Estimation of Laminar Flame Speed Using Plain Flame Photography and an Image Processing Procedure.

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The need of measuring laminar flame speeds for various fuels and fuel blends is crucial for determining flame stabilization characteristics and design parameters for practical burner configurations. The laminar flame speed (S_u^o) being one of the most important, observable, flame parameters, contains essential information about reactivity, diffusivity and exothermicity. It also serves as a scaling parameter in the development of kinetic models, in the prediction of combustor safety properties such as flashback and blow-off and in turbulent combustion models.

Various methodologies have been used over the years to estimate laminar flame speeds such as the Bunsen flame i.e.[1] the counter-flow flame i.e. [2] the stagnation flame i.e. [3], and the spherically expanding flame i.e [4] referred to in chronological order. Each of these experimental tools has its merits, drawbacks and level of complexity.

Amongst the various laminar flame configurations, the Bunsen flame being historically the oldest [5], is probably the simplest, and the most popular one. This configuration has proved convenient for the investigation and testing of a range of combustion theories and characteristics. Due to its amenability and suitability in straightforwardly quantifying, S_u^o's, interest has recently been rekindled in the exploitation of this configuration in combination with a variety of image processing techniques for application in a wide range of fuel blends and conditions, an attribute particularly useful in industrial applications.

Nevertheless, uncertainties still remain regarding the control of its operating parameters, the optimum experimental procedures and the assessment of the experimental results and ongoing research is being directed at addressing the above issues.

The present work describes a low cost laminar flame speed estimation and investigates its efficacy for methane and propane-air mixtures at different equivalence ratio values.

Experimental Methodology

Bunsen flames were stabilized on the rim of a 14 mm axisymmetric contoured nozzle with a sharp edge of 0.8 mm. The nozzle has been designed using Burger's equations with an area based contraction ratio of 12.75. The contraction ratio has been chosen to minimize the effect of the boundary layer (BL) and help in the effort to achieve a 'top hat' velocity profile of the reactants at the exit (U_{exit}). This was measured and validated by Laser Doppler Velocimetry (LDV) over a range of usefully selected operating exit velocities. The volumetric flow rates (Q) of the C_3H_8/air and CH_4/air mixtures were regulated through high accuracy (± 0.5%) sonic nozzles calibrated specifically for the operating gases and flow rates, with Omega® DPG2001B digital pressure regulators with an accuracy of ±0.25%.

The area and angle techniques were separately employed to determine the flame speed (S_u) from the images; the term S_u^o is reserved for the true laminar flame speed. Once the targeted flame is stabilized at the nozzle rim, digital camera images (Shutter speed: 1/25, Aperture: F5.6 ISO 800, 10.2 megapixel) were taken to determine the flame front angle and cone surface area. U_{exit} was determined from the mass flow rate of the mixture and the nozzle diameter. S_u's were

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then calculated from direct flame photographs using both techniques. The wavelength range of detection of the employed camera (Nikon D80) is 400 to 680nm.

Flames were evaluated using both flame cone angle and the cone surface area techniques.

For the cone angle technique, S_u's were determined from U_{exit} and the angle *(α)* of the flame front with respect to the burner axis of symmetry as:

$$S_u = U_{exit} * \sin(\alpha) \tag{1}$$

It has to be mentioned that the cone angle *(α)* has been extracted by the healthy part of the Bunsen cone side, as an average of the two half cone angles estimated, with the burner axis.

Then, for the cone surface area technique, S_u's were then deduced from the division of the volumetric flow rate of the reactants by the area of the flame cone.

$$S_u = Q/A_f \tag{2}$$

Taking into account the merits and drawbacks of each method, both techniques were exploited to illustrate the attendant limitations of the proposed code.

Preprocessing Image Techniques

In order to estimate the unburned laminar flame speed, we are going to use two different approaches. In order to achieve our goal it is vital to preprocess the initial input images. Specifically, the following preprocessing steps are proposed:

1. Background removal & Image cropping
2. Image Enhancement by 2-D Bilateral filtering and row-wise normalization
3. Flame's edges detection
4. Symmetry correction
5. Inner edges detection
6. Flame's speed estimation via cone angle estimation
7. Polynomial fitting and Flame's speed estimation via cone area estimation

Results

Experiments have been conducted for both methane and propane air flames employing both the Bunsen cone angle and surface area techniques to estimate the unburned laminar flame speeds at a range of equivalence ratio values, as depicted in Fig. 1. The estimated laminar flame speeds for the methane and propane air flames, using the cone angle and the surface area method are compared to well-established reference data from a range of works [6–17], selected for validation of the accuracy of the present methodology. For both methane and propane air flames it can be observed that the unburned laminar flame speeds estimated in the current work lie between the margins of the scatter of the literature values. This favorable comparison verifies the capability of the overall image processing methodology, in combination with either the cone angle of the surface area S_u calculation technique, to provide results of acceptable accuracy.

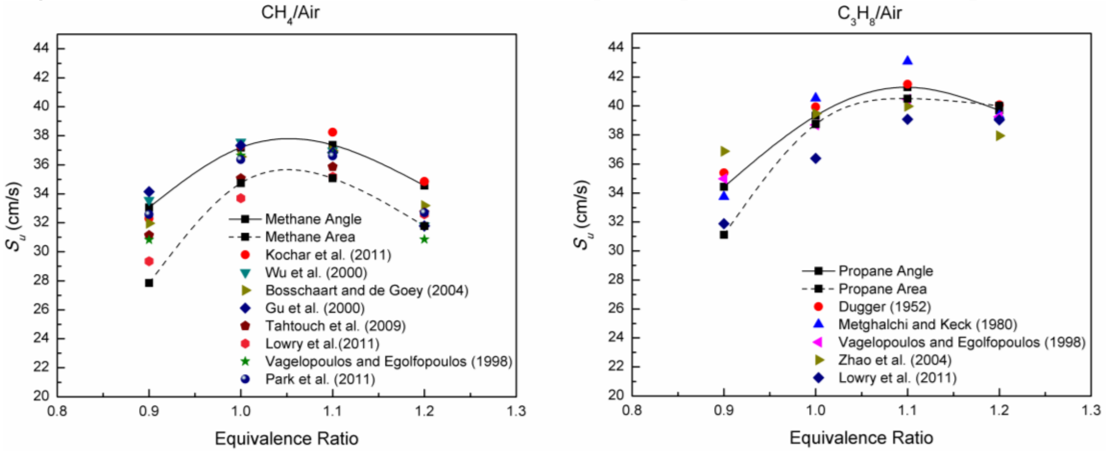

Fig. 1. Experimentally measured flame speeds using the area and angle methods for CH_4/air and C_3H_8/air mixtures.

Cone Angle Method

Using the cone angle method those results are possible due to the fact that the visible borders of the flame, captured in the camera images, lay parallel to the preheat zone of the flame, where the unburned flame speed is commonly calculated (i.e. normal to the actual flame front. Thus, the inadequacy of the plain photography, to identify the actual flame front, does not affect the final S_u results, and is suitably compensated by using the cone angle calculation. Specifically, for methane air mixtures the maximum deviation from the literature values is at 8% while for the propane air mixture the deviation reaches values up to 5.4%.

Cone Surface Area Method

Regarding the methane air mixture we can detect a relative underestimation of the flame speeds reaching a maximum of 10%. This underestimation could be attributed to the fact that the area used in order to estimate the laminar flame speeds is significantly larger than the real flame front area, since the edge of the preheat zone of the flame is closer towards the flame axis, compared to the visible edge illustrated in plain images. The edge detection procedure employed, inevitably detects the visible chemiluminesent border line, which is somewhat displaced outwardly from the preheat zone as the result of the fact that the OH* emission, at 308nm, which is mainly located in the reaction zone, is not visible by the camera. This demarcates the flame boundary at a displaced position and results in an increased cone surface area calculation and an attendant lower laminar burning velocity.

In the case of the propane air mixture the influence of flame luminosity on the flame speed estimation is expected to be of a greater impact. The higher hydrocarbon mixture produced more luminous flames, especially at higher equivalence ratio values, due to increased CH* and particularly CO_2* emissions, in comparison to the methane air flames. As the rate of formation of the electronically excited CO_2*, is proportional to the product of the concentrations of CO and O, richer propane air mixtures produced higher luminosity intensities. These higher intensities resulted in a saturation of the captured photo images particularly in certain flame regions, such as the base of the Bunsen cone making the accurate flame surface estimation more cumbersome.

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