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Paper No.

MEASUREMENTS OF LAMINAR BURNING VELOCITY OF ETHANE-AIR MIXTURES AT ELEVATED TEMPERATURES

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ABSTRACT

The current paper reports the measurement of laminar burning velocities of ethane-air at atmospheric pressure and higher mixture temperatures using planar flames stabilized in an externally heated mesoscale diverging channel. The experiments were carried out at various equivalence ratios (ϕ = 0.7-1.3) and mixture temperatures (350-600 K). The burning velocities and temperature exponents were determined using the planar flames stabilized at different channel locations due to varying mixture inlet velocities and temperatures. The measured burning velocities of ethane-air flames at ambient conditions compare well with the Aramco mech 1.3 mechanism predictions. The burning velocities increase for high mixture temperatures, which can be attributed to the higher enthalpy of the mixture at these temperatures.

Keywords: Laminar burning velocity, Elevated temperature, Ethane-Air

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NOMENCLATURE

S_u	Laminar burning velocity
ϕ	Equivalence ratio
α	Temperature exponent

INTRODUCTION

One of the primary source of energy is the combustion of fuel. A change to a cleaner, lower-carbon energy structure has been brought about by social and policy pressures. However, biomass energy and conventional fossil energy, which are primarily composed of hydrocarbon fuels, will continue to be the main energy sources for decades to come. Among conventional energy sources like coal, oil, natural gas, and ethanol, natural gas (NG) is currently considered to have the highest potential as a clean alternative energy source [1]. Methane (CH_4) and ethane (C_2H_6) are the two main components of natural gas. Because natural gas is produced in different locations, the composition of natural gas varies. For instance, Liaohe, China natural gas contains 97.05% methane, while Abu Dhabi natural gas primarily consists of 82% methane and almost 16% ethane, and natural gas produced in the USA primarily consists of 85% methane and 14% ethane [1]. Therefore, study of laminar burning velocity, fundamental flame property of fuel/oxidizer mixtures, is vital for engine design, turbulent combustion analysis, and chemical kinetic model validation.

In 1990, Egolfopoulos et. al. [2] measured LBV of ethane-air mixtures using counter flow flame method (ϕ = 0.6 - 2.0) at standard atmospheric conditions. Tseng et al. [3] used spherical flame method to measure flame speed for an equivalence ratio (0.8-1.6) at standard conditions. In 1995, Aung et al. [4] corrected the results of Tseng et al. [3] due to the error in enthalpy of formation values at the same conditions. In 1998, Vagelopoulos et al. [5] used the stagnation flow configuration with large separation distances between the nozzle and the stagnation plane, which enables the establishment of Bunsen-type flames as the flow rate is reduced to measure the flame speed (ϕ =

0.65 - 1.5) at standard conditions. Konnov et al. [6] measured LBV using heat flux method (ϕ = 0.6 - 1.5) at normal standard conditions. In 2004, Bosschaart et al. [7] used the heat flux method to measure the flame speed (ϕ = 0.6 - 1.5) at standard conditions. Dyakov et al. [8] measured flame speed using heat flux method (ϕ = 0.6 - 1.5) at standard conditions. In 2008, Kishore et al. [9] used the heat flux method to measure the LBV (ϕ = 0.7 - 1.3) at standard conditions. Dirrenberger et al. [10] measured flame speed using heat flux method (ϕ = 0.6 - 2.1) at standard conditions. They observed flame speed of 42 cm/s at ϕ = 1.1. In 2013, Park et al. [11] used the counter flow flame method to measure the LBV (ϕ = 0.6 - 1.5) at standard conditions, they employed non-linear stretch extrapolation technique for the measurement. Mitu et al. [12] measured flame speed using spherical flame method (ϕ = 0.59 - 1.36) at various initial pressures (P_u = 30–130 kPa) and initial temperatures (T_u = 298–423 K) conditions. In 2016, Goswami et al. [13] used the heat flux method to measure the LBV (ϕ = 0.8 - 1.3) at various pressures (P_u = 1 – 4 atm) and normal temperature conditions. They observed decrease in flame speed with an increase in pressure. Recently Han and co-workers [14] measured flame speed using heat flux method (ϕ = 0.7 - 1.5) at atmospheric pressure and temperatures (T_u = 298–328 K) conditions. at higher temperatures. The laminar burning velocity and inlet temperature of the mixture are correlated as $S_u=S_{uo}(T_u/T_{uo})^{\alpha}$, where T_{uo} is the reference temperature and S_{uo} is the laminar burning velocity at a reference temperature (300K).

It becomes evident from a detailed review of the existing literature that laminar burning velocity of ethane-air mixtures has been measured only up to the unburnt mixture temperature of 423 K, and that motivates the author to extend the LBV measurements for unburnt mixture temperature up to 600 K in the present study using externally heated diverging channel method for an equivalence ratio ranging from 0.7-1.3 at atmospheric pressure conditions.

EXPERIMENTAL SETUP

The present method uses a high aspect ratio (12.5) diverging channel with a divergence of 10^0 and rectangular (25 mm × 2 mm) cross-section at inlet. The quartz material for the diverging channel was utilized because it provides transparency for flame visualization, high heat capacity, and low thermal conductivity. The uniform flow field and planar flames are formed for a range of operating conditions, due to high aspect ratio of the channel [15]. The ceramic radiation heater (SHTS/2 Elstein (600 W), Germany) was used for external heating of the channel. This heater was placed 20 mm below the channel with a 20 mm overlap at the exit to heat the channel walls at a specified heating rate externally. External heating of the channel develops a positive temperature gradient along the direction of the fluid flow, and helps flame stabilization in the channel. Adiabatic conditions can be achieved by external heating, which compensates for heat loss from the stabilized flame to the solid walls of the channel [16].

Figure 1 shows a schematic diagram of the experimental setup. The premixed fuel-air mixture at ambient conditions with different inlet flow velocities, controlled by mass flow controllers, is supplied at the inlet of the diverging channel. The flame stabilizes at a location where flow velocity equals the burning velocity of the mixture. K-type thermocouple was used to measure the channel wall temperatures at different axial and transverse locations. A precise traverse mechanism was used to control the movement of the thermocouple. The flow velocities,

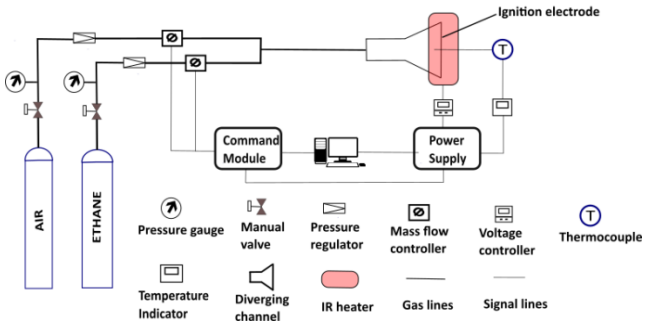

FIGURE 1. Schematic diagram of the experimental set up

mixture equivalence ratios were precisely controlled using electronic mass flow controllers, through command module with PC interface. The fuels and air feed lines pressures are regulated with the help of pressure regulators.

The channel was heated uniformly for 20 min with desired air flow to establish positive temperature gradient. After the preliminary arrangements, an appropriate fuel-air mixture is ignited at the exit of the channel. The flame ignited at the exit of the channel gradually propagates inside the channel to stabilize at a position where the flow velocity equals the burning velocity.

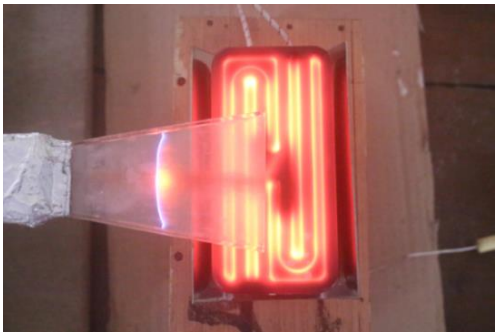

FIGURE 2. Photograph of planar flame stabilized in the diverging channel

The images of the stabilized flames were captured using a DSLR camera. The distance is measured from the channel exit to the position where the flame is stabilized using a scale attached to the traverse mechanism. The external heating rate is changed for the same inlet conditions with the help of power controller unit, and the experiment is repeated until a planar flame as shown in Fig. 2 is obtained to measure laminar burning velocity at various elevated mixture temperatures.

Computational studies to predict the laminar burning velocities with a detailed kinetic model of Aramco mech 1.3 [17] are performed using CHEMKIN-Pro 2020 [18] software tool. The mixture-averaged transport model was employed for computations with maximum grid points of 2000 along the length of the domain. The adaptive mesh parameters with CURV = 0.04 and GRAD = 0.04 assured convergence with grid independent solution. The mechanism predictions were then analyzed with the measurements of the present study.

RESULTS AND DISCUSSION

Effect Of The Mixture Temperature On Burning Velocity Measurements

The present LBV measurements and its comparison with the predictions of Aramco mech 1.3 [17] kinetic model for ethane - air mixtures at $\phi = 0.8$ are shown in Fig. 3. T_{u0} is the reference temperature (300 K in the present measurements). A solid circle symbol shows the data from current measurements, and lines represent the predictions of kinetic model. The nonlinear power-law correlation for the present data is shown with the dash-dot red line.

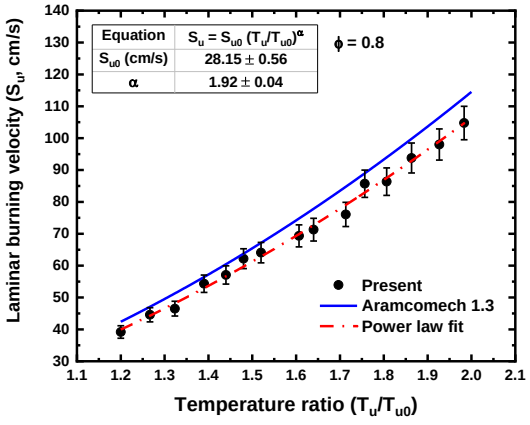

FIGURE 3. Variation of the LBV of ethane - air mixtures with temperature ratio at $\phi = 0.8$

As expected, the laminar burning velocity increases with an increase in the temperature ratio (due to the increase in enthalpy of reaction) for both experimental measurements as well kinetic model prediction. The present results under predicts all the mechanism predictions for the entire temperature ratio range, however these measured values are closer to the predictions of Aramco mech 1.3 [17] at some of the temperature ratios. The current results are shown with an uncertainty band of ± 5% [19].

The variation of laminar burning velocity with temperature ratio at $\phi = 1$ and $\phi = 1.2$ are shown in Fig. 4 and 5 respectively. Figure 4 shows that, almost the kinetic model prediction is closer to the results of present experimental investigations. Figure 5 shows that, for almost entire range of temperature ratio, the present LBV measurements at $\phi = 1.2$ significantly under-predicted by the Aramco mech 1.3 [17] mechanism.

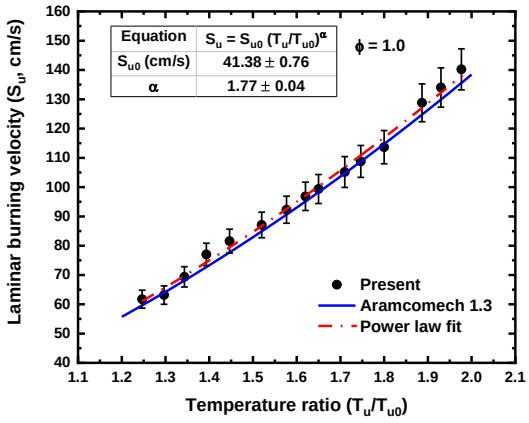

FIGURE 4. Variation of the LBV of ethane - air mixtures with temperature ratio at $\phi = 1.0$

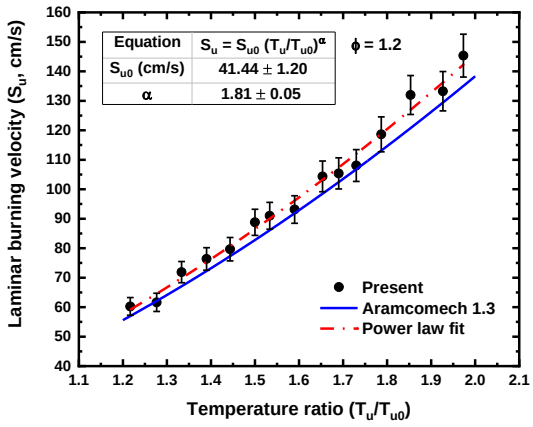

FIGURE 5. Variation of the LBV of ethane - air mixtures with temperature ratio at $\phi = 1.2$

Comparison Of Laminar Burning Velocity Data At Ambient Conditions

Figure 6 shows variation of laminar burning velocity at various equivalence ratios at ambient conditions, with

present results offset by – 0.01 on x-axis. The present results show better agreement with experimental results of Goswami et. al [13] and Kishore et al. [9] for almost entire range of equivalence ratio within margin for error.The present results shows little under predictions for lean mixture conditions, and slightly over prediction from stoichiometric to rich mixture conditions with mechanism predictions (maximum variation 5.63% at $\phi = 0.7$).

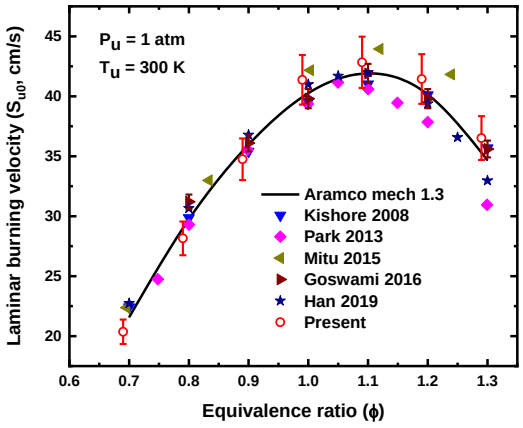

FIGURE 6. Variation of the LBV of ethane - air mixtures at standard conditions

Variation Of Temperature Exponent With Mixture Equivalence Ratio

In Fig. 7, the temperature exponent α is compared with mechanism predictions and present data across the equivalence ratio range ($\phi = 0.7$-1.3).

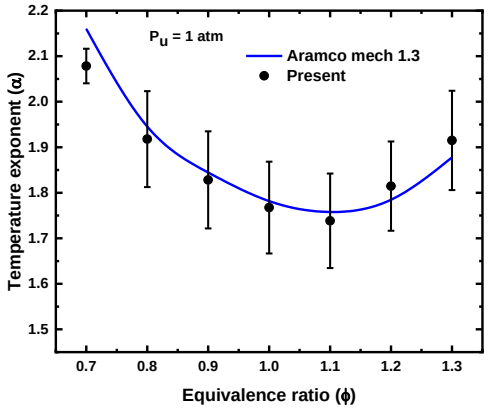

FIGURE 7. Variation of temperature exponent, (α) with mixture equivalence ratio (ϕ)

The uncertainty in the temperature exponent (α) was measured ± 6% using a least-squares method suggested by Alekseev et al. [20]. Within the margin of error, the present findings demonstrate good agreement with mechanism predictions.

Comparison Of Laminar Burning Velocity At Elevated Mixture Temperatures

In Fig. 8, a comparison of present data with the available experimental data using power law correlations and mechanism predictions is shown for unburnt mixture temperatures of 550 K. The present data under predicts for lean mixture conditions, and over predicts for rich mixture conditions with the mechanism predictions (maximum variation 10.18% at $\phi = 0.7$).

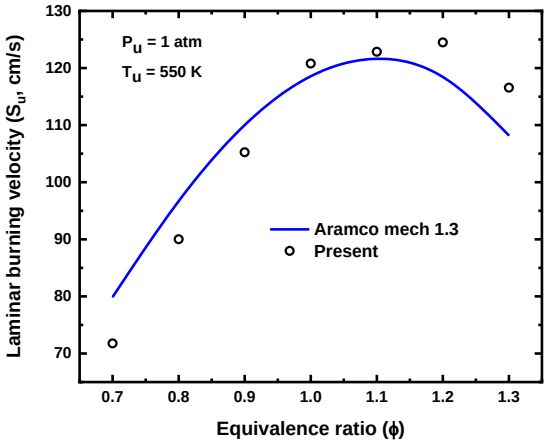

FIGURE 8. Variation of the LBV of ethane - air mixtures at 550 K.

CONCLUSION

The present work reports the experimental measurement of the laminar burning velocity of ethane-air mixtures at atmospheric pressure and elevated mixture temperatures of 350-600 K. The measurement burning velocities are consistent with the reaction mechanism predictions for various conditions with maximum values of the LBV, and minimum values of the temperature exponent at $\phi = 1.1$.

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