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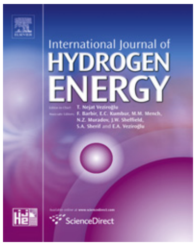

Laminar burning velocities and flame stability analysis of hydrogen/air premixed flames at low pressure

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ABSTRACT

An experimental and numerical study on laminar burning velocities of hydrogen/air flames was performed at low pressure, room temperature, and different equivalence ratios. Flames were generated using a small contoured slot-type nozzle burner (5 mm × 13.8 mm). Measurements of laminar burning velocity were conducted using the angle method combined with Schlieren photography. Numerical calculations were also conducted using existing detailed reaction mechanisms and transport properties. Additionally, an analysis of the intrinsic flame instabilities of hydrogen/air flames at low pressure was performed. Results show that the behavior of the laminar burning velocity is not regular when decreasing pressure and that it depends on the equivalence ratio range. The behavior of the laminar burning velocity with decreasing pressure can be reasonably predicted using existing reaction mechanisms; however changes in the magnitude of the laminar burning velocity are underestimated. Finally, it has been found experimentally and proved analytically that the intrinsic flame instabilities are reduced when decreasing the pressure at sub-atmospheric conditions.

1. Introduction

Hydrogen (H_2) is viewed by many as the ultimate "end-objective" fuel in order to solve the problems about world high energy demands, a future shortage of conventional fuels, and environmental pollution [1]. The design of combustion devices fueled with hydrogen demands advanced knowledge of the combustion properties of hydrogen. One of the most important properties is the laminar burning velocity, S_L, since it determines the structure and the stability of the flames. The laminar burning velocity of hydrogen has been extensively studied in the past mainly at atmospheric and high pressures [2–6] due to its importance in the development of high-power combustors. However, to the best of authors' knowledge, the availability of works on S_L of H_2 at low pressures is still limited [7–10]. Fig. 1 compiles some of the data on S_L of H_2 at atmospheric and low pressures found in those works. Fine [7] measured S_L of H_2/air mixtures using the burner method at pressures within the range 0.21–0.97 atm at different equivalence ratios. Aung et al. [8] reported experimental data on S_L of H_2/air flames at 0.35 and 0.5 atm at different equivalence ratios using the spherical bomb technique. Kwon and Faeth [9] performed measurements at 0.3 and 0.5 atm using the spherical bomb technique with $H_2/O_2/Ar$ mixtures at two equivalence ratios ($\phi = 0.6$ and $\phi = 4.5$) and with a $H_2/O_2/He$ mixture at $\phi = 0.6$. Sun et al. [10] derived computationally S_L of outwardly propagating spherical H_2/air flames at 0.6 atm within the range $0.6 \leq \phi \leq 5.0$. As can be seen in Fig. 1 there are limitations of experimental data on S_L at many equivalence ratios, there is not good agreement between experimental and

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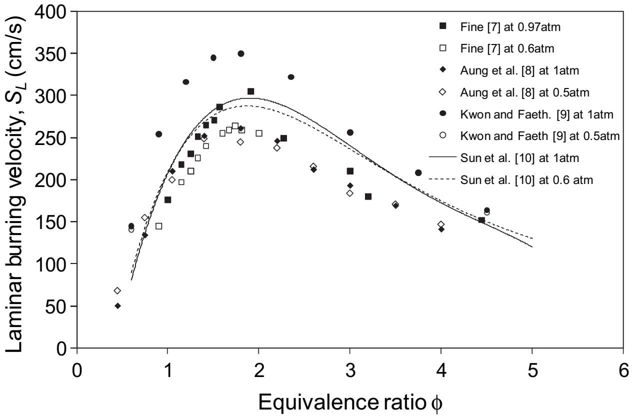

Fig. 1 – Laminar burning velocities of H_2/air flames at atmospheric and low pressures. Markers: experimental results [7–9]; lines: numerical results [10].

numerical data at the same pressure condition, and the tendency about the effect of pressure at sub-atmospheric conditions on S_L of H_2 calculated by Sun et al. [10] has not been confirmed experimentally. Information on S_L of H_2 at low pressure is particularly important in Latin- American countries since many cities, with considerable population and then high energy consumption, are located at high altitude about sea level (low pressure atmospheres). On the other hand, data on S_L at different equivalence ratios is of practical importance since industrial combustors usually work with forced air at lean equivalent ratios in order to reduce thermal NOx emissions while domestic combustors generally work with induced air at rich equivalence ratios due to power requirement and costs issues.

For these reasons, in the present study, laminar burning velocities of hydrogen/air flames were determined experimentally and numerically at low pressures and within a wide range of equivalence ratios ($0.6 \leq \phi \leq 4.4$). Experiments were conducted using the burner stabilized flame technique with instantaneous Schlieren photography, and values of S_L were determined with the angle method. In this technique only average values of S_L can be obtained since local burning velocities vary along the flame front due to effects of stretch, curvature at the flame tip, and heat losses near the burner walls; however, the experimental methodology by Pareja et al. [11] was implemented to reduce these effects. Unlike previous studies, where sub-atmospheric conditions were simulated in pressure chambers [7–9], experiments were conducted at real pressure conditions in two places located at altitudes of 500 m.a.s.l. ($P = 0.947$ atm) and 2300 m.a.s.l. ($P = 0.767$ atm). The use of the burner stabilized flame technique was convenient regarding transportation and price of the experimental setup, and simplicity to determine S_L. Experimental data of S_L were compared with numerical calculations using existing reaction mechanisms in order to evaluate their performance on reproducing present experimental data and the effect of low pressure on S_L of H_2. Additionally an analysis of the behavior of intrinsic flame instabilities (i.e., hydrodynamic instability and diffusive-thermal instability) at low pressure, using existing formulations, was performed and it is presented in this paper in order to explain the appearance of flame instabilities at certain mixture and pressure conditions.

2. Experimental method

2.1. *Experimental setup*

Fig. 2 shows a schematic diagram of the experimental setup implemented in this study. Flames were generated using a small burner with a contoured slot-type nozzle (5 mm × 13.8 mm) in order to keep laminar Reynolds numbers at every equivalence ratio studied as well as to reduce the effects of flame stretch and curvature in the direction of the burner axis. The design of the burner nozzle allowed obtaining nearly uniform exit velocity profiles, which gave defined triangular flames with fairly straight edges. Additionally, a cooling system was implemented in order to keep the mixtures at a constant temperature.

For the Schlieren technique, a high-intensity discharge Xenon lamp was used as light source. This light was focused with a biconvex lens (diameter = 50.8 mm, focus length = 38.1 mm) and a pin hole with diameter of 1 mm in order to achieve high resolution images of the flames. Next, light rays were directed to the test zone through a plane-convex lens (diameter = 50.8 mm, focus length = 250 mm). After that, deflected and non-deflected rays were focused again with an identical plane-convex lens and deflected rays were blocked with an adjustable slit while non-deflected rays were captured with a monochromatic high-resolution high-speed camera (Basler scA1400-30 gm, 1392x1040 pixels, 30 fps). In order to obtain high resolution images of such small flames, a Macro camera lens (Sigma, diameter = 72 mm, focus length = 150 mm, f/2.8) was employed. Images were transmitted to a computer through an Ethernet connection (1 Gbps) to monitor the flames in real time and to take the Schlieren photographs.

High purity certified gases were used to generate the required mixtures at every equivalence ratio. Hydrogen and air flows were measured using variable area flowmeters specifically calibrated for each gas. Hydrogen and air were mixed before entering the burner and a mixture chamber inside the burner was used in order to guarantee a thorough mixing of the reactants. Errors in the final compositions of the mixtures were estimated lower than 2%.

2.2. *Determination of the laminar burning velocity*

Laminar burning velocities were determined by the burner stabilized flame method with Schlieren photography. In this technique, the flame propagates toward the unburned mixture at an angle θ as shown in Fig. 3. The velocity component of the unburned mixture which is normal to the flame front is identical to the laminar burning velocity, therefore S_L is calculated as follows:

$$S_L = U\sin(\theta) \tag{1}$$

Where U is the average velocity of the unburned mixture at the burner exit. This method is usually called as the angle method. In this technique, local burning velocities vary along the flame front due to the effects of flame stretch and heat loss, and only average values can be obtained. Nevertheless,