On the Variation of Laminar Burning Velocity Temperature Exponent with Equivalence Ratio

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1 Introduction

Laminar burning velocity of reactive mixture depends on its equivalence ratio, initial pressure and initial temperature of fuel-air mixture. The most popular co-relation for describing the simultaneous effect of initial temperature and equivalence ratio on flame propagation speed is in the form of a power law [1-7] which is given as:

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

Where " α " is termed as temperature exponent and is a function of pressure and mixture equivalence ratio. Most of such co-relations are given for a very short range of temperatures and behave well in their given range of mixture temperatures. However, these co-relations need to be extrapolated to obtain the burning velocities at high temperatures. In many practical devices, such as, IC engines and gas turbine engines, the local pressure and temperature of the mixture is significantly higher than the STP conditions. Further, in recent years, direct preheating of mixtures or recirculation of certain amount of combustion products to preheat the mixture is being actively pursued to enhance thermal efficiency and simultaneously reduce pollutant emissions including NO_x from combustion systems [8]. If the available co-relations for burning velocities at high temperatures are extrapolated, an inaccurate behavior can be observed. For instance, Fig. 1 shows the extrapolated burning velocity variation for methane-air mixtures at 800 K (representative temperature for highly preheated air combustion processes) from the available literature [1-7]. Although these co-relations provide a closer value for stoichiometric fuel-air mixtures except for Takizawa et al. [7], the variation with equivalence ratios is quite different for lean and rich mixtures. In many cases, the value for lean and very rich mixture is substantially higher than the respective magnitude of mixture burning velocity for stoichiometric mixtures. This behavior becomes worse at higher temperatures (for instance, at 1000 K). Therefore it is very important to investigate this issue and provide an accurate co-relation which would comply with the general observation of flame burning velocity for a range of mixture equivalence ratios and mixture temperatures.

It is also interesting to note that there is a large discrepancy in the data available for variation of temperature exponent with the mixture equivalence ratio as shown in Fig. 1b. Sharma et al. [1] have given separate expressions for rich and lean mixtures and their experiments were limited for a mixture equivalence ratio range of 0.8 - 1.2. They observed that minimum value of temperature exponent, α exists for stoichiometric mixture, which was later confirmed by Gu et al. [4] and Liao et al. [5].



Fig. 1. (a) Laminar burning velocity variation for methane-air mixture in existing literature at 800 K and (b) variation of temperature exponent

A slight decrease in α was observed by Iijima and Takeno [2] for a range of $0.8 \le \Phi \le 1.3$. A slight decrease in α with lean to rich mixture was observed by Takizawa et al. [7]. In another study, Stone et al. [3] have proposed a linear co-relation, in which temperature exponent α reduces linearly with mixture equivalence ratio as shown in Fig 1b. The existence of the minimum value of α near stoichiometric mixture ratio with a sharp decrease for very lean and very rich mixtures has been reported by Yan et al. [6] as shown in Fig. 1b. Considering the large variation of the temperature exponent in the reported literature and subsequent problems in using the temperature exponent for extrapolation at high temperature as described in Fig. 1a, it becomes important to readdress this issue.

2 Present Methodology

2.1 Experimental Method

To obtain the accurate burning velocity temperature dependency of premixed fuel-air mixtures, the flame should be as planar as possible. It is essential to obtain a propagating/stationary flame which is independent of any flow stretch and heat loss. During the preliminary investigations on different flame propagation modes in high aspect ratio divergent channels, planar flames were observed to exist for a range of flow velocities varying from 0.3 to 0.65 m/s depending on the mixture equivalence ratio and a given rate of external heating [9]. The laminar burning velocities of stoichiometric methane-air [9], propane-air [12] and LPG-air [13] mixtures are reported using this preheated mesoscale high aspect ratio diverging channel technique.

Figure 2 shows the experimental set up with relative position of channel and external heater. In present investigations, channel of 12.5 inlet aspect ratio and 10° diverging angle is used. Once a planar flame is stabilized in the channel, the location of the flame is captured with a digital camera and accurate flame position is obtained. For different mixture velocities and known heating rates of the bottom burner, the mixture temperature is known apriori. The flame propagation velocity of the given mixture

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at a particular temperature is obtained using the following relation of conservation of mass of the fuelair mixture entering the flame front.

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



Figure 2 Experimental set up for the measurement of laminar burning velocity

2.2 Computational Method

A Fortran computer program PREMIX [14] that computes steady state species and temperature profiles for freely propagating premixed laminar flames is used to predict burning velocities computationally at different temperatures. The laminar burning velocity of methane-air mixtures is predicted using GRI mech 3.0 [15]. The Qin et al. mechanism [16] is used to predict the burning velocities and flame structure of propane-air mixtures. The USC mech 2.0 [17] made for C_1 - C_4 fuel-air mixtures, is utilized for LPG-air mixtures (LPG composition: 40 % propane and remaining butane by volume).

3 Results and Discussions

Laminar burning velocity temperature dependency for various hydrocarbon mixtures such as methaneair, LPG-air and propane-air with a range of equivalence ratio of $0.6 \le \Phi \le 1.4$ and preheat temperature of 350 - 650 K have been measured. Since the position of the stabilized flame inside the channel depends on the mixture equivalence ratio and temperature, the range of initial mixture temperature is different for various mixture equivalence ratios. The initial reference temperature of the unburned mixture was 300 K for all the experiments. The extensive uncertainty analysis including the effect of boundary layer, hydrodynamic strain, flame to wall heat loss and difference of wall and reactant temperature leads to an uncertainty of ± 5 %. Some of the factors which affect burning velocity were observed to mutually compensate each other. Different burning velocity correlations have been obtained for temperature dependency, α of various mixture equivalence ratios. The dependency of laminar burning velocity for fuel-air mixtures on temperature at a constant pressure (mean sea level, Mumbai, India) is presented here. The variation of measured laminar burning velocity is plotted with the ratio of mixture initial temperature, T_u to reference initial temperature, $T_{u,o}$ for various equivalence ratios. A simple power law correlation is applied to the experimental values as:

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

3.1 Methane-Air Mixture

The variation of the temperature exponents (α) with mixture equivalence ratio is shown in Fig. 3. The present experimental results show a significant influence of equivalence ratio on temperature

exponent. The present experimental results show the existence of minimum value of temperature exponent, α near $\Phi = 1.1$. Temperature exponent becomes least for slightly rich mixtures and rises off for both the rich and lean mixtures. The temperature exponent for stoichiometric methane-air mixture is 1.591 whereas a minimum value of 1.588 is obtained at $\Phi = 1.1$. The smooth curve is the best fit of the data to a third degree polynomial and well suited to describe the variation of the temperature exponent (α) for both lean and rich mixtures with least at slightly rich mixture.



Figure 3. Variation in temperature exponent of methane-air mixture with equivalence ratio

Figure 3 also shows the agreement of the present temperature exponents with the recent data available from various experiments [4-6] and numerical computations [15, 18]. Iijima and Takeno [2] and Takizawa et al. [7] have reported a moderate linear decrease and increase in temperature exponent values with equivalence ratios respectively. Stone et al. [3] reported a significant linear decrease in the temperature exponent with equivalence ratio.



Figure 4. Variation of species mole fraction and normalized adiabatic flame temperature for methaneair mixture at two temperatures

To understand this peculiar behavior of variation of temperature exponent with equivalence ratio, adiabatic flame temperatures and mole fractions of major species for two different mixture temperatures, 300 K and 600 K are computed for a range of equivalence ratios as shown in Fig. 4. As the mixture temperature is increased, a higher concentration of CO is observed for nearly stoichiometric and slightly rich mixtures as shown in Figure 4. This is because of increased dissociation of CO₂ to CO due to comparatively higher adiabatic flame temperatures for 0.85 < Φ < 1.15 range. Although, the magnitude of adiabatic flame temperature ($(T_{ad}/T_u)/(T_{ad}/T_{u,o})$) is more for lean and very rich mixture as compared to slightly rich mixtures as can be seen in Fig. 4. This leads to the existence of minimum value of temperature exponent for slightly rich mixtures.

3.2 Propane-Air Mixtures

Figure 5 shows the comparison of the temperature exponent obtained in present experiments with the data available from various experiments and numerical computations using Qin et al. [16] mechanism. There is a large discrepancy in the literature [7, 19-20] regarding the magnitude and existence of the minimum temperature exponent. Metghalchi and Keck [19] reported higher values of temperature exponent with very low burning velocity at 300 K. The correlation given by Takizawa et al. [7] gives higher and lower magnitudes for lean and very rich mixtures, respectively as compared to those obtained from Qin et al. mech. Temperature exponents reported by Razus et al. [20] provides better results for lean and rich mixtures comparatively. However, the magnitude of temperature for near stoichiometric mixtures is very small compared to that of Qin et al. [16] mechanism. The values of the temperature exponent obtained from present experiments are in good agreement with numerical computations of Qin et al. [16]. The temperature exponent reported by Metghalchi and Keck [19] and Takizawa et al. [7] shows a linear variation of α with equivalence ratio.





Figure 5. Influence of mixture temperature on laminar burning velocity of lean and rich propane-air mixtures



Figure 6. Variation of temperature exponent of LPG-air mixtures with equivalence ratio

3.3 LPG-Air Mixtures

The power of temperature ratio in power law correlations is termed as temperature exponent, α and is observed to be a function of equivalence ratio at ambient pressure. Figure 6 shows the variation of temperature exponent, α with mixture equivalence ratios and its comparison with the results of Huzayyin et al. [21] and Liao et al. [22]. A continuous non-linear decrease in the value of temperature exponent is reported by Huzayyin et al. [21]. Liao et al. [22] give a minimum value of temperature exponent for near stoichiometric mixture and the reported values are slightly higher than present

results. The present experimental investigation shows the existence of minimum value of temperature exponent, α near $\Phi = 1.1$.

 $\alpha = -2.444 \, \Phi^3 + 11 \, \Phi^2 - 14.91 \, \Phi + 7.935$

4 Conclusions

In this work, the planar flames stabilized inside preheated mesoscale high aspect ratio channel is utilized to extract the burning velocity temperature dependency of various hydrocarbon mixtures. The magnitude and variation of temperature exponent match with some recent experimental data and computational predictions. The sepcies dissociation and hence variation of adiabatic flame temperature confirm a least value burning velocity temperature exponent for slightly rich mixtures. The linear correlation for variation of temperature exponent with the equivalence ratio must be discouraged.

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