT) with a 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, with R 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

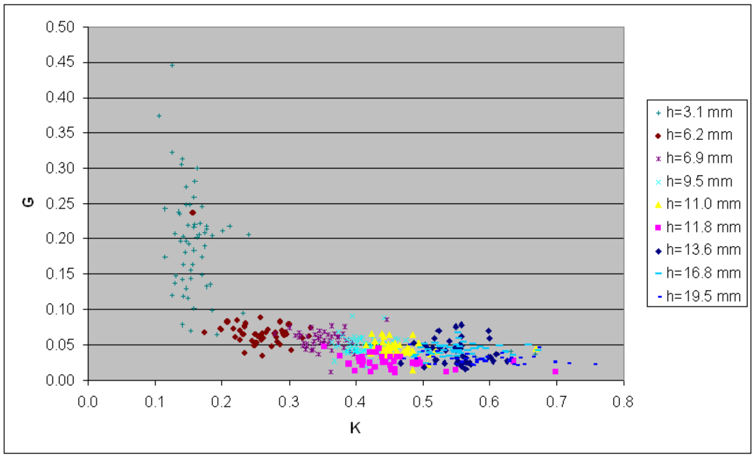

Figure 2: Contributions of the curvature (K) and the strain rate (G) to the dimensionless stretch σ in Eq. (3).

the reaction layer, should satisfy

$$U_n = U_{_L} + \mathcal{L}S, \tag{2}$$

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

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 versus S computed from these experimental data and the planar flame velocity $U_L \approx 222$ mm/s, which is determined as explained below.

The contributions K and G of the flame curvature and flow strain rate to the dimensionless stretch

$$\sigma = \frac{\mathcal{L}S}{U_{_L}} = \frac{2\mathcal{L}}{R} + \frac{\mathcal{L}}{U_L}\frac{\partial u}{\partial x} = K + G \tag{3}$$

are shown in Fig. 2. As can be seen, the contribution of the curvature dominates that of the strain rate for all but the shortest flames, with $h = 3.1$ mm. Data for these very weakly curved flames show considerable scatter and suggest a trend different from that of the other flames in our experiments. Such short flames will not be discussed here.

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 the four heights $h = 6.2$, 6.9, 9.5 and 11 millimeters have been used. It should be noted that the fitting process requires iteration, because $U_{_L}$ appears in the expression (1) of the stretch. The Markstein length determined from this fitting

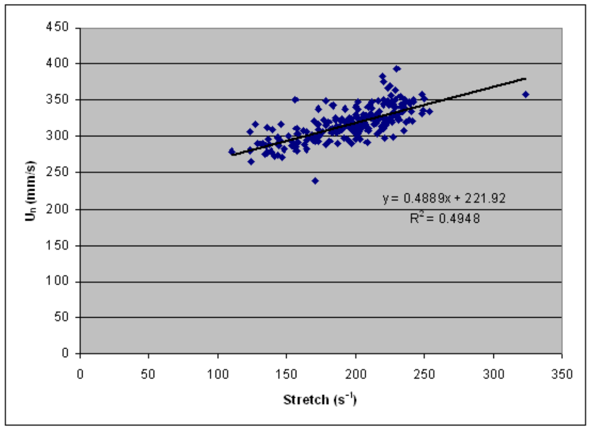

Figure 3: Determination of the planar flame velocity $U_{_L}$ and the Markstein length $\mathcal{L}$ by fitting a straight line to the experimental data for four different flame heights.

is $\mathcal{L} = 0.489$ mm, which is in reasonable agreement with other experimental values and with the theoretical value of Ref. [5]. The velocity of the planar flame, given by the intercept of the straight line in Fig. 3, is $U_{_L} \approx 222$ mm/s, as was mentioned 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 $\mathcal{L}$ obtained above are used. According to Markstein's linear relation (2) and (3), the data should fall on the diagonal $U_n/U_{_L} - 1 = \sigma$. 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.

Mungal and coworkers [3, 4] 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

$$\sigma_{_T} = \frac{\mathcal{L}}{U_{_L}} S_{_T} \quad \text{and} \quad S_{_T} = U_n \mathcal{C} + \frac{\partial u}{\partial x}, \tag{5}$$

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.

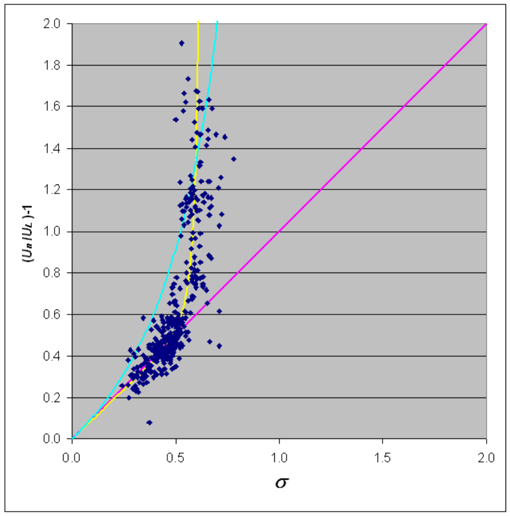

Figure 4: Left- and right-hand sides of Markstein's relation $U_n/U_L - 1 = \sigma$ evaluated with the experimental data for different flame heights. The blue curve shows Mungal's modified relation (4) and the yellow curve is a nonlinear fit to the experimental results.

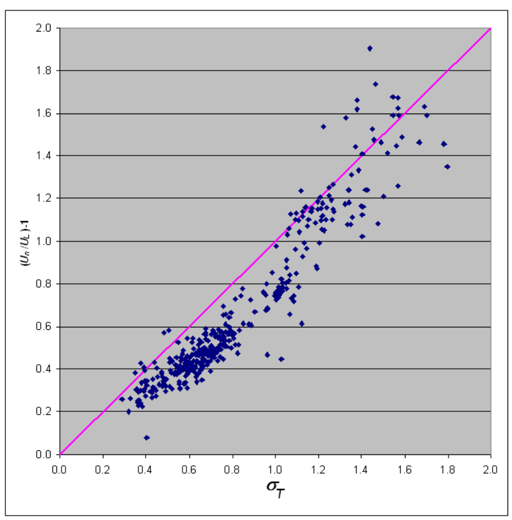

Figure 5: Left- and right-hand sides of the modified velocity-stretch relation (4) evaluated with the experimental data for different flame heights.

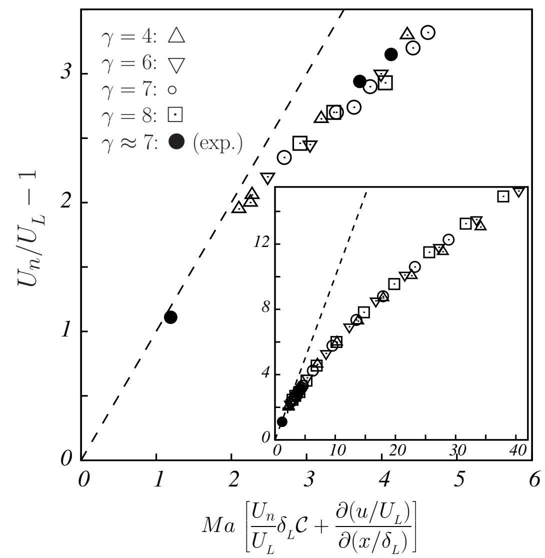

Figure 6: Left- and right-hand sides of Eq. (4) evaluated with the numerical data for $\gamma = 3$ (△), 5 (▽), 6 (○), and 7 (⊡), and with the experimental data for $\phi = 1.49$ ($\gamma \approx 6$, ●).

Some comparisons with the numerical results are shown in Fig. 6, where the measured fractional change of the flame velocity relative to the planar flame velocity is plotted as a function the measured modified stretch (in brackets in the horizontal axis), for an equivalence ratio $\phi = 1.49$ and different dilutions, measured by the ratio γ 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 $Ma = \mathcal{L}/\delta_L$ is the Markstein number, evaluated from the theoretical results of Clavin and Garcia-Ybarra [5] 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 seem to suggest 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 $U = U_n/U_L$ shows that the results of Buckmaster and Crowley [6] for slender flames are applicable when $U \gg \gamma$, leading to a curvature radius of the reaction layer at the tip smaller than the thickness of a planar flame by a factor of $O(\gamma/U)$. When $1 \ll U \ll \gamma$, 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 $O(r_b/U^{1/2})$ and expands and deflects significantly upon being heated.

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 conduction 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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