Fuel 231 (2018) 37–44

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Measurement of laminar burning velocity of ethanol-air mixtures at elevated temperatures

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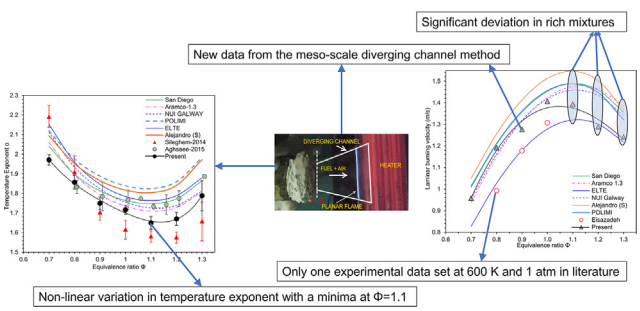
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Ethanol-air mixture
Laminar burning velocity
Diverging channel method
Temperature exponent

ABSTRACT

The present work focuses on new measurement of laminar burning velocities of ethanol-air mixtures at 1 atm pressure and elevated mixture temperatures using an externally heated *meso*-scale diverging channel technique. The burning velocity measurements were carried out for a temperature range of 350–620 K and equivalence ratio range of 0.7–1.3. Various detailed kinetic models available in literature were used for assessment and comparison with experimental results. The experimental results show a good match at lower mixture temperatures across all equivalence ratios. However, at higher temperatures, the difference between the measurements and predictions of different kinetic models is considerably higher, particularly for rich mixture regime. The effect of mixture temperature on laminar burning velocity was assessed using power law correlation, $S_u = S_{u,0}(T_u/T_{u,0})^{\alpha}$. The variation of temperature exponent, α with equivalence ratio, Φ showed a minimum value for slightly rich mixtures. This variation of the measured laminar burning velocity and temperature exponent at elevated mixture temperatures and predictions using various kinetic mechanisms shows a good match for lean mixtures.

1. Introduction

Development of newer biofuels has received considerable attention from the research and industrial community as alternative renewable energy sources. This shift has also been fostered due to increasing concerns for regulating greenhouse gas emissions, particulate generation and toxic pollutant emissions. Amongst all the biofuels, ethanol is the most widely adopted biofuel globally. It is produced from a wide variety of sources such as starch, sugarcane, lignocellulosic material derived from agricultural waste and algae [1]. Ethanol has a boiling point of 351 K and an autoignition temperature of 642 K [2,3]. Its density is 789 kg/m^3 with an octane number (RON) of 109. Recently,

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https://doi.org/10.1016/j.fuel.2018.05.083
Received 10 April 2018; Received in revised form 10 May 2018; Accepted 15 May 2018

the researchers at Oak Ridge National Laboratory proposed a newer and inexpensive nanostructured catalyst for direct electrochemical conversion of CO_2 to ethanol at ambient pressure and temperature conditions [4].

Studies have been carried out to assess the usage of ethanol as a perspective fuel in gas turbine engines, hybrid rocket engines and piston engines [5–7]. By 2012, Embraer had delivered more than 12,000 Ipanema aircraft, first in a series of agricultural aircraft certified to run on ethanol fuel. The blending of ethanol with gasoline increases the knock tolerance in SI engines, since the octane rating of ethanol is considerably higher than gasoline. This in turn increases the allowable compression ratio, engine torque and thermal efficiency [8]. Recently, a volume based blending model was developed to predict the influence of ethanol-gasoline blending ratio on octane number [9]. A theoretical study to assess the applicability of the ethanol-gasoline blends in HCCI engines concluded that such blends (upto 20%) could help significantly reduce NO emissions without increasing CO emissions in exhaust [10].

Laminar burning velocity is one of the important parameters to understand the burning behavior of various fuels thereby helping understand the various combustion characteristics of the fuels. It is defined as the steady propagation of a planar, adiabatic and one-dimensional reaction front into a relatively stationary mixture in a doubly infinite domain [11]. The construction of a detailed kinetic scheme for combustion of any fuel involves inputs from theoretical as well as experimental studies from diverse sources and such rate parameters, therefore, carry an innate uncertainty into the final model [12,13]. In this context, laminar burning velocity is a fundamental fuel characterization parameter used in validation of chemical kinetic mechanisms, characterization of premixed flame responses such as flash back, blowoff and estimation of turbulent burning velocities. It also embodies important information related to reactivity and exothermicity of a fuel. Its value depends on the type of fuel-oxidizer mixture, its temperature, pressure and equivalence ratio. High fidelity experimental data at elevated temperatures is of prime importance for the development and validation of high temperature kinetics for various fuels. At constant pressure conditions, the dependence of burning velocity on mixture temperature is described as.

$$S_u = S_{u,0}\left(\frac{T_u}{T_{u,0}}\right)^{\alpha} \tag{1}$$

where α is the temperature exponent, whose value depends on type of fuel–air mixture and equivalence ratio, $T_{u,0}$ is the reference temperature of 300 K and $S_{u,0}$ is the laminar burning velocity at $T_{u,0}$.

Although some data is available in literature for burning velocity of gaseous fuels such as hydrogen, methane etc. at higher mixture temperatures, whereas, such data for liquid fuels is scarce and shows huge scatter even at low mixture temperatures. This is primarily attributed to difficulties associated with fuel vaporization, mixture formation and its sustenance in the vapor phase for the measurement of laminar burning velocities. Considerable scatter in the reported values of laminar burning velocity and temperature exponent exists in the literature due to inherent disadvantages of each of the techniques used in researchers. For instance, the measured data using spherical flame method and stagnation flame method is subjected to significant flame stretch effects. These flame stretch effects need to be considered while deriving the laminar burning velocity from the raw data [14]. Although many newer correlations have been proposed recently for obtaining accurate information on flame stretch, significant work remains to be done [15,16]. De Goey et al. [17] have proposed and successfully demonstrated the development of heat-flux method, where a quasi-adiabatic planar flame is stabilized on the top of a perforated plate burner. The stabilized flame has negligibly small hydrodynamics stretch effects [18]. To achieve the adiabatic laminar burning velocity, the heat-loss from burner to surroundings is compensated through heating of burner body using hot water. This technique has been successfully used by Aleskeev et al. [19], Dirrenberger et al. [20] and Sileghem et al. [21] for measurement of laminar burning velocity up to a mixture temperature of 400 K. The conventional burner setup has a limitation in terms of the maximum burning velocity (40–70 cm/s) that can be measured. This is primarily due to the flow perturbations induced by the perforated burner plate at higher mixture velocities which distort the flame surface. Recently Akram and coworkers [22,23] have proposed a new externally heated diverging channel technique to stabilize planar flame for a range of mixture temperatures. Authors claim that the stabilized planar flames are subjected to very small hydrodynamic stretch conditions. The heat-loss through the channel walls is compensated through external heating of the channel. Laminar burning velocity is obtained from a mass balance between the channel inlet and flame stabilization point. The measured burning velocities have been shown to be independent of channel angle, channel aspect ratio, heating rate and other parameters.

A significant variation in the reported data of laminar burning velocity and temperature exponent has been reported in the literature for ethanol-air fuels. For instance, variation of temperature exponent, α from a linear decrement [24] to inverted parabolic variation [21] has been reported in literature. Table 1 gives a brief summary of the existing data on laminar burning velocity of ethanol–air mixtures at 1 atm pressure.

Gulder [25] reported laminar burning velocity values for methanol, ethanol, *iso*-octane and their blends using spherical flame method. They used ionization probes to measure the flame radius growth in a constant volume bomb and reported a constant value of $\alpha = 1.75$ for temperature exponent across all equivalence ratios. This data is not considered in the present comparison, since there was no correction for flame stretch effects in this work and segregation of measured laminar burning velocities is prone to instabilities. Egolfopoulos and Law [26] used the counterflow twin flame technique along with linear extrapolation of stretch to zero values to determine the laminar burning velocities. The authors stated that some previous theoretical studies indicated a possibility of 5–10% variation in measurements due to such linear extrapolation, however excluded such corrections in their results due to lack of validated and established experimental studies. Liao et al. [24] and Bradley et al. [27] used high-speed schlieren imaging in a constant volume bomb to capture flame growth history for ethanol-air mixtures. They employed a linear stretch correction model proposed by Wu and Law [28]. Liao et al. [24] reported a linear decrement relationship between temperature exponent and equivalence ratio, given as: $\alpha_T = 1.783–0.375(\Phi - 1)$. Bradley et al. [29] also reported a nearly linear decrement in temperature exponent values with equivalence

Table 1
Summary of experimental data for burning velocities of Ethanol + air mixtures at 1 atm. CV – Constant volume method, HF – Heat-flux method and CF – Counter flow burner method. * indicates work where α values are reported.

Reference	Year	Method	ϕ_{range}	T_{range}
[25]	1982	CV	0.7–1.4	***300–500***
[26]	1992	CF	0.55–1.5	***363, 428, 453***
[24]*	2007	CV	0.7–1.4	***358, 453–480***
[27]*	2009	CV	0.7–1.5	300, 358, 393
[30]	2010	CF	0.7–1.5	343
[32]	2011	CV	0.8–1.4	393
[34]*	2011	CV	0.8–1.1	***298, 363, 453, 600***
[39]	2011	HF	0.7–1.6	298, 338
[40]*	2011	HF	0.65–1.55	298, 308, 318, 328, 338, 348, 358
[41]	*2012*	*CV*	*0.7–1.5*	*373*
[33]	2013	CV	0.7–1.4	423
[20]*	2014	HF	0.55–1.6	298, 358, 398
[21]*	2014	HF	0.7–1.5	298, 318, 328, 338, 358
[36]	2014	HF	0.7–1.6	373, 423
[38]*	2015	CV	0.7–1.5	***318, 358, 373, 473***

Bold and italic font implies data sets where measurements are available above 450 K.