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An experimental investigation of the explosion characteristics of dimethyl ether-air mixtures

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ABSTRACT

In this work, experiments are performed to study the explosion characteristics of DME (dimethyl ether) -air mixtures using a standard 20-L spherical explosion test apparatus. The experimental data reported in this paper includes: the maximum explosion pressure (p_{max}), flammability limits, maximum rate of pressure rise $(dp/dt)_{max}$, and combustion properties (i.e., laminar burning velocity, flame radius) of DME-air mixtures at different initial conditions. The experimental results indicate that the variation between p_{max} and DME concentration (C_{DME}) exhibits a typical inverse "U" shaped behavior, with the peak p_{max} at slightly larger than the stoichiometric concentration. p_{max} is also found to decrease as the initial pressure goes down. As the initial pressure decreases from 100 kPa to 40 kPa, the LFL (lower flammability limit) is observed to vary slightly, while the UFL (upper flammability limit) is found to have a more significant drop. The relation between $(dp/dt)_{max}$ and C_{DME} behaves similarly as that of p_{max} as a function of C_{DME}, and the explosion pressure rises more abruptly at higher initial pressure. A satisfactory agreement is also found between the laminar burning velocity determined experimentally from the pressure measurement and that computed by PREMIX simulations. The present experimental results also show that the increase of the dimensionless radius of the flame is slower at higher initial pressure.

1. Introduction

Dimethyl ether (DME:CH_3OCH_3) is a promising oxygenated fuel that has the potential to be used as an alternative to natural gas for power production and as a substitute for diesel fuel. DME (dimethyl ether) has high oxygen content of 35% by weight, making the combustion smokeless and a high tolerance to exhaust gas recirculation [1]. The use of DME has been proven to significant decrease particulate formation, nitrogen or sulfur oxides (NO_x and SO_x), and carbon monoxide (CO) emission [2,3]. DME also has a high Cetane number of 55–60 and a boiling point of −25 °C. These properties are ideal for fast mixture formation, reduction in ignition delay, and cold start for diesel engines [4].

Due to its potential as a future alternative fuel, the combustion characteristics of DME have attracted significant attention in recent years [5–10]. A number of experimental and numerical studies can be found in the literature on the combustion and emission characteristics of DME under engine conditions [11–13]. Fundamental properties such as flammability and laminar burning velocities [14–17], and combustion processes of DME under turbulent conditions [3] were also reported. Detailed chemical mechanisms for low and high temperature DME oxidation have been developed and validated [18,19], and a recent mechanism for DME mixture at high pressures was also constructed by Burke et al. [20]. Furthermore, the effects of DME addition on the high-temperature ignition and burning properties of methane-air mixtures were studied experimentally and numerically [21]. Premixed and non-premixed ignition of methane/DME binary fuel blends with hot air has been investigated through numerical simulation with detailed chemistry and complete thermo-chemical as well as transport properties [22]. Detonation velocities and characteristic cell sizes of DME-oxygen and DME-air mixtures have been measured by Ng et al. [23] and Diakow et al. [24], and the explosion and detonation characteristics of DME were experimentally investigated using a 180-L spherical vessel and a large-scale detonation tube by Mogi and Horiguchi

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[25]. In addition, experiments were also carried out to examine the leakage and explosion of liquid DME [26].

While DME flames have been studied extensively, comparatively little information exists on the explosion characteristics, e.g., flammability limits, maximum explosion pressure, p_{max}, maximum rate of pressure rise, $(dp/dt)_{max}$ of DME at various initial conditions. The knowledge of the explosion characteristics of DME is thus of importance to ensure the safety in industries that produce or use it. A realistic assessment of the explosion hazards of DME is necessary for preventive measures of explosion accidents and the design of effective mitigation schemes. Among those aforementioned combustion and explosion characteristics, a key combustion property is the laminar burning velocity (S_L) which is the velocity of a steady one-dimensional adiabatic free flame propagating in the doubly infinite domain [27]. It received particular attention not only because it represents a basic characteristic property (e.g., reactivity, diffusivity, and exothermicity) of the premixed combustible gasses [28], its accurate knowledge is also essential for engine design, modeling of turbulent combustion, and validation of chemical kinetic mechanisms. In addition, the determination of laminar burning velocity is very important for the analysis and calculations used in the field of explosion protection [29]. Besides experimental measurement, the laminar burning velocity can also be estimated by numerical calculation through PREMIX simulations [30], or by semi-empirical mathematical model [31,32]. The results obtained from experimental measurement and numerical calculation can then be compared for validation and assessment, together with data reported in the literature [4,33].

The objective of the present study was twofold. First, the explosion parameters of DME-air mixtures are systematically measured from experiment. The explosion parameters include: the maximum explosion pressure p_{max}, both LFL (lower flammability limit) and UFL (upper flammability limit), and the maximum rate of pressure rise $(dp/dt)_{max}$. Second, the combustion characteristics (i.e., laminar burning velocity and the evolution of flame radius) are examined in detail under different initial conditions. The laminar burning velocity obtained from different methods are also compared and discussed.

2. Experimental details

2.1. Experimental setup

Measurements of the explosion parameters in DME-air mixtures were carried out in a standard 20-L explosion spherical vessel conforming to the international standard ISO6184-1, see Fig. 1. It essentially consists of an explosion chamber, an electric ignition system, a control unit, a data acquisition system, a release valve, a vacuum pump and an air compressor. High-voltage electric spark was used to supply ignition energy as in previous studies [34–39]. The igniter was mounted at the center of the spherical bomb and a spark energy of 10 J, estimated from $1/2\,CU^2$ ("C" and "U" refer the capacitance and voltage, respectively. $C = 0.1102 \times 10^{-3}$ F, $U = 426$ V), was delivered by an electric ignition system.

2.2. Experimental procedure and conditions

For the explosion experiments, gas concentrations were regulated by the gas partial pressures. The purity of the DME used in this experiment is 99.8%. During the experiments, the explosion pressure evolutions were measured by a PCB pressure transducer installed in the vessel wall and recorded by a data acquisition system for each shot. These data yielded values of the maximum explosion pressure and maximum rate of pressure rise as illustrated in Fig. 2. This figure shows a typical pressure history of the DME-air of $C_{DME} = 10\%$ at an initial pressure p_0 of 100 kPa. The combustion time t_c is defined as the period from ignition to the time when the overpressure reaches its maximum. The measurements were

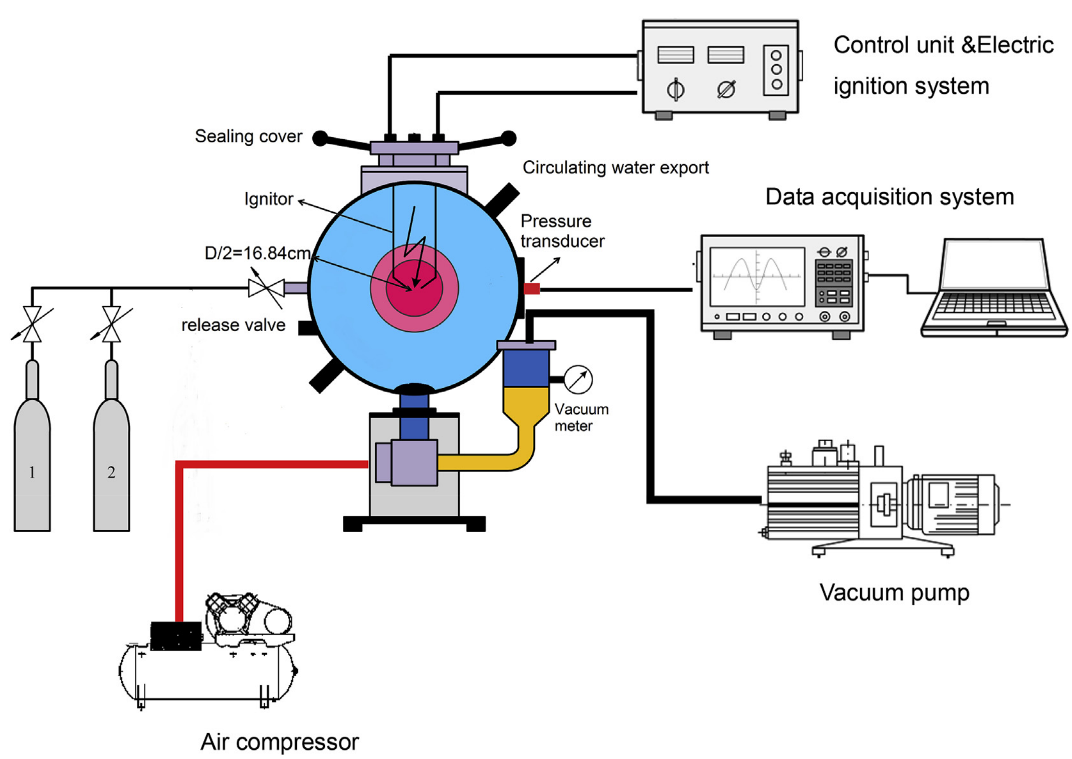

Fig. 1. The 20-L explosion spherical vessel (1 = DME, 2 = air).