

Adiabatic Burning Velocity of H₂-O₂ Mixtures-Diluted With CO₂/N₂/Ar

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Abstract

Global warming due to CO₂ emissions has led to hydrogen being projected as fuel for future in a big way and lot of research is going on to design combustion appliances which can be used with hydrogen as fuel. This has necessitated fundamental research on combustion characteristics of hydrogen fuel. In this work a combination of experiments and computational simulations were carried out to study effects of diluents (CO₂, N₂, and Ar) on the laminar burning velocity of premixed hydrogen/oxygen flames. Heat flux method was used for measurement of burning velocities. The experiments were conducted to measure laminar burning velocity at various fuel-equivalence ratios at atmospheric pressure with reactants containing varying concentrations of CO₂, N₂, and Ar as diluents. Burning velocities were compared with computed results obtained by one dimensional laminar premixed flame code PREMIX with detailed chemical kinetics, transport properties and good agreement was obtained.

Introduction

The burning velocity is an important characteristic needed for the understanding of combustion processes. Moreover, it is one of the key parameters which governs the stabilization of flames on burners and has for instance a direct important influence on the limits of flash-back and lift-off of the flame.

The laminar burning velocities of hydrogen-air mixtures for various unburnt gas temperatures, pressures and equivalence ratio have been measured by many investigators using constant pressure outwardly propagating spherical flame method [1-5]. Faeth and coworkers [6] had studied H₂-air mixture by varying O₂/O₂+N₂ proportion in the unburnt mixture from 0.125 to 0.210 at different reduced pressures and atmospheric temperature. Hermanns et al [7] compared the measured burning velocity of H₂/O₂/N₂ flame with O₂/ (O₂+N₂) = 7.7% obtained by using heat flux method with the corresponding value presented by Egolfopoulos and Law [8] obtained by using counter flow flame method. Qiao et al [9] studied effect of dilution on laminar burning velocity of H₂/O₂/ N₂ mixtures for various equivalence ratios at different low pressures and room temperature. Qiao et al [11] extended the study of effect of dilution on laminar burning velocity on near limit H₂-air flame in microgravity at reduced pressure.

The present work was undertaken to investigate experimentally and computationally the effect of dilution with Ar, N₂, and CO₂ on adiabatic burning velocity of H₂-O₂ mixture. Heat flux method (HFM) was used to determine the burning velocity. Non-stretched premixed flames were stabilized through heat loss to the surface of a perforated plate burner where fresh mixture was introduced at atmospheric pressure. The setup was validated by comparing the experimental data of H₂-O₂-N₂ mixtures with literature. Computations were carried

out using the steady one-dimensional laminar premixed flame code, PREMIX of Kee et al. [12]. Li et al [13] reaction mechanism and corresponding thermal and transport data files were used.

Experimental Details

The experimental setup used in the present work has been described elsewhere [14] and the most relevant details are repeated below. It consists of a perforated burner plate attached to the burner head. The burner plate is made of brass plate having 2 mm thick perforated with a hexagonal pattern of 0.5 mm diameter holes with 0.7 mm pitch. It is surrounded by a hot water jacket maintained at a temperature higher than the ambient temperature. A cooling water jacket surrounds the lower portion of burner head which prevents the heating of the burner head due to heating fluid jacket. The burner head is mounted on a plenum chamber. Five K-type thermocouples of 75 μm wire were soldered into selected holes on perforated plate on the upstream side. The holes were selected at different radii and different circumferential locations to measure the temperature profile on the burner plate.

Before conducting the experiments the temperature of the hot water flowing through the jacket is made 343K and kept constant throughout the experiments since it is recommended [7] that the jacket temperature has to be at least 30 K higher than the unburnt gas temperature.

While doing experiment the flame is stabilized in two different conditions, sub-adiabatic and super-adiabatic. The flame is stabilized under sub-adiabatic condition when velocity of the flow of gas mixture is lower than the adiabatic burning velocity. The consequence of this is that the net heat loss from the flame, i.e, the sum of heat loss and heat gain is greater than zero. Then the temperature at the centre of the burner plate is higher than that of the heating jacket. If the velocity of flow is increased gradually at certain flow velocity, a condition

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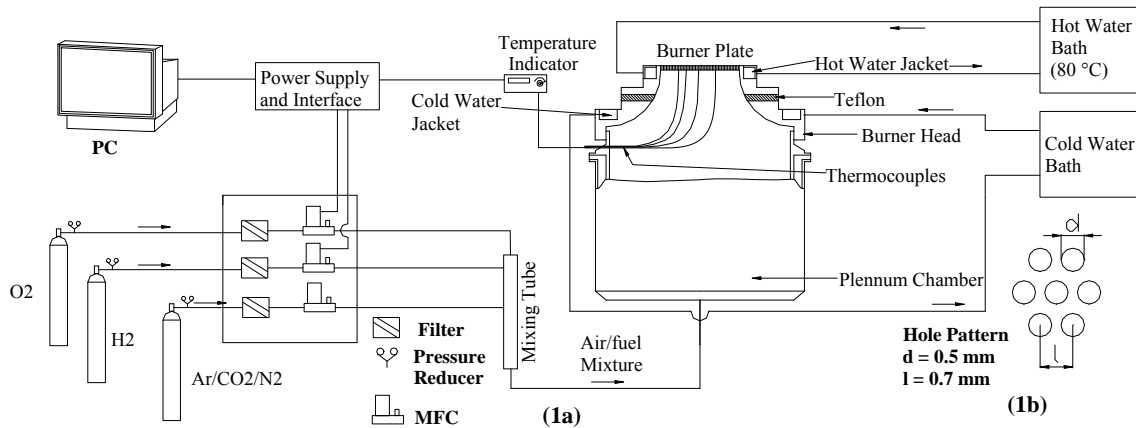


Figure 1. Schematic of heat flux method set up

is obtained where the net heat loss is lower than zero, called super-adiabatic condition. In this case the velocity is higher than the adiabatic laminar burning velocity. Thus by varying the flow rate of the gas mixture, an appropriate value of gas velocity could be found where net heat loss is zero.

Fuel (H₂), O₂ and diluent cylinders were individually connected to mass flow controller. Before passing through the mass flow controller the gases were filtered by 40 μm filters which also act as a buffer vessel. All the gas lines were connected to a mixing tube in order to mix the gas before entering to the plenum chamber of the burner as shown in figure (1).

In the region near the edge of the burner plate, a boundary layer exists due to which flame will not flat. Therefore the thermocouples were located in an area where these boundary layer effects are negligible, and the area is termed as 1-D area. This area is determined for this setup to be about <12mm radius [10].

In order to experimentally obtain the adiabatic burning velocity of a fuel/oxidizer mixture at a particular equivalence ratio, first a range of velocities are determined using burning velocity values predicted computationally. For this range of velocities, fuel oxidizer and diluent flow rates are calculated. Keeping the equivalence ratio fixed for a particular dilution percentage, the velocities of fuel and oxidizer are increased and at each combination fuel and oxidizer velocity, temperature profile across the burner plate is measured using the thermocouples.

The temperature distribution along radial direction of the burner plate is measured with the thermocouples attached

to it is also obtained by solving the following energy equation

$$T_p(r) = T_{center} - \frac{q}{4\lambda h} r^2 \text{----- (1)}$$

Here T_p is the temperature profile across the burner plate, T_{center} is the plate temperature, q is the net heat loss into the plate, λ is the thermal conductivity of the burner plate, h is the plate thickness and r is the radial coordinate. Once the measurements are taken a least square parabolic curve is fitted to the points to obtain an equation of the form of the following

$$T_p(r) = T_{center} - \alpha^2 r^2 \text{----- (2)}$$

Here α² is a constant and proportional to heat loss q in above equation (1). As the velocity is increased the temperatures reduce and also the curve becomes flatter. Fitting the profile given in equation (2) gives the value of T_{center} and α². α² is then plotted against the corresponding total mixture velocity. The velocity at which α² becomes zero gives the value of adiabatic burning velocity at the equivalence ratio.

Computational Methodology

Burning velocity computation for comparison with experimental data was performed on freely propagating steady adiabatic flame on one dimensional laminar premixed code- PREMIX which can shown to be equivalent to the flat burner stabilized flame [7]. By fixing the temperature at one point in the flame-fixed coordinate system (keyword TFIX), the program calculated the flame's burning velocity as an eigenvalue. Multi component diffusion and thermal diffusion has

taken into account. Li et al [13] reaction mechanism was used in PREMIX.

The governing equations and boundary conditions are transformed into a system of algebraic equations using finite difference approximations. The resulting non linear algebraic equations are solved using the modified damped Newton's method. By using adaptive grid parameter GRAD = 0.1 and CURV = 0.5, the burning velocity obtained is grid independent.

Validation Results

Initially experiments were conducted for measurement of adiabatic laminar burning velocities over a range of equivalence ratios for H₂-O₂-N₂ mixtures. The dilution ratio with R_{O₂} = 7.7% where R_{O₂} = O₂ / (O₂ + N₂) was used for validation of the experimental setup. The experiments was carried out at atmospheric pressure and unburnt gas temperature 300 ± 2 K. Results are compared with the experimental measurements of Hermann et al [7] and Egolfopoulos and Law [8]. Hermann et al. [7] also used the same experimental method, i.e., the heat flux method but Egolfopoulos and Law [8] used counter-flow flame method. The comparison is depicted in figure 2. The present measurements are in good agreement with that of Hermanns [7] as both had used same method (heat flux method). The maximum deviation between the two is 1.2 cm/s at equivalence ratio 1.4. The measured burning velocity of Egolfopoulos and Law [8] on stoichiometric and slightly rich mixture show significantly higher values compared to the present experimental and Hermanns [7] values. The difference between the two methods reaches up to 5.5 cm/s. In the equivalence ratio range of 1.2 to 1.6, the measured values of both the heat flux method and the counterflow measurements of Egolfopoulos and law [8] are comparable. At equivalence ratios above $\phi = 1.6$ the measurements with the counterflow method are lower than the heat flux method results.

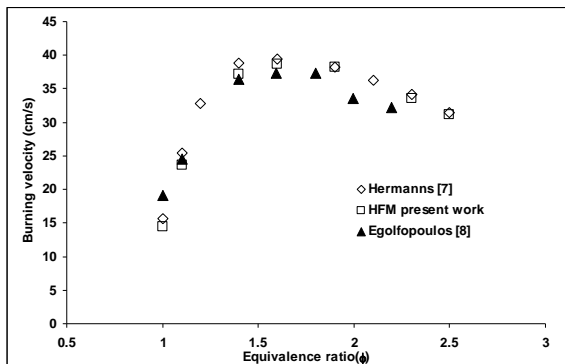


Figure 2: Comparison of experimental results for H₂+O₂+N₂ flames at 7.7% R_{O₂} with varying equivalence ratio with the literature data at atmospheric pressure and temperature = 300 ± 2 K.

Results and Discussion

In the present work the effects of dilution with Ar, CO₂, and N₂ on the adiabatic laminar burning velocity of H₂-O₂ mixture were studied. In the literature, most of the work considers both the fuel and oxidizer contain the diluent in which it is difficult to vary diluent fraction and equivalence ratio independently. So a mixture diluent approach as proposed by Prathap et al [15] was adopted for conducting experiments, considering the composition of premixed unburnt mixture of y% diluent + (100-y)% (H₂+O₂); i.e. 80% Ar in the mixture represents Ar percentage is 80% and the remaining 20% is divided into H₂ and O₂ on the basis of equivalence ratio.

Measured unstretched adiabatic burning velocities as function of equivalence ratio at different N₂, Ar, and CO₂ dilutions in H₂/O₂ flame are shown in figure 3 to 5 respectively. The experiments were conducted by using heat flux method at atmospheric pressure and 300 ± 2 K temperature. Concentration of dilution of N₂, Ar, and CO₂ in the unburnt mixture was varied from 70% to 75%, 80% to 85% and 60% to 70% respectively. The range of equivalence ratio is taken from 0.8 to 2. The corresponding computational values of laminar burning velocities have also been compared with the experimental values in these figures.

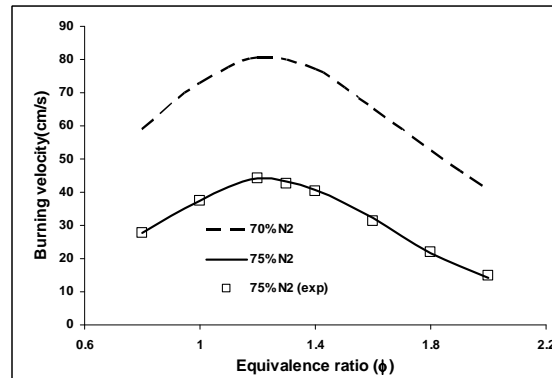


Figure 3: Comparison of computational and experimental results of adiabatic burning velocity in H₂-O₂-N₂ mixture flames at atmospheric pressure and temperature = 300 ± 2. Lines represent computational data and points represent experimental data.

Nitrogen dilution

The variation of measured and predicted unstretched burning velocity as a function of ϕ at dilution of N₂ is shown in figure 3. From the figure it is clear that due to dilution with N₂ there is substantial reduction in burning velocity. At 70% N₂ in the unburnt mixture the peak burning velocity is 80.7 cm/s at equivalence ratio 1.2; which decreases to 44.2 cm/s by increasing the dilution to 75%. It is recommended [10] that heat flux method should only be used for burning velocity values up to 60

cm/s. Therefore experiment was carried out only at 75% dilution with N₂. Comparison of measured burning velocity with that from computational predictions is quite good and the deviations are within the experimental uncertainties. The maximum discrepancy is 1 cm/s at equivalence ratio 1.6. Burning velocity increases with equivalence ratio till $\phi = 1.2$ and starts declining thereafter. The reasons for substantial reduction in burning velocity due to N₂ dilution at a given equivalence ratio are the decrease in heat release and increase in heat capacity of the mixture with dilution.

Argon dilution

Figure 4 shows the variation of measured and predicted unstretched burning velocity as a function of equivalence ratio at dilutions with Ar by 80% and 85%. The maximum burning velocity comes down below 60 cm/s at and above 80% Ar dilution; the peak value of burning velocity from experiment is 50.5 cm/s at equivalence ratio 1.2. The peak value of burning velocity for 85% Ar dilution is 20.7 cm/s at same equivalence ratio as the 80% dilution case. The experimental results show very good agreement with predicted computational data. Burning velocity increases with equivalence ratio till $\phi = 1.2$ and then starts declining with further increase in ϕ . The specific heat of Ar is less than that of N₂; and hence the effect of dilution on burning velocity is comparatively lower in case of Ar.

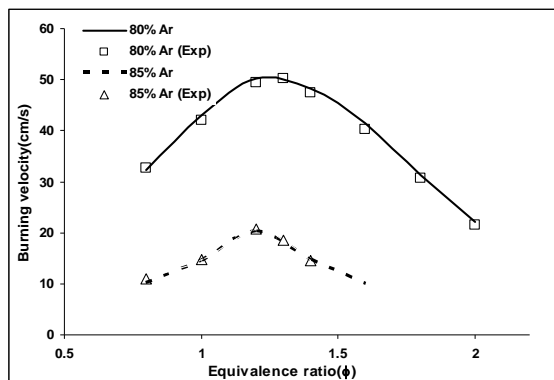


Figure 4: Comparison of computational and experimental results of adiabatic burning velocity in H₂-O₂-Ar mixture flames at atmospheric pressure and 300 ± 2 K. Lines represent computation data and points represent experiment data.

Carbon Dioxide dilution

The variation of measured and predicted unstretched burning velocity as a function of equivalence ratio at dilution with Ar by 60%, 65%, and 70% is depicted in figure 5. Burning velocity increases with equivalence ratio till $\phi = 1.2$ and starts declining with further increase in ϕ . At 60% CO₂ dilution, peak value of burning velocity is 67.7 cm/s at equivalence ratio 1.2 and

corresponding values at 65% and 70% CO₂ dilutions are 35.81 cm/s and 14.61 cm/s respectively. Experiment was carried out for 65% CO₂ dilution and compared with predicted values. The agreement was reasonable at most of the equivalence ratios except at $\phi = 1.4$. Cellular flames were observed up to stoichiometric mixture

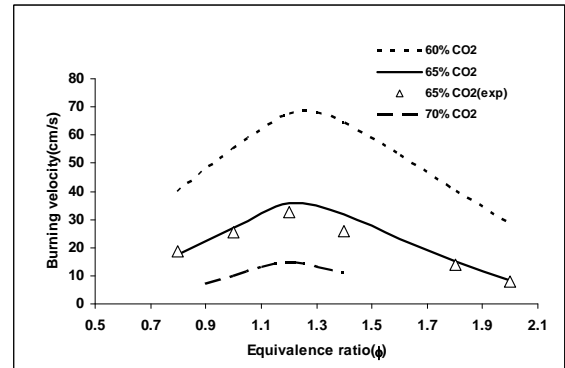


Figure 5: Comparison of computational and experimental results of adiabatic burning velocity in H₂-O₂-CO₂ mixture flames at atmospheric pressure and temperature = 300 ± 2. Lines represent computational data and points represent experiment data.

Conclusions

The effects of diluents on laminar burning velocities of Hydrogen/Oxygen mixture at atmospheric pressure and temperature 300 ± 2 K were investigated at various equivalence ratios. The experiments were conducted by using heat flux method with N₂, Ar, and CO₂ as diluents at varying concentrations in the H₂/O₂ mixture flame. The laminar burning velocity increases with increase in equivalence ratio up to 1.2 and then declined with further increase of equivalence ratio. By adding diluents in the unburnt H₂/O₂ mixture the burning velocity decreases. The order of dilution effect on burning velocity H₂/O₂ mixture flame is Ar < N₂ < CO₂. The specific heat to absorb heat is more in case for CO₂ and then N₂ which progressively reduce flame temperature and hence reduce burning velocity. Measured and computed values of laminar burning velocities are in good agreement for Ar and N₂ diluents unburnt mixture than unburnt mixture with CO₂ diluent.

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