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Full Length Article

Laminar burning velocity measurement of hydrous methanol at elevated temperatures and pressures

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HIGHLIGHTS

- A constant volume combustion bomb and schlieren imaging system were used.
- Laminar burning velocity of methanol water mixture was measured.
- Burning velocity decreases with pressure and increases with temperature.
- Water as a diluent led to reduction of the burning velocity.
- Cellularity occurred earlier for rich mixture and higher water fraction delayed cellularity.

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ABSTRACT

Methanol is an important renewable energy source that absorbs water easily. The water can be present inadvertently or as a result of the manufacturing process. Although adding water into methanol will further improve the anti-knock rating for spark ignition engines, the burning velocity, flame stability and the flammability range will be reduced. The laminar burning velocity of methanol containing up to 40% water in volume (W0, W20 and W40) has been measured for a wide range of temperature (350–450 K), pressures (1–4 bar) and equivalence ratio (0.7–1.4) using a constant volume vessel and a schlieren imaging system. The experimental data using the pressure rise data (but excluding cellularity) have been fitted to a correlation with twelve coefficients. The laminar burning velocities for W0, W20 and W40 are 54 cm/s, 31 cm/s and 24 cm/s respectively for stoichiometric mixture at 2 bar and 400 K. Results showed a decrease in burning velocity with pressure and an increase with temperature. Water as a diluent led to reduction of the burning velocity. The correlated burning velocity data for methanol are in good agreement with published data. The cellularity occurred earlier as the initial mixture became rich, while a higher water fraction delayed the onset of cellularity.

1. Introduction

Methanol is an alternative fuel for internal combustion engines, which has gained popularity due to its lower cost compared to ethanol. Methanol can be produced from a wide range of renewable sources such as gasification of wood, agricultural by-products and urban waste, in addition to using fossil fuels based feedstock (coal and natural gas) [1]. Widespread production from renewable sources has a potential to offer methanol at a low cost and with benefits to the environment. Due to its high octane rating, high latent heat and low combustion temperatures, the power and efficiency are significantly higher for methanol (and ethanol) compared to gasoline. This is especially true for highly pressure-charged engines, where aggressive downsizing is possible using these alcohols [2].

Methanol is hygroscopic, meaning purified methanol by distillation will absorb water vapour directly from the atmosphere. Although adding water will improve the anti-knock rating, it dilutes the calorific value of the methanol, and may cause phase separation of methanol-gasoline blends. The water diluent will reduce the burning velocity, the flame stability and the flammability range, all of which would lead to adverse effects on the combustion system performance. Pearson et al. [3] characterised the physicochemical properties for mixtures of gasoline, ethanol, methanol and water including the phase separation. They concluded that the blends with only gasoline and ethanol have the

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highest water tolerance, which decreases monotonically as the ethanol was displaced by increasing amounts of methanol.

The laminar burning velocity is among the most fundamental properties characterizing the combustion of homogeneous fuel-air mixtures. It can also be used to validate the chemical-kinetic mechanism and estimate the turbulent burning velocity. The laminar burning velocity depends on the initial pressure, mixture temperature and equivalence ratio of the unburned mixture. The equivalence ratio is the inverse of lambda (λ), the ratio of actual air-fuel ratio (AFR) to stoichiometry for a given mixture.

The laminar burning velocity of methanol has been measured by many researchers using different experimental approaches. Saeed and Stone [4] used a multi-zone thermodynamic model to determine the temperature distribution within the burned gas and the relationship between the pressure rise and the mass fraction burned in a constant-volume vessel. They used a constant volume bomb to measure the laminar burning velocity of methanol at elevated temperature and pressures. The onset of cellular flame was estimated by looking at the calculated burning velocity. Results show that the variation of temperature exponent with equivalence ratio was linear. Metghalchi and Keck [5] had previously used a constant volume bomb to measure the laminar burning velocity of methanol. Gulder [6] also adopted a constant volume bomb for measuring burning velocity of methanol at atmospheric pressure. Neither of these two studies considered the onset of cellularity when calculating the laminar burning velocity. Liao et al. [7,8] and Zhang et al. [9,10] used a constant volume bomb and a schilieren image system with high speed camera to determine the unstretched laminar burning velocity of methanol at elevated temperatures and pressures.

Steady flame techniques have also been widely used, but are normally limited to conditions close to ambient. Davies and Law [11] and Egolfopoulos et al. [12] adopted a counterflow flame configuration to measure the laminar flame speed of methanol. Gibbs and Calcote [13] used a Bunsen burner and a camera to study the burning velocity of methanol. Vancoillie et al. [14] used a perforated plate burner to obtain measurements of the laminar burning velocity of methanol at unburned mixture temperature of 298–353 K and atmospheric pressure. The heat flux method was used to determine burning velocities under conditions when the net heat loss from the flame to the burner is zero. Sileghem et al. [1] used a similar method to study the temperature dependency at atmospheric pressure in order to validate the reaction mechanism. However, experiments with higher pressures have not been reported.

Recently Beeckmann et al. [15] measured the laminar burning velocity of methanol at an unburned temperature of 373 K and a pressure of 10 bar in a spherical combustion vessel using schlieren optical system. The sensitivity analysis for methanol/air flames suggested that further investigation of the pressure dependent reactions would be beneficial. Most recently, Katoch et al. [16] used an externally heated meso-scale diverging channel technique to measure the laminar burning velocity of methanol. Experiments were carried out for unburned mixture temperature of 350–650 K at atmospheric pressure. Good agreement was observed at 300 K with published experimental data.

The constant volume combustion method is capable of exploiting the increase in pressure and the resulting increase in unburned gas temperature. Values of the burning velocity can be calculated for multiple temperatures and pressures from a single experiment as the pressure rise causes an isentropic temperature increase in the unburned gas. Therefore, the burning velocity can be determined from the pressure trace inside the combustion bomb by assuming a smooth spherical flame front and an appropriate combustion model [17]. Although there are many published data for methanol, the burning velocity of hydrous methanol has not been investigated so far. The objective of the present work is to extend the constant volume method and schlieren image system to measure the laminar burning velocity of methanol/water blends at higher unburned mixture temperatures and pressures. W0 is pure methanol. W20 and W40 mean water volume fractions of 20% and 40%, respectively. The mole fractions of water for W20 and W40 are 35.9% and 59.9%, respectively.

2. Experimental apparatus

The combustion bomb for this work is the same as described elsewhere [17–19]. The constant volume bomb shown in Fig. 1 is a stainless steel spherical vessel with a diameter of 160 mm rated to 34 bar. The combustion vessel was enclosed by a temperature controlled fan oven, which can increase the initial temperature up to 450 K. Two electrodes formed a spark gap at the centre of the vessel. An automotive inductive ignition system was used. The compressed intake air was controlled by a mass flow controller and heated before going into an injection block, which was also heated to ensure evaporation of the liquid fuel. The liquid fuel volume and injection speed of the syringe actuator were controlled by a syringe controller. A Kistler 710A piezo-electric pressure transducer was employed to measure the pressure rise during combustion. Three piezo-resistive pressure transducers with different ranges were also used for measuring pressures during evacuation and mixture preparation. An exposed junction K-type thermocouple was fitted into the vessel to measure the temperature during mixture preparation. A LabVIEW Program has been written to display the pressure and temperature during mixture preparation and record the pressure data after ignition. The sampling rate during combustion was 10 kHz. A heated wideband lambda sensor was located in the exhaust line for the combustion bomb, in order to monitor the air fuel ratio of the burned products.

The pressure vessel had a pair of plane windows with 40 mm diameter along the optical axis (see Fig. 1) to allow a schlieren imaging system, which was adopted to track early flame growth and help detect the cellularity. The schlieren images were recorded using a Photron 1024 PCI high speed camera with a 512 × 512 pixel resolution, allowing a frame rate of 3000 frame per second (fps).

The experimental procedure was similar to [17–19] apart from using a digital balance with 0.1 mg resolution to measure the mass of liquid fuel injected. The fuel was injected using a Hamilton precision syringe with a motorised actuator, and the mass was measured before and after injection. For each test, the volume of fuel required was determined by the initial temperature, target pressure and equivalence ratio. The target pressure was set to be higher than the pressure at the start of combustion. After injection of fuel, the bomb pressure was raised by increasing the air flow rate up to the target pressure that had been calculated on the basis of the mass of fuel that had been injected. The waiting time was 5 min before reducing the bomb pressure down to the mixture pressure for ignition.

3. Laminar burning velocity

Fig. 2 shows the schematic of the calculation and correlation of the laminar burning velocity in MATLAB. For every single experiment, the pressure trace $p(\mathrm{t})$ during combustion recorded by LabVIEW (Fig. 2a) was used to calculate the burning velocity according to the equation given by Lewis and Von Elbe [20]:

$$S_u = \frac{dr_i}{dt}\left(\frac{r_i}{r_b}\right)^2\left(\frac{p}{p_i}\right)^{\frac{1}{\gamma_u}} \tag{1}$$