Laminar Burning Velocity of H_2-N_2/CO_2-Air Mixtures at Elevated Temperatures

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1 Introduction

The increasing global warming and environmental degradation calls for alternate fuels which are cleaner and more efficient. Hydrogen is considered one of the cleanest fuels since it produces heat and water only unlike hydrocarbon fuels that produce undesirable products like carbon dioxide and carbon monoxide. The laminar burning velocity is a physiochemical property of a premixed mixture of fuel and oxidizer [1]. Various studies were reported with an attempt to measure the laminar burning velocity of diluted hydrogen-air and syngas-air mixtures [2-4]. Recently Natrajan et al. [2] have studied effect of CO_2 dilution on laminar burning velocities of lean mixtures for a wide range of fuel composition, temperatures and pressures. Prathap et al. [3] and Ratna Kishore et al. [4] have reported the effect of dilution with Nitrogen and CO_2 on equimolar H_2-CO mixture. However, all the data available is limited to very low mixture temperatures. Many practical devices like IC engines, gas turbine etc. require burning velocity data at high temperatures. Therefore, in the present study N_2/CO_2 diluted pure H_2 was used.

The measurement of laminar burning velocity requires stabilization of planar flames at given mixture conditions A planar (stretched-free) flame propagation mode was observed to exist for certain conditions of the flow rate and mixture equivalence ratios in high aspect ratio divergent channels [5-7]. This preheated high aspect ratio diverging channel method is simple and produces apparatus independent near adiabatic burning velocity. Therefore, in this work, a meso-scale 12.5 aspect ratio 10 channel is utilized.

The present work reports laminar burning velocities of N_2/CO_2 diluted hydrogen-air mixtures using meso-scale diverging channel at high temperatures. The burning velocities were measured for a range of equivalence ratios ($0.8 \leq \Phi \leq 1.3$) and percentage dilutions at high temperatures (350-600 K).

2 Experimental set up

In the present work meso scale diverging quartz channel of rectangular cross section and high aspect ratio was used. The inlet dimensions of the channel and angle of divergence were 25mm X 2mm and 10^o respectively. High heat capacity, low thermal conductivity, low thermal expansion and transparency for good visibility make quartz a suitable material. Low thermal conductivity materials have lower

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tendency to absorb radicals and minimize the quenching at walls [1]. The volumetric flow rate of H_2 /diluent–Air mixtures was controlled by using calibrated mass flow controllers. The temperatures were measured using a K-type thermocouple of diameter 0.5 mm. A precisely controlled traverse having a minimum resolution of 0.25 mm was used to move the thermocouple in and out of the channel. The measured temperatures were accurate within ±5 K of the actual value. To reduce the heat loss of the flame to the walls of the channel, it was heated externally by a porous sintered metal burner placed at a downstream location and below the channel. This creates a positive temperature gradient along the direction of fluid flow [8] and helps in initial ignition and stabilization of the flame.

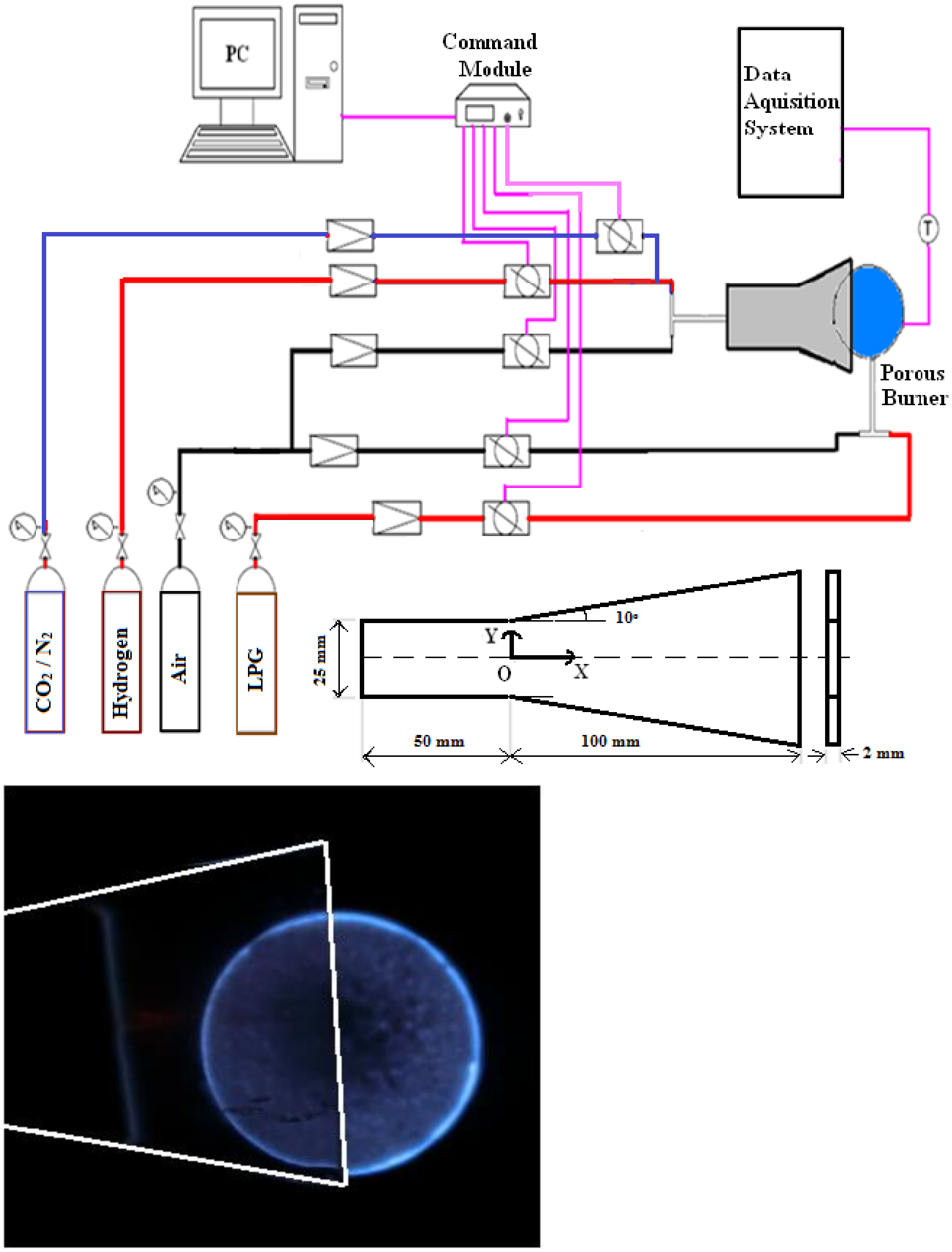

Figure1. Schematic diagram of apparatus and direct flame photograph of 70% CO_2 dilution flame at $\Phi = 1.0$ and $U_{inlet} = 1.2$ m/s.

3 Preliminary Results

3.1 Obtaining Planar Flames

The primary flame propagation modes observed in the present study were planar, negatively stretched and positively stretched. The velocity was almost linear in the axial direction. The temperature and velocity in the transverse direction were found to be nearly uniform which helped in the formation of planar flames [5]. The flames obtained were very thin in the depth direction which confirms their planarity in depth direction. The flames obtained in the diluted hydrogen flames are fainter than the flames obtained with hydrocarbon fuels.

3.2 Burning Velocity Calculation

Planar flames were observed to exist for a range of inlet velocities of fuel air mixtures. The stabilized planar flames were captured using a high speed digital camera and accurate flame positions were obtained using image processing in MATLAB. The wall temperature profiles for different equivalence ratios, diluent percentage and heating rate of bottom burner were known apriori. Mass averaged temperature at the location of flame over transverse direction was used.

The conservation of mass of the H_2-diluent-Air mixture entering the flame front was used for measuring the burning velocity of the mixture at a given temperature [9].

$$S_u = U_{inlet} \times \left(\frac{A_{inlet}}{A_f}\right) \times \left(\frac{T_u}{T_{u,o}}\right)$$

4 Results and Discussion

In the present study the inlet temperature and pressure of the fuel air mixtures were maintained at 300 K and 1 atm respectively. The percentage dilution refers to the molar percentage of diluent in H_2 – diluent mixture. Laminar burning velocities were measured for a range of equivalence ratios ($0.8 \leq \Phi \leq 1.3$) and preheat temperatures. The effect of dilution was studied for 60% and 70% dilution with CO_2 as diluent and for 70% and 80% dilution with N_2 as diluent. Variation of laminar burning velocity with temperature, equivalence ratio and extent of dilution was studied. The variation of laminar burning velocity with the ratio of mixture temperature, T_u to reference temperature $T_{u,0}$ for various equivalence ratios at various percentage dilutions with CO_2 and N_2 was plotted and a power law correlation was applied to the data as:

$$S_u = S_{u,o} \times \left(T_u/T_{u,o}\right)^{\alpha}$$

4.1 Effect of Initial Temperature on Laminar Burning Velocity

The burning velocity was observed to increase with increase in fuel-air mixture temperature. The variation of burning velocity for a lean 30% H_2 - 70% CO_2 -Air mixture ($\Phi = 1.1$) is shown in figure 1. The continuous line shows the power law trend line. Such graphs were plotted for a range of equivalence ratios for every percentage dilution of N_2 and CO_2 and a similar trend was observed. The values of $S_{u,0}$ and temperature exponent, α were noted in each case.

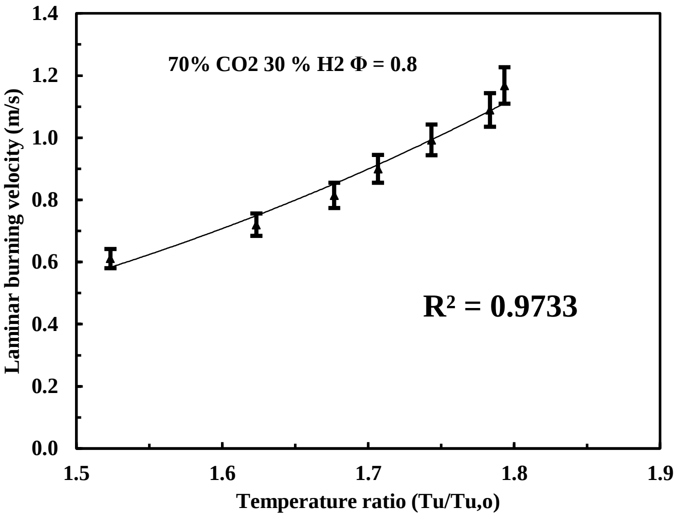

Figure 2. Laminar burning velocity variation with temperature ratio and power law trend line.

4.2 Effect of Equivalence Ratio on Temperature Exponent

The variation of temperature exponent, α with equivalence ratio was observed to be a nonlinearly decreasing function for a range of equivalence ratios and percentage dilutions. In several cases α increased after attaining a minimum at a slightly rich mixture (Φ = 1.1 or 1.2). In the other cases there may be a minima at a richer mixture. The experimental data fits well on a second degree polynomial. The continuous line in the figure represents the quadratic trend line. Similar variation was observed earlier in the case of methane, propane and LPG [5,6,10] and the minimum was also observed at around Φ = 1.2. The variation can be seen in the graphs in figure 3.

4.3 Effect of Equivalence Ratio on Laminar Burning Velocity at Ambient Conditions

The laminar burning velocity of fuel air mixture at a given temperature is a strong function of equivalence ratio. The laminar burning velocity increases non-linearly and then decreases after attaining a maximum value at a slightly richer mixture. The laminar burning velocity at ambient temperature attains a maximum at around Φ = 1.2 for 80% and 70% nitrogen dilution and at around Φ = 1.1 and 1.2 for 70% and 60% Co_2 dilution. The data can be fit very well on a quadratic i.e. second degree polynomial curve. The variation at ambient conditions can be seen in figure 4. The continuous line represents the second degree trend line.

4.4 Effect of Equivalence Ratio on Laminar Burning Velocity at Higher Temperatures

With increase in temperature the laminar burning velocity increases for all equivalence ratios. The variation of laminar burning velocity with equivalence ratio at higher temperatures is similar to that at ambient conditions. Figure 5 shows the variation of laminar burning velocity at elevated temperatures for 40% H_2 – 60% CO_2 – Air mixture.

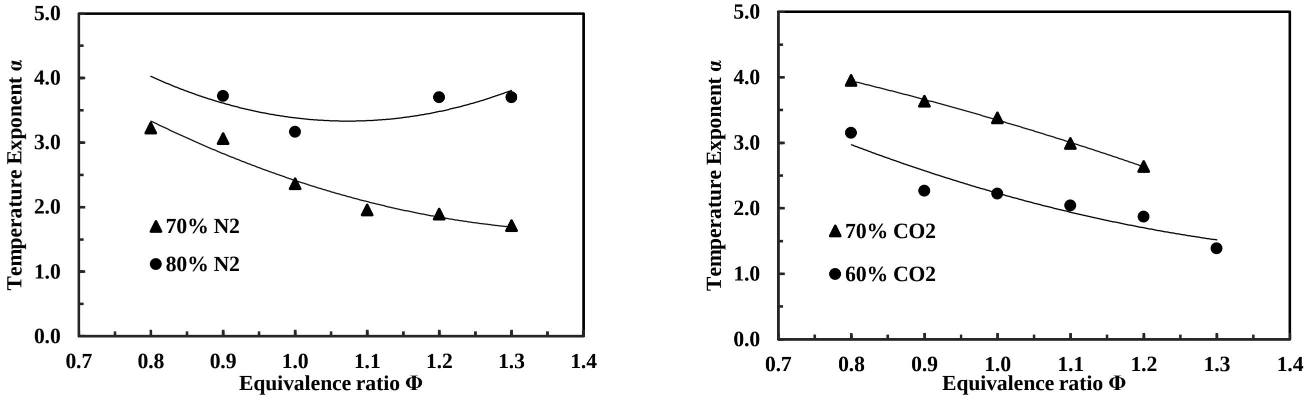

Figure 3. Variation of temperature exponent α with equivalence ratio for various cases of dilution. The continuous line represents the second order polynomial fit.

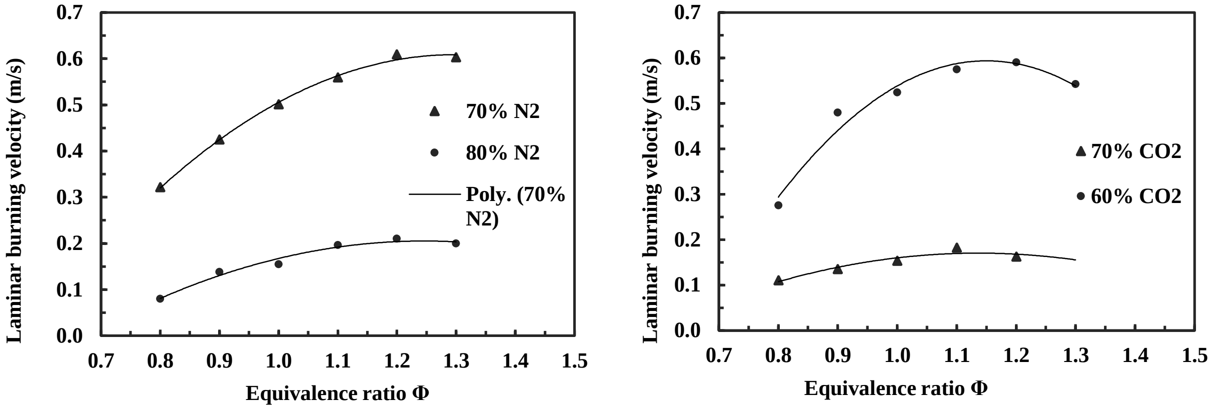

Figure 4. Variation of laminar burning velocity at ambient conditions $S_{u,o}$ with equivalence ratio for various cases of dilution.

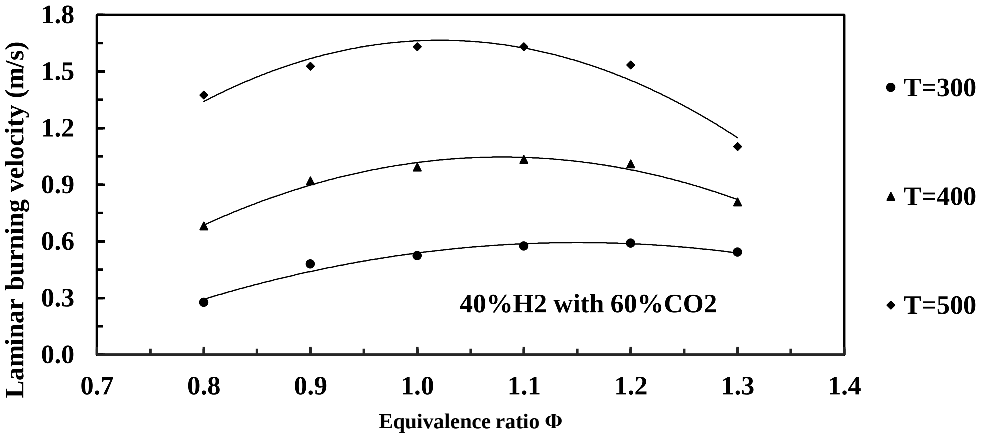

Figure 5. Variation of laminar burning velocity at higher temperature (on Kelvin scale) with equivalence ratio.

4.5 Effect of Dilution on Laminar Burning Velocity and Temperature Exponent

The laminar burning velocity was seen to decrease and the temperature exponent was seen to increase with increase in percentage of N_2 and CO_2 dilution. The plots in figure 3 and 4 show the variation of laminar burning velocity and temperature exponent respectively with equivalence ratio at different dilution conditions. These will be helpful in understanding the extent to which the dilution effects the burning velocities at different temperatures.

The effect of CO_2 as a diluent can be seen to be more pronounced than that of N_2 in decreasing laminar burning velocity from the plots in figure 4. This can be clearly seen by comparing laminar burning velocities at 70% CO_2 and 70% N_2.

5 Conclusion

The present work reported the laminar burning velocities of hydrogen diluted with N_2 and CO_2 at high temperatures using planar flames obtained in mesoscale diverging channel. Variation of laminar burning velocity and temperature exponent (and hence burning velocities at high temperatures) with equivalence ratio and percentage of dilution was studied. The temperature exponent decreased on the leaner side with increasing Φ for almost all cases and increased after attaining a minima at a slightly lean mixture ($\Phi = 1.1$ to 1.3) in most cases. Laminar burning velocity was found to increase on the leaner side with Φ and then decrease after attaining a maxima on the richer side ($\Phi = 1.1$ to 1.3). Laminar burning velocity was found to increase with decreasing percentage of dilution in case of both N_2 and CO_2. Temperature exponent was found to increase with increasing dilution. It was also noted that as a diluent CO_2 decreases burning velocity more than N_2. The data at high temperatures is very useful in the design of various high temperature combustion devices.

6 References

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