



Full Length Article

Measurement of laminar burning velocities of methanol–air mixtures at elevated temperatures



Amit Katoch^{a,*}, M. Asad^a, S. Minaev^b, Sudarshan Kumar^a

^a Department of Aerospace Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India

^b Far Eastern Federal University, Vladivostok, Russia

HIGHLIGHTS

- Meso-scale diverging channel method extended for the first time toward measurements of laminar burning velocity of liquid fuel–air mixture (methanol).
- High temperature experimental data for mixture temperature above 480 K reported for the first time.
- Significant deviation from mechanism predictions for richer mixtures and mixture temperatures beyond 400 K.
- Non-linear variation of temperature exponent with a minima at $\Phi = 1.2$.

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ABSTRACT

In this paper, the measurement of laminar burning velocities for liquid fuel (methanol)–air mixtures is reported at higher mixture temperatures using externally heated meso-scale diverging channel technique. Laminar burning velocity is determined using mass balance between the channel inlet and flame stabilization location for the planar flames appearing at certain conditions of mixture flow rate and equivalence ratio. A linear temperature gradient in the direction of fluid flow was employed to establish planar, stretch free and nearly adiabatic flames in an externally heated diverging quartz channel. Detailed experiments were carried out for an equivalence ratio range of 0.7–1.3 and a mixture temperature range of 350–650 K at 1 atm pressure with an uncertainty of $\pm 5\%$ of the actual value. Experimental results are compared with the available results. A good match was observed for $S_{u,0}$ values at 300 K with the literature data and mechanism values. The temperature dependence of laminar burning velocity was also assessed using the correlation $S_u = S_{u,0}(T_u/T_{u,0})^\alpha$, where α is the temperature exponent. A minimum α value was observed for rich mixtures even at high temperature conditions.

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1. Introduction

The problems associated with global warming and increased pollutant emissions have provided a major push toward the usage of alternate fuels such as methanol, di-methyl ether, butanol and fuels derived from various bio-resources. Methanol as a biofuel has gained popularity due to its ease in production from urban and agricultural waste as well as fossil fuels. These waste materials can be readily converted to syngas, which on further catalytic treatment yields methanol [1]. Methanol has higher octane rating than gasoline, which leads to superior engine performance and lower emissions from the combustion of methanol based systems [2].

Laminar burning velocity is an important parameter, which embodies information about the reactivity, exothermicity and diffusivity of the fuel. It is also used in the validation of chemical-kinetic mechanisms, estimation of turbulent burning velocities and flame structure studies. The value of this parameter depends on initial pressure, mixture temperature and mixture equivalence ratio of the unburnt mixture under study. The following correlation describes the dependency of laminar burning velocity on mixture temperature as:

$$S_u = S_{u,0}(T_u/T_{u,0})^\alpha \quad (1)$$

where α is the temperature exponent and a function of mixture type and equivalence ratio. $T_{u,0}$ is the reference temperature and $S_{u,0}$ is the laminar burning velocity at reference temperature, 300 K.

Various methods such as spherical bomb, heat flux burner, counterflow burner, and Bunsen burner have been used by

* Corresponding author.

E-mail address: amitkatoch15@gmail.com (A. Katoch).

researchers to measure the laminar burning velocity of methanol–air mixtures (see Table 1). The maximum unburnt mixture temperature for reported measurements in the literature is 480 K [3]. For higher mixture temperatures, burning velocity values deduced from correlations based on the limited data sets ($T_{mix} < 480$ K) are available and being used. The most widely used mechanisms for development of alcohol chemistry are Li et al. [4,5] and San Diego mechanism [6].

Saeed and Stone [3] used a multizone thermodynamic model to analyze flame behavior inside combustion bomb. They ignored the stretch effects stating that the error in the burning velocity due to stretch exclusion would be less than 1% since the measurements were taken only after a pressure rise of 50%, which corresponds to flame radii greater than 0.05 m and a strain rate ~ 0.01 s⁻¹. The onset of cellular instabilities was reported for certain conditions of pressure and temperature and such data were excluded from reported correlations. The variation of temperature exponent with equivalence ratio was linear and was reported as $\alpha = 1.32$ – 1.32 ($\Phi - 1$). Metghalchi and Keck [8] used a constant volume bomb method with a single burned gas zone model to measure the laminar burning velocities of methanol–air mixtures. The linear decrease of temperature exponent with equivalence ratio was established with α varying as 2.18–0.8 ($\Phi - 1$). Gulder [9] reported the burning velocities of methanol, isooctane and their blends for a range of equivalence ratios. The author reported the use of ionization probes in combustion bomb to measure the flame speed and employed a density correction scheme in the calculations. A constant value of temperature exponent, $\alpha = 1.75$ for was reported for all equivalence ratios. Ryan and Lestz [13] determined the burning velocities of methanol–air mixtures by tracing the pressure–time history of explosions in a combustion bomb and assumed negligible flame front thickness which perhaps led to under-predicted values. A major drawback of the combustion bomb experiments carried out by various researchers [8,9,13] was that the effects of flame wrinkling or cellularity were not accounted while determining the mixture burning velocity. This perhaps led to over prediction of the burning velocity since the presence of cellular structures in a flame front leads to increase in burning velocity due to increased surface area [3]. Egolfopoulos et al. [10] employed counterflow flame technique to measure the burning velocities of methanol–air mixtures. They extrapolated the stretched flame speeds linearly to zero stretch which increases the burning velocity by 5–10% [14]. Liao et al. [11] and Zhang et al. [15–17] used a high speed camera coupled with a schlieren optical system to record the flame propagation in a combustion bomb and extrapolated the stretched flame speeds linearly to zero-stretch to deduce the unstretched laminar burning velocity. Liao et al. [11,18] proposed linear correlation for the variation of temperature exponent, $\alpha = 1.85$ – 0.6 ($\Phi - 1$). Recently Sileghem et al. [12] used the heat flux burner in conjunction with a CEM (controlled evaporator mixer) for burning velocity measurements of methanol, ethanol, isooctane and heptane and their blends. Similar setup was used by Vancoillie et al. [14] for $\Phi = 0.7$ – 1.1 and 1.5 where they could not investigate intermediate equivalence ratios due to limitations of the fuel mass flow controller. Sileghem et al. [12] reported

slightly lower burning velocity values than Vancoillie et al. [14] for similar mixture flow conditions. They attributed this difference to the condensation of fuel vapors in lines connecting the vaporizer to the burner, instabilities in flow meter and non-symmetry effects. Sileghem et al. [12] reported a parabolic variation in temperature exponent with a minima at $\Phi = 1.2$ for the first time. Amongst various data sets reported in the literature, the most accurate data set is that from heat flux method. However, it is restricted to a smaller range of unburnt mixture temperature (~ 360 K). It is evident from detailed discussions on the existing literature that a huge variation and inconsistency exists in the values of laminar burning velocities and temperature exponent data as discussed later while comparing the present results – from linear decrements to constant values to parabolic variation.

The diverging channel based technique recently proposed by Akram and coworkers has been shown to address the shortcomings of other methods with regard to burning velocity measurements of various gaseous fuels at elevated mixture temperatures [19–23].

The objective of the present work is to extend the externally heated meso-scale diverging channel technique to measure the laminar burning velocities of methanol–air mixtures at higher temperatures ranging up to 650 K and to investigate its dependence on mixture temperature and mixture equivalence ratios. The reported data of laminar burning velocities at higher mixture temperatures would help in validation of existing kinetic mechanisms.

2. Experimental setup

The meso-scale diverging channel method was developed by Akram et al. [19–21,24,25] and used for laminar burning velocity measurements of gaseous fuels like methane [20], LPG [21,26], propane [19] and diluted hydrogen–air mixtures [23] with different diluents such as CO₂ and N₂. The details of the setup for gaseous fuels can be found in [20]. Various distinct features of this setup for measuring the burning velocities of liquid fuel–air mixtures are shown in Fig. 1 and briefly described here.

High aspect-ratio diverging channels made of quartz material with inlet dimensions of 25 × 2 mm and divergence angles 10° and 15° were employed in the present setup. The diverging portion of the channel is externally heated from the bottom side using a sintered metal burner to generate a steady linearly varying temperature gradient in the direction of mixture flow [27]. The external heating burner also serves as ignition source. External heating of the channel walls helps reduce the heat losses from the flame to the solid walls, thereby avoiding thermal quenching and making the flame nearly adiabatic [21]. Quartz material is chosen due its high heat capacity, ease in flame visualization, low thermal expansion and low thermal conductivity which minimizes the effects of wall radical quenching [28]. Unlike gaseous fuels, liquid fuels need to be prevaporized and mixed with the oxidizer before entering the combustion domain. It becomes challenging to ensure the homogeneity of the fuel–air mixture entering the channel. Inhomogeneity in the fuel–air mixture may lead to unstable flames due to local fluctuations in mixture equivalence ratio [29]. Various

Table 1
Summary of data for burning velocities of methanol–air mixtures. CV – Constant volume combustion bomb, BB – Bunsen burner, HF – Heat flux burner and CF – Counter flow.

Ref.	Method	Φ_{range}	T_{range} (K)	P_{range} (bar)	$S_{u,0}$ ($\Phi = 1$) (m/s)	$(S_{u,0 max} - m/s) \Phi$
[3]	CV	0.7–1.5	295–650	0.5–13.5	0.46	(0.49) 1.1
[7]	BB	0.8–1.4	298	1	0.48	(0.47) 1.0
[8]	CV	0.8–1.5	298–700	0.4–50	0.35	(0.37) 1.1
[9]	CV	0.7–1.4	300–600	1	0.44	(0.48) 1.1
[10]	CF	0.5–2	318–368	1	0.43	(0.43) 1.1
[11]	CV	0.7–1.4	385–480	1	0.41	(0.42) 1.1
[12]	HF	0.7–1.5	298–358	1	0.41	(0.44) 1.2

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