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# Effect of N<sub>2</sub>/CO<sub>2</sub> dilution on laminar burning velocity of H<sub>2</sub>–air mixtures at high temperatures

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## ABSTRACT

The laminar burning velocities of H<sub>2</sub>–air mixtures diluted with N<sub>2</sub> or CO<sub>2</sub> gas at high temperatures were obtained from planar flames observed in externally heated diverging channels. Experiments were conducted for an equivalence ratio range of 0.8–1.3 and temperature range of 350–600 K with various dilution rates. In addition, computational predictions for burning velocities and their comparison with experimental results and detailed flame structures have been presented. Sensitivity analysis was carried out to identify important reactions and their contribution to the laminar burning velocity. The computational predictions are in reasonably good agreement with the present experimental data (especially for N<sub>2</sub> dilution case). The burning velocity maxima was observed for slightly rich mixtures and this maxima was found to shift to higher equivalence ratios ( $\Phi$ ) with a decrease in the dilution. The effect of CO<sub>2</sub> dilution was more profound than N<sub>2</sub> dilution in reducing the burning velocity of mixtures at higher temperatures.

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## 1. Introduction

The alarming issues of fossil-fuels depletion and increasing concern for protection of environment calls for a shift from hydrocarbon fuels to cleaner alternatives, such as hydrogen fuel based economy. Considering the slow developments in fuel cell technology, the implementation of hydrogen or fuels blended with hydrogen in gas turbine combustors and reciprocating type internal combustion engines seems to be a feasible solution [1,2]. The characteristics of a combustion process are mainly governed by laminar burning velocity of the fuel–air mixture and it is defined as the velocity with which a combustion wave propagates into the unburned fuel–air mixture in a direction normal to the surface of combustion wave. Laminar burning velocity is an important thermochemical property that characterizes a

combustible fuel–air mixture and provides important information about reactivity, diffusivity and exothermicity of the given fuels and their blends. The laminar burning velocity is also a function of percentage of fuel in a given fuel–air mixture, also known as mixture equivalence ratio ( $\Phi$ ). Mixture equivalence ratio is defined as the ratio of actual fuel–air mass ratio to that of stoichiometric fuel–air mass ratio. It further indicates about the availability of oxidizer in a mixture to completely burn the available fuel in the mixture (lean mixture,  $\Phi < 1$ , stoichiometric mixture,  $\Phi = 1$  and rich mixture,  $\Phi > 1$ ). It is an important property and helps in the development of new combustion systems, their flame stability, flame safety and emission control [3].

Laminar burning velocities of hydrogen, syngas (mixture of H<sub>2</sub> and CO), hydrogen enriched hydrocarbons and diluted hydrogen mixtures have been reported in the literature [3–20].

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Various methods have been widely used in the literature such as constant-volume combustion bomb (expanding spherical flame) method [3–12] using high-speed Schlieren photography, heat-flux method [13,19], counter-flow stagnation method [14,20] and burner-stabilized flame technique [16,21]. Qin et al. [15] have used a particle tracking velocimetry (PTV) based technique and carried out image processing for burner-stabilized flames to obtain the laminar burning velocities of hydrogen–air mixtures. In these methods, the measured data of burning velocities has been either extrapolated to zero heat loss [13,19] or zero strain-rate conditions [3–12] to obtain laminar burning velocity of a given fuel–air mixture.

Recently, Natrajan et al. [16] have studied the effect of CO<sub>2</sub> dilution on laminar burning velocity of lean syngas mixtures for a wide range of fuel compositions, temperatures and pressures using Bunsen flame approach and wall stagnation flame approach. This study was limited to lean and stoichiometric fuel–air mixtures. Prathap et al. [17] and Kishore et al. [18] have studied the effect of dilution with N<sub>2</sub> and CO<sub>2</sub> on equimolar mixture of H<sub>2</sub>–CO gases. Prathap et al. [17] observed a significant decrease in laminar burning velocity of H<sub>2</sub>–CO mixtures with N<sub>2</sub> dilution and a shift in the burning velocity peak from very rich to slightly rich mixtures ( $\Phi = 1.4$  for 60% N<sub>2</sub> dilution from  $\Phi = 2.0$  for no dilution). Kishore et al. [18] observed an increase in burning velocity on increasing the hydrogen content and compared the experimentally observed results to the Davis mechanism [22] predictions. In most of these studies, the laminar burning velocities at low temperatures (near ambient) have been reported and very limited data exists for flames at high temperatures. Since the operating temperatures in many combustion systems of practical importance such as gas turbines and IC engines are relatively much higher, it is important to measure the burning velocities at higher mixture temperatures.

Present work reports the effect of N<sub>2</sub> or CO<sub>2</sub> dilution as individual components on laminar burning velocities of H<sub>2</sub>–air mixtures at high mixture temperatures using the planar flames appearing in high aspect-ratio diverging mesoscale channels suggested by Akram et al. [23–26]. In this technique, planar flame propagation mode appears for a range of mixture flow rate and equivalence ratio conditions in these diverging channels [23–26]. This method produces apparatus independent and near adiabatic burning velocities [26]. The burning velocities were measured for a range of equivalence ratios ( $0.8 \leq \Phi \leq 1.3$ ) and percentage dilutions at high temperature (350–600 K).

The experimental data has been compared to the existing kinetic models for H<sub>2</sub>–air mixtures with N<sub>2</sub> and CO<sub>2</sub> dilution. The effect of dilution with these gases is expected to help understand the role of specific heat and molecular weight of different diluents on laminar burning velocity of H<sub>2</sub>–air mixtures. The key chemical reactions affecting the combustion characteristics and burning velocities of diluted H<sub>2</sub>–air mixtures have been discussed.

## 2. Methods and materials

### 2.1. Details of the experimental setup

In the present work, an externally preheated diverging channel based technique has been used. This technique has been

proposed and validated by Akram et al. for various fuel–air mixtures [23–26]. Details of the experimental setup are shown in Fig. 1. A high aspect-ratio mesoscale diverging channel with a rectangular cross-section has been used. The inlet dimensions and divergence angle of the channel are 25 mm × 2 mm and 10° respectively. The properties of quartz such as low thermal conductivity, high heat capacity, low thermal expansion and transparency make it a suitable material for flame visualization. The channel was externally preheated with liquefied petroleum gas–air (LPG–air) mixture burnt at the top of a porous burner. External preheating of the channel helps compensate for the heat loss from the propagating flame to the walls and stabilize the flame in the channel. The H<sub>2</sub>–air mixture diluted with N<sub>2</sub>/CO<sub>2</sub> gases was supplied at the inlet of the channel at ambient conditions ( $T_u = 300$  K and 1.0 atm). The flow rates of these gases were controlled and monitored using mass flow controllers connected to a personal computer through a command module. These mass flow controllers were accurate within ±1.5% of the full scale. The channel wall temperatures were measured using K-type thermocouples of diameter 0.5 mm. The motion of the thermocouples was controlled using a precise traverse with a minimum resolution of 0.25 mm. The measured wall temperatures were accurate within ±5 K of the actual value. Akram and co-workers [17,18] have shown that the temperature varies linearly in the longitudinal direction and remains almost uniform in the transverse direction except near the exit plane for all mixture flow rate conditions.

### 2.2. Measurement of laminar burning velocity

The planar flames obtained in the diverging channel were considered for different equivalence ratios, percentages of dilution and external heating rates. The flame positions were recorded using a photographic camera and the velocity of propagating flame was obtained by applying the mass conservation equation for the diluted fuel–air mixture supplied at the channel inlet and mixture entering the planar flame front as given below.

$$\rho_{\text{inlet}} \times A_{\text{inlet}} \times U_{\text{inlet}} = \rho_f \times A_f \times S_u \quad (1)$$

Here  $\rho$  is the density of the mixture,  $A_f$  flame area,  $S_u$  laminar burning velocity and  $U_{\text{inlet}}$  is the mixture velocity at channel inlet. Since,  $\rho_f/\rho_{\text{inlet}} = T_{u,o}/T_u$  (using ideal gas equation), this equation can be rewritten in the following form.

$$S_u = U_{\text{inlet}} \times (A_{\text{inlet}}/A_f) \times (T_u/T_{u,o}) \quad (2)$$

Here,  $A_f$  is determined from the position of the stabilized flame in the channel. With all other parameters known and prior knowledge of temperature variation along the length of the channel helps determining  $T_u$ . Substituting the values of various parameters in Eq. (2) helps in determining the burning velocity and its variation with mixture temperature as shown in Fig. 2. The experiments are carried out for a range of mixture velocities and equivalence ratios. For a given equivalence ratio, the laminar burning velocity at standard conditions ( $S_{u,o}$ ) and the temperature exponent ( $\alpha$ ) can be determined by fitting a power law correlation to experimental data as shown in Fig. 2. The laminar burning velocity at

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