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Effects of argon/nitrogen dilution on explosion and combustion characteristics of dimethyl ether–air mixtures

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ABSTRACT

In this study, an investigation of the explosion parameters, which include maximum explosion pressure (p_{max}), maximum rate of pressure rise $(dp/dt)_{max}$, and combustion characteristics, i.e., laminar burning velocity (S_L), activation temperature (T_a) and Zel'dovich number (Ze) of dimethyl ether (DME)–air–argon/nitrogen mixtures are systematically carried out. The dilution effects on the explosion and combustion characteristics are also explored through the addition of two diluents, i.e., argon (Ar) and nitrogen (N_2), into the DME–air mixture. It is found from experiment that, the explosion parameters of fuel-lean and fuel-rich mixture exhibit different behaviors. For the fuel rich mixture, p_{max} decreases with increasing amount of Ar and N_2 dilution, and a significant drop of $(dp/dt)_{max}$ is observed as the amount of added diluent increases. For the fuel lean mixture, p_{max} is first increased with increasing diluent, afterwards it decreases as inert gas dilution ratio larger than a critical value, it is also found $(dp/dt)_{max}$ fluctuates with more addition of diluent. The present results also confirm that S_L decreases more abruptly in the DME–air mixtures with dilution of N_2 than with Ar, which indicates that the increase in density dominates over the retarding effect for laminar burning velocity in the cases of inert gases dilution. The activation temperature of DME–air–Ar is larger than DME–air–N_2 at the same condition, which demonstrates N_2 dilution is more sensitive than N_2 on the suppression of chemical reaction. Results illustrate that Ze goes up with the increase of dilution ratio, and the values of Ze for argon diluted mixtures are larger than that of nitrogen diluted.

1. Introduction

With the growing demand of energy resources, the global community is seeking nonpetroleum based alternative fuels and more advanced energy technologies, to meet the increasing concerns on environmental pollution, energy security, and future oil supplies [1]. Dimethyl ether (DME:CH_3OCH_3) is a promising oxygenated fuel that has the potential to be used as a clean high-efficiency compression ignition fuel with reduced NO_x, SO_x, the combustion characteristics of DME have attracted significant attention in recent years [2–16], the physical and chemical properties of DME are shown in Table 1.

To reduce nitrogen and sulfur oxides emission from the combustion of fuels (e.g., DME) and to relieve the environmental pollution, many effective techniques were proposed, for example the highly oxygen-enriched air (up to pure oxygen) has been used in the previous study [17]. Pure oxygen combustion is possible to decrease the nitrogen concentration, thus favoring the CO_2 separation process and also lowering NO_x emissions. However, the use of pure oxygen combustion poses safety issues, which is because pure oxygen increases the laminar burning velocity and enlarges the flammability range with respect to air [18,19]. Another alternative technique to decrease NO_x emission is the introduction of exhaust gas recirculation (EGR) by reducing the flame temperature and oxygen concentration as residual gas is added into the combustible mixture [20–25]. Many fundamental combustion properties, e.g., laminar burning velocity, flame structure and Markstein length have been extensively performed in the past for DME–air [2,15,26–28], however, the fundamental explosion and combustion characteristics of DME–air mixtures in the presence of diluent have not been fully understood.

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Table 1
Physical and chemical properties of DME.

Formula	CH_3OCH_3
Molar mass	46 g/mol
Cetane number	55–60 [64]
Auto-ignition temperature	508 K
Density	713 kg/m^3
Boiling point at 1 atm	248.1 °C
Kinematic viscosity of liquid	<0.1 cSt
Vapor pressure	530 kPa
Flash point	−41 °C
Stoichiometric air fuel ratio (mass basis)	9
Explosion limit in air (vol.%)	3.5–19 [47]

Dilution has a significant influence on fuel–air combustion [29]. The role of diluents in reducing the flame temperature can be judged on the basis of the change in the thermal enthalpy per unit mass of the diluents between the air stream temperature and the flame temperature [30]. With the addition of proper diluents the burning velocity of fuel mixtures treated with exhaust gases can be measured [31]. It has been found that the presence of diluents, e.g., argon (Ar), nitrogen (N_2), may affect the laminar burning velocity, flammability range and the flame temperature of both hydrocarbons [32] and hydrogen [33,34] in air. Zhang et al. [35] measured the explosion characteristics parameters of argon/nitrogen diluted natural gas (NG)–air mixtures, the behavior of the laminar burning velocity of NG–air between different amount of diluents were analyzed. Zhang et al. [29] performed an experimental study on the combustion characteristics of diethyl ether (DEE)–air–N_2 diluent at different initial temperatures, equivalence ratios, and dilution ratios using an outwardly expanding spherically flame and high-speed schlieren photography system. Nitrogen was used as a diluent in the premixed $CH_4/H_2/O_2/N_2$ mixtures to develop correlations for the laminar burning velocity using the method of High Dimensional Model Representation (HDMR) [36]. Fundamental unstretched laminar burning velocities, and flame response to stretch were investigated both experimentally and computationally for laminar premixed flames in mixtures of hydrogen and oxygen diluted with nitrogen, argon and helium [37]. Laminar flame speeds of propane–air mixtures were determined experimentally over an extensive range of initial condition, in which nitrogen dilution was used to simulate effects of exhaust gas dilution on the laminar flame speed [38].

For the potential usage of DME as an alternative energy and to ensure its safe operation in industrial processes, the explosion characteristics including maximum explosion pressure (p_{max}), maximum rate of pressure rise $(dp/dt)_{max}$, and combustion parameters, e.g., laminar burning velocity (S_L), activation temperature (T_a) and Zel'dovich number (Ze) need to be addressed properly. In this study, experiments are performed in a standard 20-L explosion spherical vessel, the pressure histories which yield explosion pressure and the rate of pressure rise are systematically obtained to analyze the explosion and combustion characteristics for DME–air–Ar/N_2 mixtures. Different role that argon and dilution play in the dynamic behaviors during explosion and combustion processes are also studied.

2. Experimental details

Experiments were performed in a standard 20-L explosion spherical vessel (Fig. 1) according to the international standard ISO6184-1 to measure the explosion trajectories of DME–air–Ar/N_2 mixtures. The experimental apparatus essentially consists of an explosion chamber, the inner diameter of the chamber is 16.84 cm. An electric ignition system, a control unit, a data acquisition system, a release valve, a vacuum pump and an air pump.

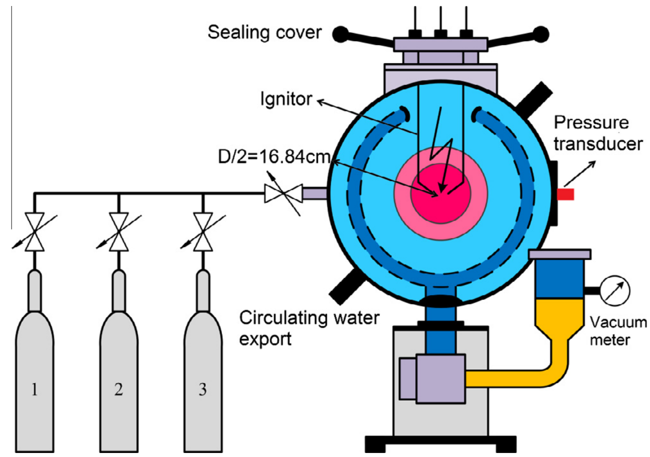

Fig. 1. The 20-L explosion spherical vessel (1 = DME, 2 = air, 3 = argon/nitrogen).

High-voltage electric spark was used to supply ignition energy as in previous studies [39–46]. 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. Detailed description can be found in our previous study [35,47].

For each experiment, the sphere is initially evacuated to at least 100 Pa and then incrementally filled through the ball valve with mixtures at various test pressures. For the explosion experiments, gas concentrations were regulated by the gas partial pressures. The purity of DME used in this experiment was 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 explosion pressure and rate of pressure rise (dp/dt), which are important in the combustion parameters analysis. It should be noted that $(dp/dt)_{max}$ is obtained at the steepest location of the pressure trajectory, a typical figure that determine $(dp/dt)_{max}$ is shown in Fig. 2. The measurements were repeated at least 3 times, the mean values with the error of the measurements were shown in the following section.

Here, a dilution ratio (ϕ) is introduced, which was also used in the previous study to examine the effect on diluent on the combustion characteristics of DEE–air mixtures, and the reference therein [29]. ϕ is a ratio of diluent partial pressure over total pressure, which is given by:

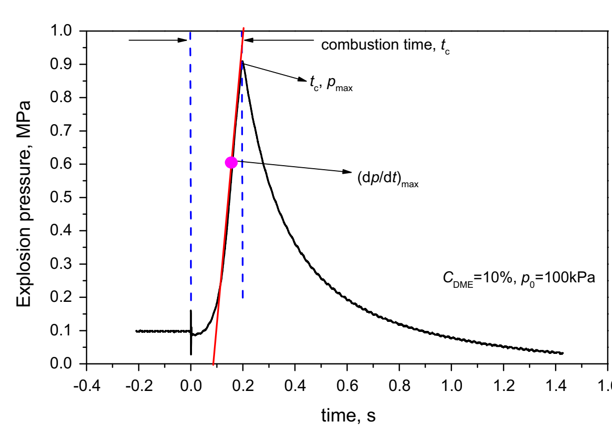

Fig. 2. p_{max} and $(dp/dt)_{max}$ of the pressure trajectory.