

Laminar Flame Velocity and Temperature Exponent of Diluted DME-Air Mixture

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Abstract. In this paper, the laminar flame velocity and temperature exponent diluted dimethyl ether (DME) air mixtures are reported. Laminar premixed mixture of DME-air with volumetric dilutions of carbon dioxides (CO_2) and nitrogen (N_2) are considered. Experiments were conducted using a preheated mesoscale high aspect-ratio diverging channel with inlet dimensions of $25 \text{ mm} \times 2 \text{ mm}$. In this method, flame velocities are extracted from planar flames that were stabilized near adiabatic conditions inside the channel. The flame velocities are then plotted against the ratio of mixture temperature and the initial reference temperature. A non-linear power law regression is observed suitable. This regression analysis gives the laminar flame velocity at the initial reference temperature and temperature exponent. Decrease in the laminar flame velocity and increase in temperature exponent is observed for CO_2 and N_2 diluted mixtures. The addition of CO_2 has profound influence when compared to N_2 addition on both flame velocity and temperature exponent. Numerical prediction of the similar mixture using a detailed reaction mechanism is obtained. The computational mechanism predicts higher magnitudes for laminar flame velocity and smaller magnitudes of temperature exponent compared to experimental data.

1. Introduction

With the recent progress in the implementation of alternative fuels, dimethyl ether (DME) has emanated as one of the prominent clean fuels [1]. It is the simplest of ethers with high reactivity due to higher cetane number (≈ 60), low boiling point (-25°C) and low auto-ignition temperature. It reduces the formation of particulates due to the presence of high oxygen content (about 35% by mass), no carbon-carbon bond and low C:H ratio which results in almost smoke-free combustion [1].

The flame velocity of DME-air/diluent mixtures has been reported by very few. Daly et al. [2] used the combustion bomb method to report the flame velocity of the DME-air mixture. Zhao et al. [3] used the stagnation flame burner method to calculate the flame velocity of the DME-air mixture with the help of PIV technique, the flame velocity obtained through the stagnation flame burning is slightly higher than the spherical bomb method as reported by Zhao et al. [3]. This might be due to the linear exploration methods been used for specifying the stretch effect. Qin and Ju [4] reported the flame velocity for the DME-air diluent mixture at elevated pressure by using a constant pressure bomb method and Schlieren system to capture the images and found to reasonably good when compared with the results of Daly et al. [2] and Zhao et al. [3] at ambient conditions. Recently Huang et al. [5] and De Vries et al. [6] measured the flame velocity of DME-air diluent mixtures by using a constant



volume spherical bomb and a high-speed Schlieren system and found much lower than the flame velocity obtained through PIV technique.

The exercise of inert gasses as diluents for DME-air combustion elucidates the increasing array of experimental and computational studies on combustion characteristics such as flame propagation and extinction. The combustion of DME in the presence of these gasses was studied in connection with the EGR (exhaust gas recirculation) technique, which was intended to lower combustion instabilities and reduce NO_x emissions and the rate of heat transfer in engines. Considering this growing interest in reliable values of laminar flame velocities for DME-air under various initial conditions of temperatures and dilutions becomes very essential. The dilution gasses result in a decrement of the flame velocity of fuel-air mixtures. However, studies in literature were limited to ambient temperature condition only and can worsen at elevated temperatures.

Considering the practical application of diluted DME-air mixtures at higher mixture temperature in exhaust gas recirculation conditions, the objective of this paper is to measure the laminar flame velocity of CO₂/N₂ diluted stoichiometric DME-air mixtures at elevated temperatures. A preheated mesoscale diverging channel method validated by Akram et al. [7] was used for measurements.

2. Experimental method

2.1. Experimental setup

Direct image of the experimental setup is shown in Fig. 1. A mesoscale channel with a 10° divergent

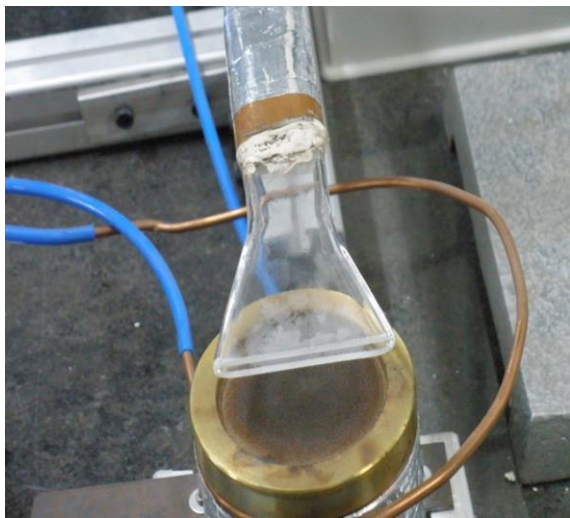


Figure 1. High aspect ratio diverging channel with external heater

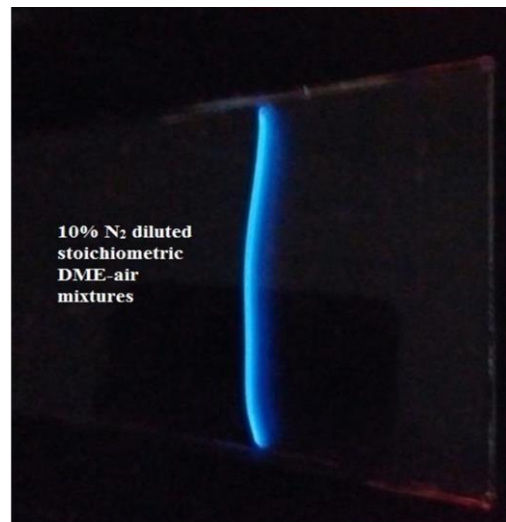


Figure 2. Direct photograph of a planar flame

angle, and inlet dimension of 25 mm × 2 mm is used as referred by [7]. The channel is made up of fused quartz. An external heater is used to preheat the channel and stabilize the flames at different initial temperatures. The temperature inside the channel due to this heating is noted apriori in both axial and transverse directions by supplying constant airflow through the channel. The temperature of the channel walls at the location of the stabilized flame is measured using a K-type thermocouple.

The diluted stoichiometric mixture is fed to the channel through electric mass flow controllers (MFCs). The fresh mixture is ignited at the outlet of the channel. The flame moves upstream and stabilizes at a location where the mixture velocity matches with its flame velocity at that particular temperature. Once stabilized, the flame remains stationary at the same location. Direct images of the stabilized flame are taken with a digital camera. One of such photographs is shown in Fig. 2 taken for a nitrogen-diluted stoichiometric DME-air mixture. These flames were planar in both crosswise and depth direction of the channel. Other details of the setup and method can be found in [7].

Measurement of flame position is also carried out extinguishing the flame for each case. The experiments are repeated to confirm the reproducibility of the method and data.

2.2. Computational method

The freely propagating steady adiabatic flames were simulated to compute the laminar flame velocity of the different mixtures. The PREMIX code [8] of CHEMKIN II package [9] was used for computations. Zhao et al. mechanism [10] is used for laminar flame velocity calculations of diluted mixtures. The thermodynamic and transport properties were taken from supplementary data available in ref. [10]. Thermal and multi-component diffusion were considered. The upwind difference scheme is chosen for the study, which permits for the adaptive grid refinement. Zhao et al. [3] have reported some discrepancies in the computational values due to the degree of refinement of the numerical domain with grid adaptations. Accurate and the grid independent flame velocities were confirmed with very refined mesh using $GRAD = 0.02$ and $CURV = 0.03$.

3. Results and Discussion

3.1. Effect of temperature on laminar flame velocity

The change of laminar flame velocity for CO_2/N_2 diluted stoichiometric DME-air mixture with three different percentage dilution rates of $\Phi_d = 10, 20$ and 30% is observed from measurements. The experiments were carried over a range of temperatures (330-570 K). The initial unburned mixture temperature $T_{u,0}$ and pressure for the entire experiments are maintained at 300 K and 1 atm respectively. The magnitudes of laminar flame velocity and the temperature exponent of pure stoichiometric DME-air mixture were taken from Varghese et al. [11] for comparison purpose.

The laminar flame velocity variation for pure, 30 % N_2 and 30 % CO_2 diluted stoichiometric DME-air mixtures at elevated mixture temperatures is shown in Figs. 3 and 4 respectively. Symbols with continuous lines show the experimental data (power law fits) while dashed lines show the computational data obtained using Zhao et al. mechanism [10]. Experimental data are associated with their respective uncertainty calculated as per the method reported in [7] for this experimental method. The continuous line shows the power law correlation fitted on the measured experimental data to obtain the values of temperature exponent α and reference flame velocity $S_{l,0}$ at temperature $T_{u,0}$. The flame velocity of the diluted mixture increases with an increase in the temperature for both the

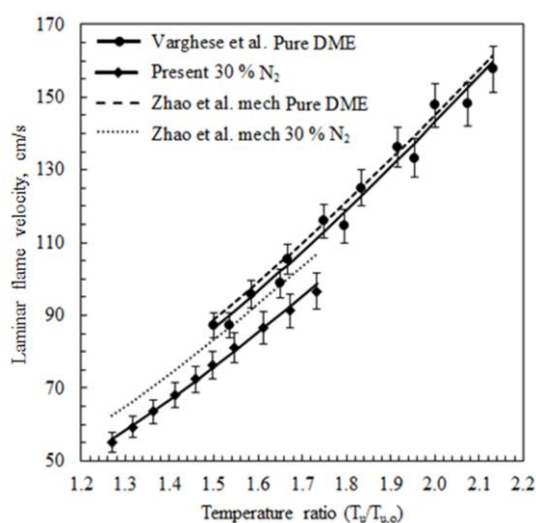


Figure 3. Laminar flame velocity of pure and 30 % N_2 diluted stoichiometric DME-air mixtures at elevated temperatures.

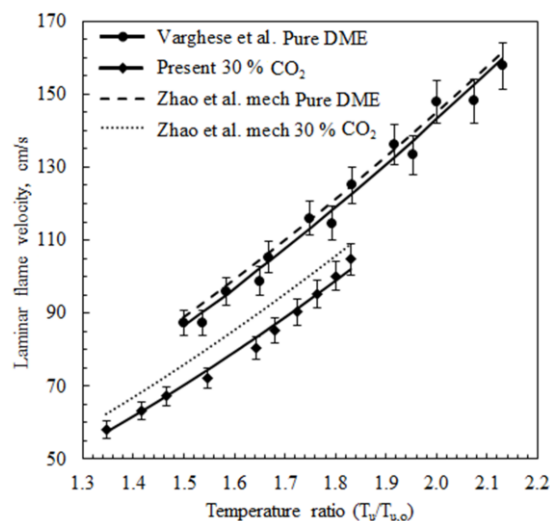


Figure 4. Laminar flame velocity of pure and 30 % CO_2 diluted stoichiometric DME-air mixtures at elevated temperatures.

mixtures. The computations predict higher magnitudes of laminar flame velocity for same initial mixture temperatures for diluted mixtures.

3.2. Effect of dilution on laminar flame velocity

The laminar flame velocity for DME-air mixture falls with an increase in dilution ratio Φ_d of an inert gas at all temperatures. Figure 5 shows the flame velocity of stoichiometric DME-air mixture at 300 K with the addition of different diluents. The addition of chemically inert diluents witnessed to reduce the flame velocity. This could be due to drop in the molar fraction of oxygen and fuel in the presence of inert diluents, lowering the likelihood of molecular collisions leading to the formation of final combustion products. Moreover, mixture dilution reduces the flame temperature as a result of increase in the specific heat of the mixture. These lead to the decrease the chemical reaction rate and hence the flame velocity. Thus diluent acts as better flame extinguishers.

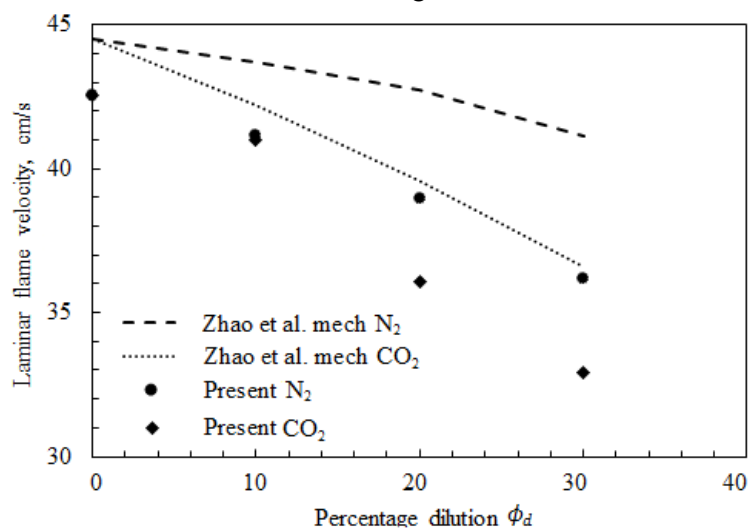


Figure 5. Effect of dilution on the flame velocity of the stoichiometric DME-air mixture at the mixture temperature of 300 K.

For a specific percentage of dilution, the laminar flame velocity with CO₂ dilution gives a smaller value than that with N₂ dilution, as can be seen in Fig. 5. This is due to the fact that specific heat ratio of CO₂ (triatomic molecular gas) is greater than that of N₂ (diatomic molecule gas) and hence, CO₂ will absorb the more heat released and consequently more drop in the flame temperature compared to N₂.

3.3. Effect of dilution on temperature exponent

Figure 6 shows the increase in the temperature exponent with the addition of dilution. Zhao et al. mechanism [10] slightly over-predicts the flame velocity at 300 K and under-predicts the temperature exponent. Under a specific percentage dilution, a higher increase in temperature exponent is observed for CO₂ addition as compared to N₂ addition case.

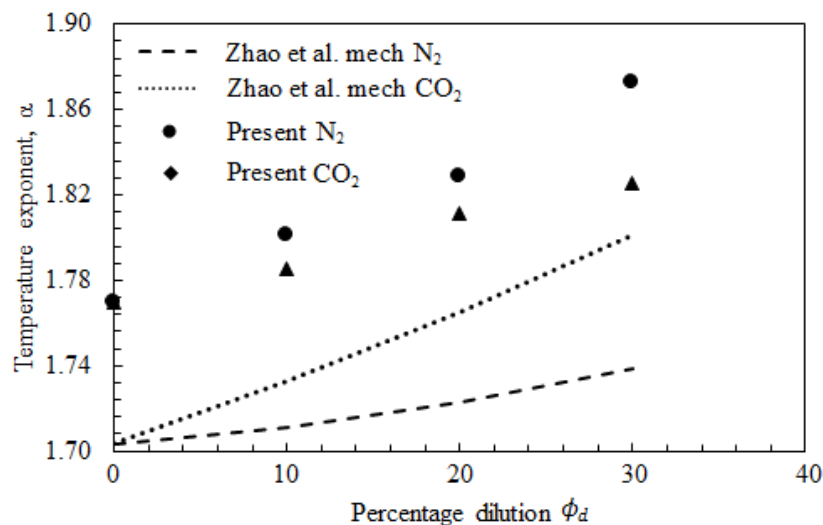


Figure 6. Variation of the temperature exponent of the stoichiometric DME-air with the addition of CO_2 and N_2 dilution at ambient conditions.

4. Conclusion

The effect of inert gas (N_2 and CO_2) dilutions on the laminar flame velocity of stoichiometric DME-air mixtures at elevated temperatures is computed and validated against the experimental results. Reaction mechanism slightly over-predicts the laminar flame velocity and over-predicts the temperature exponent for higher dilution cases. Dilution of these gases decreases the flame velocity of DME-air mixtures significantly. CO_2 dilution has a better extinguishing effect compared to N_2 dilution. A higher dilution of inert gases to the DME as in EGR should be considered cautiously.

5. References

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