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The turbulent burning velocity of methanol–air mixtures

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HIGHLIGHTS

- There is a lack of accurate data of the turbulent burning velocity of methanol mixtures.
- This is particularly the case for engine-relevant conditions of pressure and temperature.
- This paper addresses this by reporting measurements in a fan-stirred constant volume bomb.
- A comparison is made with the predictions from various turbulent combustion models.

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ABSTRACT

Methanol is a sustainable and versatile alternative fuel for spark-ignition engines and other combustion applications. To characterize the combustion behavior of this fuel, a good understanding of the factors affecting its turbulent burning velocity is required. This paper presents experimental values of the turbulent burning velocity of methanol-air mixtures obtained in a fan-stirred bomb, for $u' = 2–6$ m/s, $\phi = 0.8–1.4$, $T = 358$ K and pressures up to 0.5 MPa. In combination with laminar burning velocity values previously obtained on the same rig, these measurements are used to provide better insight into the various factors affecting u_t of methanol, and to assess to what degree existing turbulent combustion models can reproduce experimental trends. It appeared that most models correctly accounted for the effects of turbulent rms velocity u'. With respect to the effects of ϕ and pressure, however, models accounting for flame stretch and instabilities, through the inclusion of model terms depending on thermodiffusive mixture properties and pressure, had a slight edge on simpler formulations.

1. Introduction

The use of light alcohols as spark-ignition engine fuels can help to increase energy security and offers the prospect of carbon neutral transport. Compared to other alternatives, such as hydrogen or battery-electric vehicles, liquid alcohols entail less issues regarding fueling and distribution infrastructure and are easily stored in a vehicle. In addition, the properties of these fuels enable considerable improvements in engine performance and efficiency as several investigations on converted gasoline engines have demonstrated [1].

In addition to bio-ethanol, methanol is interesting since it is versatile from a production point-of-view. Biofuels can only constitute part of our energy supply because of the limited area of arable land [2,3]. Methanol, on the other hand, can be produced from a wide variety of renewable (e.g. gasification of wood, agricultural by-products and municipal waste) and alternative fossil fuel-based feed stocks (e.g. coal and natural gas). A sustainable closed-carbon cycle where methanol is synthesized from renewable hydrogen and atmospheric CO_2 has been proposed [4].

To characterize the combustion behavior of methanol–air mixtures in practical applications, data for the laminar burning velocity are needed, together with a good understanding of the factors affecting turbulent burning velocities. The laminar burning velocity of methanol–air mixtures has been studied by the current authors in previous work [5–8]. Turbulent burning velocity data for methanol–air mixtures are scarce, and difficult to compare due to reasons associated with the definition of the turbulent burning velocity as well as its dependency on experimental techniques and rigs [9].

This paper presents experimental values of the turbulent burning velocity of methanol–air mixtures measured during spherical explosions in a fan-stirred bomb. Measurements were made at rms turbulent burning velocities u' between 2 and 6 m/s, equivalence ratios between 0.8 and 1.4, pressures up to 0.5 MPa and at an initial temperature of 358 K. Next to obtaining better understanding of

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the different parameters affecting the burning velocity, an additional objective of this study was to assess to what degree the different models proposed in the literature can reproduce the trends observed over the full range of conditions investigated here. Therefore, comparisons have been made with data derived using several widely used turbulent burning velocity correlations.

2. Experimental methods

2.1. The Leeds Mk II combustion vessel

The turbulent burning velocity was measured using the spherically expanding flame technique. The experiments were performed in the Mk II high pressure fan-stirred combustion vessel at Leeds University. The details of the experimental apparatus have been extensively described in [10]. The spherical, stainless steel vessel has a 380 mm inner diameter and is capable of withstanding temperatures and pressures generated from explosions with initial pressures up to 1.5 MPa and initial temperatures up to 600 K [11]. The vessel is equipped with three pairs of orthogonal windows of diameter 150 mm. An electric heater at the wall provided up to 2 kW for preheating the vessel and mixture up to 358 K. Gas temperatures were obtained from a sheated type-K thermocouple. Pressures were measured during the explosion with a Kistler type 701A pressure transducer. A central spark plug was used with ignition energies of about 23 mJ, supplied from a 12 V transitorized automotive iginition coil. The spark gap was set to 1.2 mm for all present experiments.

Turbulence was generated in the vessel by four identical eight bladed fans in a regular tetrahedron configuration. These were also used to mix the reactants. The fans were directly coupled to electric motors with separate speed controllers. Each fan was separately adjustable between 200 and 10,000 rpm. The speed of individual fans was maintained within 5% of each other and adjusted to attain the required turbulence intensity. The rms turbulent velocity and integral length scale have been determined using Laser-Doppler Velocimetry (LDV) [9]. In the central, optically accessible region of the vessel, a reasonably uniform isotropic turbulence was found with u' given by Eq. (1).

$$u' \ (\mathrm{m/s}) = 0.00119 f_s(\mathrm{rpm}) \tag{1}$$

where f_s is the fan speed in rpm. The estimated maximum deviation of u' from this equation is 10%. From a two-point correlation using a second LDV system the integral length scale Λ was found to be 0.02 ± 0.001 m and was independent of all operating variables from 1000 to 10,000 rpm.

2.2. Schlieren flame photography

Following central spark ignition, the growth rate of spherically expanding flames was studied by high speed schlieren cine photography. This is a well established method for flame imaging in combustion studies at Leeds University [12,13]. A high speed Phantom digital camera with 256 megabytes integral image memory was used to capture flame propagation. The camera speed was between 5000 and 10,000 frames/s with 384 × 384 pixels, the resolution was 0.4065 mm/pixel. At small flame radii the measured flame speed is very sensitive to determination of the flame radius from the digital images [14]. However, at these radii, the flame speed is affected by spark effects [10]. It was therefore decided to sacrifice spatial resolution at small radii in favor of higher frame rate and visibility of the entire vessel window area. In order to determine the turbulent burning velocity, image processing techniques were employed to automatically and robustly detect and reconstruct the flame front based on the maximum grayness gradient in the schlieren images.

Due to the turbulent flame brush thickness, a problem particular to turbulent burning velocity measurements is the choice of the flame front surface to evaluate the burning velocity. This choice can affect the burning velocity by a factor up to 4 [15,16]. This is shown diagrammatically in Fig. 1. For a general spherical radius R_j, between the flame root radius R_r and the flame tip radius R_t, there will be a certain mass of unburned gas m_{ui} and burned gas m_{bi} within that sphere, but outside the sphere of radius R_r. Similarly, outside a sphere of that radius, but within a radius of r_t, there will be a mass of unburned gas m_{uo} and burned gas m_{bo}.

In order to quantify the influence of the selected flame front surface on the burning velocities obtained in the present rig, Bradley et al. performed simultaneous high speed photography of images from schlieren and laser sheet Mie scattering during spherical explosions [17]. This work yielded radial distributions of the progress variable $\bar{c}$, extending from a value of $\bar{c} = 0$ at R_t, to $\bar{c} = 1.0$ at R_r. An important result from their study is that for a certain radius r_v, at which the total volume of unburned gas inside the sphere is equal to the total volume of burned gas outside it, the associated turbulent burning velocity, u_{tv} is given by the following simple expression:

$$u_{tv} = \frac{\rho_b}{\rho_u}\frac{\mathrm{d}r_v}{\mathrm{d}t} \tag{2}$$

In the present study, this basic expression was used to obtain u_t from the schlieren images. It was assumed that the radius R_{sch}, where the projected surface area of unburned gas inside it was equal to the projected surface area of burned gas outside it, was in fact r_v. The work of Bradley et al. also yielded an empirical expression to relate this burning velocity to the turbulent velocity associated with the production of burned gas u_{tr}. This expression has been used throughout the rest of this work.

$$u_{tr} = 0.9\frac{\rho_b}{\rho_u}\frac{\mathrm{d}R_{sch}}{\mathrm{d}t} \tag{3}$$

2.3. Mixture preparation

Before an explosion, the vessel was first flushed with dry air to remove most of the residuals from a previous experiment, after which it was evacuated down to 0.03 bar, filled with dry air to atmospheric pressure, and evacuated again to less than 0.03 bar. The liquid methanol volume to be injected into the bomb was found from the required molar mixture composition, the liquid methanol density and the known volume of the bomb. Liquid methanol was injected with a calibrated gas tight syringe, through a needle valve. Four syringes were employed, in this study, with volumes of 5, 10, 25 and 50 cm^3, depending upon the volume of fuel required. Injection was carried out under vacuum at 0.03 bar

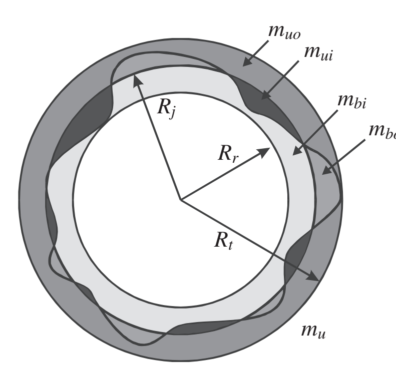

Fig. 1. Masses of burned and unburned gas at a given instant during spherical explosive propagation. Mass of unburned gas inside sphere of radius R_j is m_{ui}, mass of burned gas outside it is m_{bo}. From [17].