Measurements of burning velocities of dimethyl ether and air premixed flames at elevated pressures

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Abstract

Laminar burning velocities of dimethyl ether (DME) and air premixed flames at elevated pressures up to 10 atm were measured by using a newly developed pressure-release type spherical bomb. The measurement system was validated using laminar burning velocities of methane–air flames. A comparison with the previous experimental data shows an excellent agreement and demonstrates the accuracy and reliability of the present experimental system. The measured flame speeds of DME–air flames were compared with the previous experimental data and the predictions using the full and reduced mechanisms. At atmospheric pressure, the measured laminar burning velocities of DME–air flames are in reasonable agreement with the previous data from spherical bomb method, but are much lower than both predictions and the experimental data of the PIV based counterflow flame measurements. The laminar burning velocities of DME–air flames at 2, 6, and 10 atm were also measured. It was found that flame speed decreases considerably with the increase of pressure. Moreover, the measured flame speeds are also lower than the predictions at high pressures. In addition, experiments showed that at high pressures the rich DME–air flames are strongly affected by the hydrodynamic and thermal-diffusive instabilities. Markstein lengths and the overall reaction order at different equivalence ratios were extracted from the flame speed data at elevated pressures. Sensitivity analysis showed that reactions involving methyl and formyl radicals play an important role in DME–air flame propagation and suggested that systematic modification of the reactions rates associated with methyl and formyl formations are necessary to reduce the discrepancies between predictions and measurements.
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Keywords: Dimethyl ether; Laminar burning velocity; High pressure

1. Introduction

Being the simplest aliphatic ether, dimethyl ether (DME) has no carbon–carbon bonds and can be mass produced from natural gas, coal or biomass [1]. It has a low boiling point ($-25.1\,°C$), a high cetane number (55–60), and a high oxygen content ($\sim35\%$ by weight); these properties create a great potential for DME as the diesel substitute to achieve low soot emission combustion in diesel engines [2,3]. Moreover, DME is also expected to be used in power generation and home appliances. As such, its combustion property has received extensive studies recently. Fischer et al. [4] and Curran et al. [5] developed a detailed kinetic mechanism of DME oxidation and showed that the model was able to reproduce the low temperature results of a

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jet-stirred reactor [6] and shock tube experiments [7]. Kaiser et al. [8] measured the profiles of different species using the DME–air flat flame at atmospheric pressure and obtained reasonable agreement with the results from the kinetic model of Fischer et al. [4]

Laminar burning velocity is one of the most fundamental characteristics of a combustion mixture. Using the constant volume spherical bomb, Daly et al. [9] measured the burning velocities of DME–air mixtures at one atmosphere and 295 K. No account of flame stretch corrections was taken in their flame speed measurement. Their results were in rather poor agreement with the prediction using the oxidation model of Fischer et al. [4]. They suggested the need of modifications of some rate constants of formyl decomposition. However, formyl formation is important in all hydrocarbon oxidations and the proposed change of reaction rates was not validated using other hydrocarbon oxidations such as methane. Recently, Zhao et al. [10] measured flame speeds of DME–air using particle image velocimetry (PIV) method in a stagnation flame configuration. Stretch corrections were made by using the linear extrapolation method [11]. Their data agree well with the prediction based on their own kinetic model and the model by Fischer et al. [4]. However, their data are much higher than those of Daly et al. [9] in the whole range of equivalence ratio. Because no other flame speed data of DME–air mixtures are available in the literature, the reason causing the huge discrepancy between these two experiments remains unknown. On the other hand, combustion in diesel engine occurs at high pressure. Unfortunately, there is no reported flame speed data of DME combustion at high pressure (even at 2 atm). Therefore, it is necessary to independently re-measure the laminar burning velocities of DME–air mixtures at one atmosphere using a different experimental method. Moreover, it is of great importance to measure laminar burning velocity at elevated pressures for the validation of kinetic model and the design of internal combustion engines.

In the present work, our objective was to measure the laminar burning velocities of DME–air mixtures at different pressures using a different experimental method and data analysis. A newly designed pressure-release spherical bomb was developed for the study of high pressure combustion up to 30 atm. The obtained data will be compared with the previous experimental data and with numerical predictions obtained using the one-dimensional planar flames with the detailed chemistry of Fischer et al. [4] and a reduced chemistry developed by the authors. The pressure dependence of Markstein length as a measure of the flame response to stretch and the overall reaction order are then evaluated. Finally, sensitivity analysis will be carried out to identify the key

reactions for DME oxidation at elevated pressures.

2. Experimental and computational methods

Figure 1 shows the schematics of the present pressure-release type high pressure combustion chamber. The chamber consists of two concentric cylindrical vessels of inner diameter 10 and 28 cm, respectively. In the lateral wall of the inner vessel, 12 holes of 2.2 cm in diameter are made for pressure release. These holes are sealed with O-rings under the compression of the iron plates attracted by a series of permanent magnets imbedded in the wall. The iron plates can provide completely vacuum sealing with a pressure difference above 0.3 atm. Pressure release via gas leakage from inner to outer chamber or the opening of the iron plates occurs when the pressure difference vanishes or reverses. In experiments, the outer vessel is initially filled with an inert gas (nitrogen), and then combustible mixtures are filled into the inner vessel up to a pressure that is 0.5 atm lower than the outer one. After ignition, the pressure in the inner chamber will increase until the pressure increase is high enough to cause gas leakage or iron plate opening. Although the idea of using dual chamber is similar to that in [12], the usage of magnetic controlled pressure release door is new and has never been tried in previous research. This idea is originated from the fact that the inner chamber pressure after combustion is always much below one atmosphere due the gas expansion to outer chamber so that the iron plate will be immediately pushed back due to the large pressure difference and the magnet attraction. As such, the present combustion chamber is a
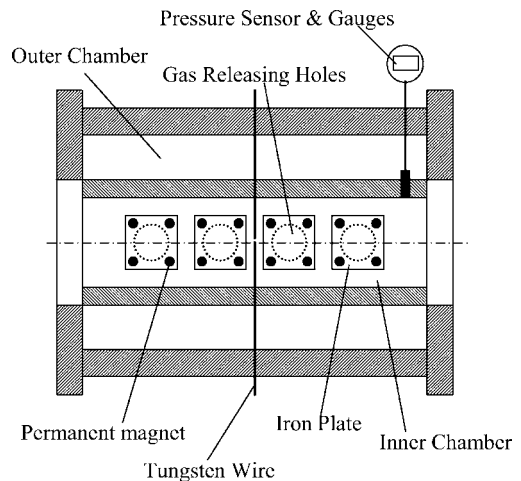

Fig. 1. Schematic of pressure-release type spherical bomb and Schlieren photography setup.