

Laminar Burning Velocities of Propane-air Mixtures at Elevated Temperatures and Pressures

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1 Introduction

Engines and gas turbines, two common examples of practical combustion applications, operate at pressures 10–30 times greater than atmospheric pressure. Therefore, accurate knowledge of the laminar burning velocity of alternative fuels like liquefied petroleum gas (LPG), natural gas fuels and their constituents at high pressures is necessary for the design and optimization of these devices. Liquefied petroleum gases (LPGs) are primarily composed of propane. Since liquefied petroleum gases emit fewer pollutants than other conventional fossil-based fuels, they are crucial alternative fuels for internal combustion engines. Because propane contains fewer carbon atoms per hydrogen than gasoline or diesel, it emits around 13% less CO₂ [1].

Laminar burning velocity (LBV) is the major property of a combustible mixture. LBV research advances our knowledge of a variety of combustion phenomena, such as blow-off, quenching, and flashback. It also makes it easier to create updated kinetic models and then refine them for different uses. The spherically expanding flame method [2], counter-flow stagnation flame method [3], heat-flux method [4], and Bunsen burner method [5] are some of the LBV measurement techniques. With the exception of the heat-flux method, the reported values of burning velocities in these methods are extrapolated to either zero strain rate conditions or zero heat loss. Inaccurate estimates could also result from the various extrapolation techniques used to measure the non-linear effect of stretch and heat-loss on burning velocity [4].

Metghalchi et. al [6] determined the laminar burning velocity for propane-air mixtures over an equivalence ratio of 0.8-1.5, a pressure range of 0.4 – 40 atm, and a temperature range of 298 – 750 K. Hassan et al. [7] investigated the laminar flame speed of propane-air mixtures at ambient temperature, equivalence ratios (0.8 – 1.6), and initial pressures (0.5 – 4 atm). Jomaas et al. [8] determined the laminar burning velocities and the counterflow ignition temperatures of C₂ and C₃ hydrocarbons at atmospheric and elevated pressures. Huzayyin et al. [9] determined the explosion indexes and the laminar flame speeds of C₃H₈-air and LPG-air mixtures using the constant volume method at varying initial temperatures (295 – 400 K), equivalence ratios (0.7-2.2), and initial pressures (50 – 400 kPa). Tang et al. [10] inspected the laminar flame speeds and Markstein lengths for propane-air mixtures with nitrogen dilution using the constant pressure method at varying pressures and temperatures. Goswami et al. [11] carried out the theoretical and experimental study of the laminar flame speeds for

C_2H_6 and C_3H_8 flames at varying equivalence ratios (0.8 - 1.3) and initial pressures (1 - 4 atm). Yelishala and co-workers [12] examined the effect of CO_2 on the laminar flame speed of propane-air mixtures using the constant volume spherical flame method for a range of equivalence ratios (0.7 - 1.2), pressures (0.5 - 6.2 atm) and temperatures (298 - 420 K). Recently Wang and co-workers [13] studied the effects of CO_2 on the laminar flame speed of C_3H_8 -air blends at elevated pressures (0.5 - 4.5 atm) and temperatures (298 - 590 K) using the spherical flame method.

The fundamental combustion parameter of propane-air flames has been extensively studied. However, investigation of the combined effect of elevated temperatures and pressures on the laminar burning velocity is scarce. The externally heated diverging channel technique, which is recognised as an accurate method for measuring the flame velocities at high temperatures [14, 15], has been extended to higher pressures by Varghese et al. [18]. The experimental data for propane-air mixtures are provided for 2 atm, 3 atm and higher temperatures of 350–600 K for various equivalence ratios ($\phi = 0.7$ –1.3). The temperature exponents of the mixtures are also reported. Chemical kinetic simulations using the kinetic scheme of San Diego Mech [16], have also been compared with the experimental data.

2 Experimental set up

A cylindrical pressure vessel (40 L) contains the externally heated diverging channel for measurement of LBV as shown in Fig. 1 Right. The position of the stabilized planar flame in the diverging channel section can be observed with the help of a viewing window (toughened glass) provided on the top of the pressure vessel. A DSLR camera captures the position of the stabilized flame inside the channel. The top flange of the vessel holds a pressure gauge and a pressure relief valve. The infrared heater is placed 20 mm below the diverging channel and with a 20 mm horizontal overlap from the exit plane. Initially, to ignite the mixture in the high-pressure chamber, an ignition device is placed at the exit of the diverging channel. For temperature measurements at different heating rates and various flow rates, a K-type thermocouple is used. With the aid of a traverse mechanism, the thermocouple could be moved along the length of the channel. The temperature profile of the channel inside the chamber is measured at different inlet velocities (cold flow) in advance at various preheat conditions. For pressurizing the vessel, the chamber is provided with two air inlets. The pressure relief valve maintains pressure with accuracy ± 0.05 atm of the indicated value on the pressure gauge and also controls the pressure inside the chamber.

Fig. 1 Left shows the schematic diagram of the experimental setup. The diverging mesoscale channel provides a uniform velocity field and temperature in the transverse direction, and the divergence helps prevent the flame flashback in the channel. The infrared heater of 600 W capacity is used to heat the diverging section of the channel. This induces a positive temperature gradient along the direction of the mixture flow. The external heating of the channel walls (infrared heater) helps minimize the heat loss from the stabilized flame to the channel walls and, in the stabilization of the flames in the channel [14]. The stabilization of the planar flame is due to the positive temperature gradient for a range of mixture conditions. The flow velocity inside the channel and mixture equivalence ratio is precisely controlled and monitored using a coupled system of electric mass flow controllers (MFCs), a computer and a command module. The ignition energy provided through the electrode is minimal (100–200 J), and has a negligible effect on the flow field inside the diverging channel. The flame travels inside the channel gradually and stabilizes at a position, where the mixture flow velocity equals the local LBV of the mixture. The heat loss from the stabilized flame to the channel walls is compensated through external heating of channel walls, thereby attaining nearly adiabatic conditions [14]. The low flow rates of fuel and air mixture and, small divergence angle (10°) lead to negligible hydrodynamic strain in the diverging section of the externally heated channel (30 – 50 s $^{-1}$) [14]. Different preheat temperatures, pressures (2 - 3 atm) and equivalence ratios (0.7 - 1.3) were used in the trials. Initially, the cylindrical vessel is filled with air at a pressure of 2 atm, and the relief valve regulates the pressure. The desired heating rate (400 - 600 W) is applied to the infrared heater. The flame is

established inside the channel after the ignition device is turned on. After mixing with the pressurised air inside the chamber, the exhaust products are released through the relief valve after filling the 40 L chamber. The properties of the stabilised flames are unchanged because the products only constitute 5% of the chamber's total volume. The laminar burning velocity, S_u for the given mixture is determined using a readjusted mass conservation equation signified as $S_u = U_{inlet} \times \left(\frac{A_{inlet}}{A_f}\right) \left(\frac{T_u}{T_{u0}}\right)$, where A_{inlet} and U_{inlet} represents the channel area (m^2) and mixture velocity (m/s) at inlet respectively, T_u and A_f represents the unburnt mixture temperature and channel area at the flame position respectively, and T_{u0} represents the inlet mixture temperature of the channel.

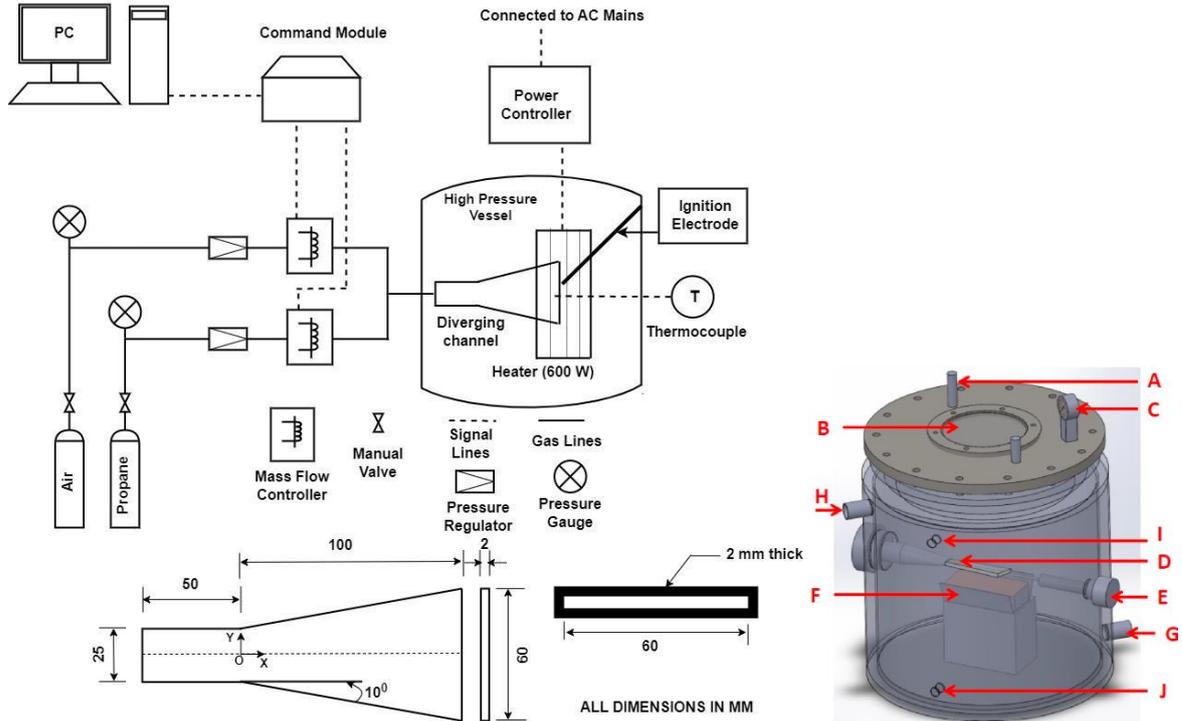


Figure 1: Left: Schematic of the experimental setup. Right: High-pressure vessel; A – Pressure relief valve, B – Glass window, C – Pressure gauge, D – Diverging channel, E – Thermocouple, F – Infrared heater, G – Cooling water inlet, H – Cooling water outlet, I, J – Air inlet.

3 Results and discussion

Fig. 2 Left shows the variation of the burning velocities at an elevated pressure of $P_u = 2$ atm for various higher mixture temperatures, and these results are for equivalence ratios $\phi = 0.7$ and 1.0 . The flame speed increases with an increase in mixture temperature, due to rise in enthalpy of the reactant mixture with mixture temperature. The temperature of the unburnt mixture before the flame has a higher enthalpy than the ambient conditions. The adiabatic flame temperature of these mixtures increases due to higher energy content. It is evident from Figure 2 that the present results are close to mechanism predictions of San Diego mech [16] for both $\phi = 0.7$ and 1.0 , with a slight over prediction compared to Wang et al. [13] for the stoichiometric mixture. The equation and the power law fit parameters are displayed in the inset table of Fig. 2 Left. The figure also depicts the temperature exponent for both equivalence ratios and the laminar burning velocity at 300 K.

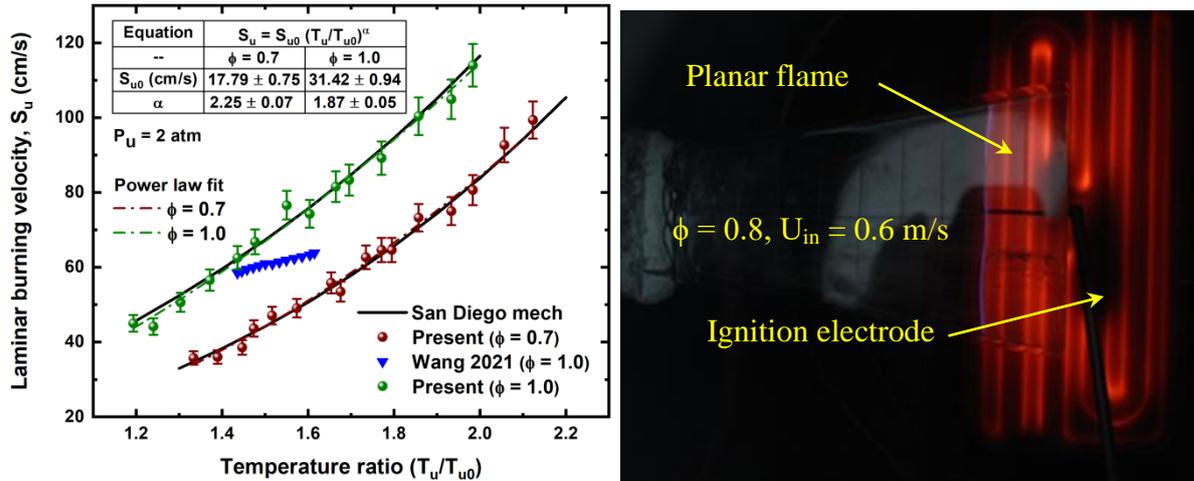


Figure 2: Left: Laminar burning velocity of the propane-air mixture at elevated temperatures ($P_u = 2$ atm, $\phi = 0.7, 1.0$), comparison with the literature [12]. Right: Direct photograph of a stabilized planar flame of the propane-air mixture.

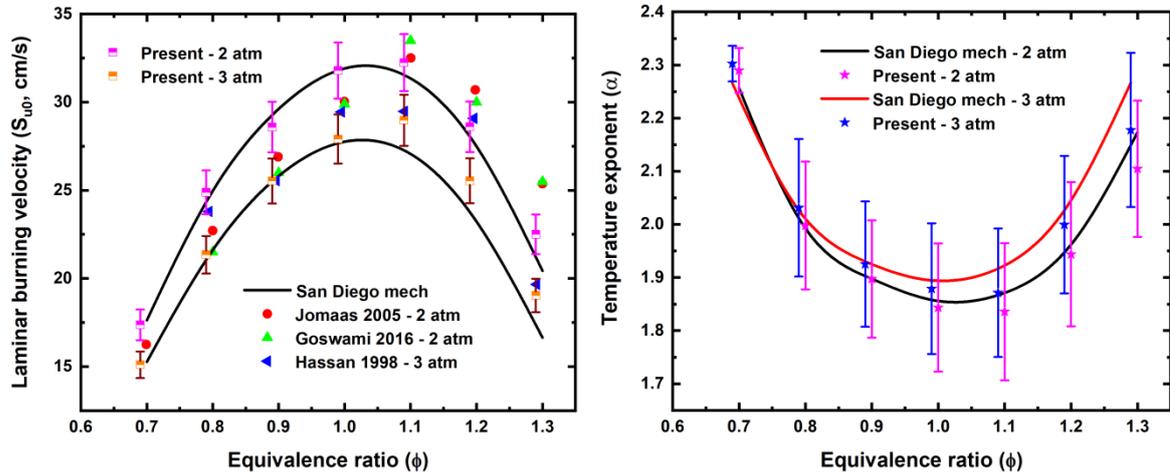


Figure 3: Left: Comparison of the laminar burning velocity for the propane-air mixture measured at 2 – 3 atm, and 300 K with the literature [7], [8], [11]. Right: Comparison of temperature exponent of propane-air mixtures at 2 – 3 atm. Symbols: experiments, lines: mechanism predictions.

In Fig. 3 Left, the LBV is compared with predictions made using the reaction mechanisms, San Diego mech [16], as well as prior experiments [7], [8], [11] at 300 K for a range of equivalence ratios at a pressure of 2 and 3 atm. The laminar burning velocities were observed to decrease with an increase in the pressure for the range of equivalence ratio. The present results are close to the San Diego mech mechanism predictions from lean to the stoichiometric mixture, and slightly over predict for rich mixture conditions. The present results over predict with the literature (Jomaas et al. [8], Goswami et al. [11]) from lean to stoichiometric, and under predict for rich mixture conditions at 2 atm, while at 3 atm pressure, it matches at $\phi = 0.9, 1.1$ and 1.3 with Hassan et al. [7]. The results are obscured by $\pm 5\%$ due to uncertainty analysis that takes into account the influence of several parameters. The uncertainty of burning velocities estimated using the diverging channel method is explained in detail in [14], [15]. The temperature exponents obtained from the reported laminar burning velocities for various equivalence ratios are shown in Fig. 3 Right at 2 and 3 atm pressure. To obtain the temperature exponents, the procedures in Fig. 2 Left are repeated for various equivalence ratios. The temperature exponent shows non monotonic behaviour with an equivalence ratio, and it is observed to be minimum at slightly rich mixture conditions. The temperature exponents were observed to increase slightly with

an increase in the pressure for the range of equivalence ratio. The values of temperature exponents deduced from the experiments are in good agreement with the mechanism predictions of San Diego Mech [16] within the uncertainty band for the majority of the equivalence ratios. The uncertainty associated with the temperature exponent was calculated by employing the least-squares method proposed by Alekseev et al. [17].

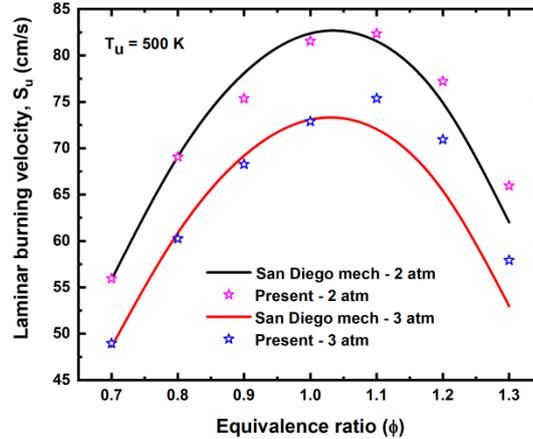


Figure 4: Laminar burning velocities at various pressures ($P_u = 2, 3$ atm) for an unburnt mixture temperature $T_u = 500$ K.

Fig. 4 shows the variation of LBV for various initial pressures of $P_u = 2\text{--}3$ atm, and at an elevated temperature of $T_u = 500$ K with equivalence ratio, $\phi = 0.7\text{--}1.3$. The values of temperature exponent, α , were used in power law correlations to deduce the present measurements at all mixture and pressure conditions. At all pressure conditions, the experimental results are closer to mechanism predictions of San Diego Mech [16] for lean to stoichiometric, and it over predicts for rich mixture conditions.

4 Conclusions

At elevated pressures of 2 – 3 atm and temperatures between 350 and 600 K, measurements of the laminar burning velocities of propane-air mixtures were obtained throughout a range of equivalence ratios ($\phi = 0.7 - 1.3$). Laminar burning velocities were estimated using the properties of planar flames stabilized in the channel. The laminar burning velocities were observed to be increased with mixture temperature due to the higher reactant enthalpy and decreased with an increase in the pressure for the range of equivalence ratio. The non-monotonic behaviour of the burning velocities is followed by the laminar burning speeds of propane-air mixtures, with a maximum at $\phi = 1.1$. The comparison with the results obtained from the experiments matches well with the CHEMKIN-Pro 2020 software package using San Diego Mech mechanism. The temperature exponents were deduced from power law correlation at various elevated pressures for a range of equivalence ratios ($\phi = 0.7\text{--}1.3$). The temperature exponent were observed to be minimum at $\phi = 1.1$ and increase slightly with pressure. The laminar burning velocities of propane-air mixture obtained using the externally heated diverging channel technique were used to validate the predictions of chemical kinetic model (San Diego Mech) at higher pressure conditions.

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