Fuel 217 (2018) 160–165

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Burning velocities of dimethyl ether (DME)–nitrous oxide (N_2O) mixtures

Yohji Yamamoto[a,*], Takeshi Tachibana[b]

[a] Department of Creative Engineering, National Institute of Technology, Kitakyushu College, 5-20-1 Shii, Kokuraminami, Kitakyushu 802-0985, Japan
[b] Department of Mechanical Engineering, Kyushu Institute of Technology, 1-1, Sensui-cho, Tobata, Kitakyushu 804-8550, Japan

ARTICLE INFO

Keywords:
Laminar burning velocity
Dimethyl ether
Nitrous oxide
Closed spherical bomb technique

ABSTRACT

From a usability and capability perspective, dimethyl ether (DME) fuel with nitrous oxide (N_2O) as oxidant is a promising combination for next-generation combustion devices or propellants for space vehicles. However, to ensure proper and profitable application of this fuel, we must clarify the combustion characteristics of the DME–N_2O mixture. To this end, we conducted burning velocity experiments using the closed spherical bomb technique initiated at 0.1 MPa and 295 K and ran numerical models considering the DME oxidation and N_2O decomposition reaction mechanisms in the DME–N_2O mixtures. To characterize the N_2O oxidant, we compared the experimental and theoretical results of DME–N_2O with those of air and $N_2/0.5O_2$ gases as oxidants. Among the three mixtures (containing the same amount of DME 6.54% by volumetric fraction), DME–N_2O exhibited the lowest burning velocity, although N_2O has large heat of formation. The experimental burning velocity of DME–N_2O was slowed by the low thermal diffusivity and the delay caused by the decomposition reactions of N_2O, $N_2O\ (+M) \leftrightarrow N_2 + O\ (+M)$, $N_2O + H \leftrightarrow N_2 + OH$, and $N_2O + H \leftrightarrow NH + NO$, which are same as those that are considered important in the oxidation of C1–C3 hydrocarbon–N_2O mixtures.

1. Introduction

As the simplest ether, dimethyl ether (CH_3OCH_3: DME) can be inexpensively produced from methane and other various carbon-based resources. DME is highly ignitable owing to its high cetane number, and shows good combustion characteristics with little soot formation. Moreover, its low toxicity renders it suitable for commercial spray propellants. Given these desirable characteristics, DME is expected to become an alternative fuel for next-generation diesel engines [1,2].

Nitrous oxide (N_2O) is a commercially available liquid oxidizer with higher oxygen content than air. At high temperatures, N_2O decomposes into oxygen (O_2) and nitrogen (N_2). In addition, owing to its large heat of formation (+81.6 kJ/mol), N_2O can combust more intensively than air. Therefore, adding N_2O to fuel improves the power of internal combustion engines.

For the above reasons, adding N_2O oxidant to DME fuel is one of the most promising approaches for delivering high energy with good combustion and environmental characteristics in engineering and scientific applications. The DME and N_2O combination is also advantaged by preferable vapor pressures (0.6 MPa for DME and 3.2 MPa for N_2O at room temperature) and low freezing points (−142 °C for DME and −102 °C for N_2O at atmospheric pressure), negating the need for pressurants to drive the propellants to the combustion chamber and heaters to prevent the propellant from freezing. As a rocket propellant, DME–N_2O would enable small, simply structured, safe and high-performance satellite thrusters for attitude or orbital control. Our research group has already proposed the application of DME–N_2O in space vehicles [3–5].

To ensure the correct and profitable use of DME–N_2O in combustion devices or thrusters, we must elucidate the combustion properties (typified by the laminar burning velocity) and clarify the combustion characteristics of DME–N_2O mixtures. The laminar burning velocity of a premixed gas, which is uniquely determined by the equivalence ratio, pressure and temperature of the gas, is among the most important indicators of combustion phenomena [6]. Although various studies have reported the burning velocities of DME–air mixtures [7–12], hydrogen–N_2O mixtures and hydrocarbon fuels such as methane and propane–N_2O mixtures [13–18], DME–N_2O mixtures appear to have been largely neglected. In the present study, we clarify the combustion characteristics of DME–N_2O mixtures through burning velocity experiments using the closed spherical bomb technique, which measures the laminar burning velocities under a wide range of conditions, and in theoretical reaction calculations. To characterize N_2O as an oxidant, we compare the experimental and theoretical results of DME–N_2O with those of air (containing the same constituent elements as N_2O) and mixed $N_2/0.5O_2$ gas (with the same nitrogen-to-oxygen ratio as N_2O).

---

* Corresponding author.
E-mail addresses: yyohji@kct.ac.jp (Y. Yamamoto), takeshi@mech.kyutech.ac.jp (T. Tachibana).

https://doi.org/10.1016/j.fuel.2017.12.067
Received 16 August 2017; Received in revised form 1 December 2017; Accepted 17 December 2017

Nomenclature

c_p	specific heat at constant pressure (J/(kg·K))
c_v	specific heat at constant volume (J/(kg·K))
$F_1(\pi)$	non-dimensional function of π calculated from the initial conditions of mixtures (–)
h_i^0	heat of formation of species *i* at reference temperature (J/kg)
P	pressure (Pa)
P_e	theoretical burn end pressure (Pa)
q	non-dimensional calorific value of unburned mixture (–)
r_*	theoretical instantaneous flame radius (cm)
r_c	radius of combustion vessel (cm)
S_u	experimental laminar burning velocity (cm/s)
$S_{u,\,cal}$	calculated laminar burning velocity (cm/s)
T	temperature (K)
T^0	reference temperature (K)
t	time (s)
Y_i	mass fraction of species *i* (–)
α	thermal diffusivity (m^2/s)
γ	specific heat ratio (–)
λ	thermal conductivity (W/(m·K))
ξ_*	non-dimensional theoretical instantaneous flame position ($=r_*/r_c$) (–)
π	non-dimensional pressure ($=P/P_0$) (–)
ρ	density (kg/m^3)
σ	non-dimensional density ($=\rho/\rho_0$) (–)
τ_b	experimental burn time (s)
ø	equivalence ratio (–)

Subscripts

0	initial
b	burned
u	unburned

2. Experimental apparatus and test procedure

Fig. 1 schematizes the experimental combustion apparatus with a spherical vessel. The vessel shell, made of 304 stainless steel with an inner diameter of 160 mm and a volume of 2.14 L, was manufactured as previously described [19]. The vessel is equipped with intake valves, an exhaust valve, observation windows, pressure sensors, and a thermocouple, and its maximum operating pressure is 10 MPa. A pair of ignition electrodes was manufactured by extending the middle electrode of a spark plug (BCP6ET, NGK Spark Plug Co.) to the vessel center. The electrodes (diameter 2 mm, tapering toward a conical tip) were made of SUS 304 and placed face-to-face at the center of the vessel. Ignition was induced within 1 mm of the electrode gap at the vessel center by electrical discharge from storage capacitors. The ignition energy can be ranged from 11 to 500 mJ by varying the capacitance (2500–10000 pF) and the output voltage (3–10 kV) of the capacitors.

After evacuating the spherical vessel with a vacuum pump, the oxidant and DME fuel were sequentially introduced to the vessel until the partial pressure reached the desired amount. The partial pressure was monitored by a diaphragm-type pressure sensor (ZSE50F, SMC Co.). Within the vessel, the DME–oxidant mixture was stirred for 10 min by the reciprocating motion of a piston mixer connected to the vessel. After thorough stirring, the initial temperature was checked using a thermocouple (E52-P6DF, OMRON Co.). Once the mixture had settled into quiescence, it was ignited. The initial temperature of the mixture, T_0, was 295 K (± 2 K), and the ignition energy was below 45 mJ. The time-varying pressure in the spherical vessel was measured by a piezoelectric pressure sensor (6013CA, Kistler Co.) in line with a charge amplifier (5018A, Kistler Co.), and was stored on an oscilloscope (TDS2014C, Tektronix Co.).

The laminar burning velocity S_u was derived by the technique of Takeno and Iijima [19,20] among various closed spherical bomb techniques [21]. This method derives S_u by applying the measured time-varying pressure in the spherical vessel to a closed-vessel flame propagation analysis, based on a quasi-steady one-dimensional flame surface model. By reading the rate of change of pressure (d*P*/d*t*) from the measured pressure–time (*P*–*t*) diagram, S_u is given by

$$S_u = \frac{1}{F_1(\pi)}\frac{r_c}{P}\frac{dP}{dt}, \tag{1}$$

where π is the non-dimensional pressure ($\pi = P/P_0$) normalized by the initial pressure P_0 and r_c is the radius of the spherical vessel. The non-dimensional quantity $F_1(\pi)$, which is a function of π alone, can be calculated in advance from the initial conditions of the mixture (if specified):

$$F_1(\pi) = \frac{3\gamma_u\gamma_b\xi_*^2\sigma_u}{\gamma_b + (\gamma_u-\gamma_b)\xi_*^3}\left\{\frac{(\gamma_b-1)q}{\gamma_b(\gamma_u-1)}\frac{1}{\pi} - \frac{\gamma_u-\gamma_b}{\gamma_b(\gamma_u-1)}\pi^{-\frac{1}{\gamma_u}}\right\}. \tag{2}$$

In Eq. (2), q is the non-dimensional calorific value of the unburned mixtures, calculated as

$$q = \frac{(\Sigma_{i=1}^{N} Y_{i0} h_i^0 - c_{pu} T^0) - (\Sigma_{i=1}^{N} Y_{ib} h_i^0 - c_{pb} T^0)}{c_{vu} T_0}. \tag{3}$$

Although this method is applicable and valid only for known mixtures, S_u can be obtained only from *P*–*t* records without observing flame position. The composition of the burned gas, the adiabatic flame temperature (T_b), and the specific heat ratios of the unburned and burned gases, (γ_u and γ_b respectively), were evaluated beforehand by the Chemical Equilibrium of Applications (CEA) program [22]. The unburned gas temperature (T_u) was calculated numerically while increasing the vessel pressure, assuming isentropic compression. Fig. 2

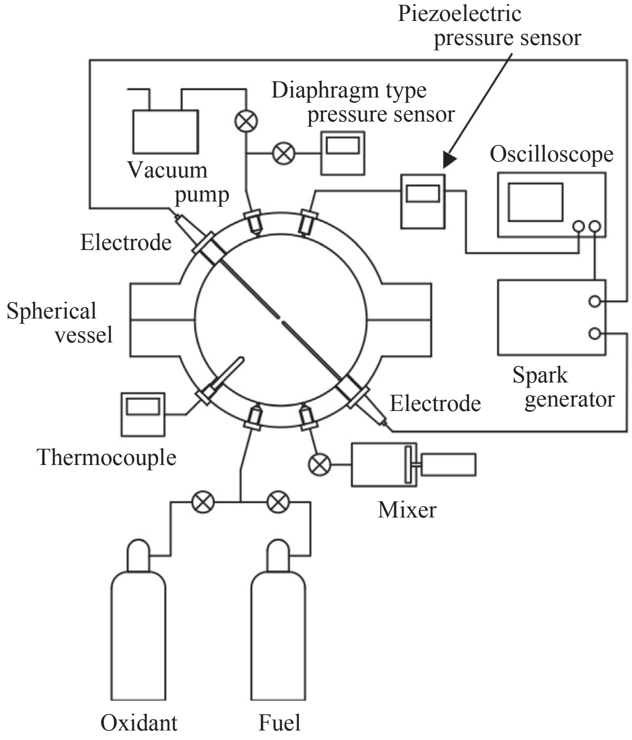

Fig. 1. Schematic of the spherical vessel combustion apparatus.