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An experimental study on premixed laminar and turbulent combustion of synthesized coalbed methane

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ABSTRACT

Coalbed methane is an economic and sustainable alternative fuel for spark ignition engines. In a constant volume combustion bomb, an experimental study was conducted about laminar and turbulent burning characteristics of the premixed coalbed methane/air flames. The turbulent burning velocities of coalbed methane-air mixtures were obtained as well as unstretched laminar burning velocities and Markstein lengths of coalbed methane at different rms (root-mean-square) turbulent velocities of 0.03, 0.05, 0.1 m/s, equivalence ratios of 0.8–1.2, and pressures of 0.1, 0.3 MPa. The results reveal that the unstretched laminar burning velocities of the premixed coalbed methane/air mixtures decrease with the increase of N_2 volumetric fractions and the initial pressures. The Markstein lengths increase with the rise of the N_2 volumetric fractions and the equivalence ratios, but decrease with the increase of initial pressures. With the increase of rms turbulent velocity, the turbulent burning velocities of coalbed methane/air mixtures are promoted at the equivalence ratios ranging from 0.8 to 1.2. The ratio of turbulent burning velocity to laminar burning velocity decreases with the increase of the equivalence ratios, while it increases with the increase of N_2 volumetric fractions in coalbed methane.

1. Introduction

With the increase of the energy price and the exacerbation of urban air pollution, the study of the alternative clean fuels has attracted more and more attentions in the field of engine research. Methane is one of the most promising alternative fuels, mainly stored in the form of CBM (coalbed methane) in the Earth. The geological reserve of coalbed gas is approximately 36.8 trillion cubic meters in China, which is the third largest reserve in the world [1]. The coalbed methane is mainly composed of 63% ~ 99% (in volume) methane and 34% ~ 1% (in volume) nitrogen [2]. Although the coalbed methane is successfully applied in the fields of power generation [3,4], it is difficult to use it efficiently as the engine's fuel [5]. The inert gases in the coalbed methane reduce the flame propagation speeds of the fuel/air mixtures, which leads to instable combustion [5,6]. Hence, SI (spark ignition) engines have much lower efficiency and higher cycle-to-cycle variations when fueled by the coalbed methane. The above problems have become the key challenges for the application of coalbed methane in the IC (internal combustion) engines.

In order to effectively use the coalbed methane in the IC engines, it is necessary to obtain the laminar burning velocity and have a deeper understanding of the factors affecting the turbulent burning velocity of the coalbed methane. In recent years, some researches have been conducted to analyze the laminar combustion characteristics of coalbed methane. Qiao [7] and Galmiche et al. [8] obtained the laminar burning velocities and Markstein lengths of the methane/diluent/air mixtures under near stoichiometric conditions. Li et al. measured the flammability limits of methane/nitrogen mixtures at atmospheric pressure and wide temperature range from 150 to 300 K [9]. Bougrine et al. [10] studied the effect of N_2 on the Markstein lengths of methane/diluent/air mixtures at near stoichiometric conditions. Miao [11] analyzed the laminar flame speeds of methane/nitrogen mixtures by using both conventional method and nonlinear method, and obtained the Markstein lengths at a wide range of equivalence ratios. Dyakov [12] measured the adiabatic burning velocities of methane/O_2/N_2 mixtures. Numerical simulations were performed to analyze the combustion characteristic of CH_4/O_2/N_2 by using detailed chemical kinetic models

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Nomenclature

A	flame area, m^2
P_0	initial mixture pressure, MPa
r_u	laminar flame radius, mm
r_{sch}	turbulent flame front mean radius, mm
L_b	Markstein length, mm
R_{N_2}	Volumetric fraction of N_2 except for N_2 contained in the CNG and in the air
V_{CNG}	CNG volume in fuel/air mixtures, m^3
V_{air}	Air volume in fuel/air mixtures, m^3
ϕ	equivalence ratio
α	flame stretch rate, s^{-1}
R	Mole number of air in actual combustion process, mol
S_n	Stretched flame speed, m/s
S_l	unstretched flame speed, m/s
T_0	initial temperature, K
u_l	unstretched laminar burning velocity, m/s
u_{tr}	turbulent burning velocity, m/s
u'	root mean square turbulent velocity fluctuation, m/s
u'_{tr}	turbulent burning velocity at an average flame front radius of 20 mm, m/s
t	time, s
V_{N_2}	Volumetric fraction of N_2 except for N_2 contained in the CNG and in the air, m^3
ρ_u	density of unburned gases, kg/m^3
ρ_b	density of burned gases, kg/m^3
R	Mole number of air in actual combustion process, mol
ρ_0	density of the coalbed methane, kg/m^3
$\tilde{H}_0$	Wobbe index, at the combustion reference conditions of 298 K, 0.1 MPa and the metering reference conditions of 288 K, 0.1 MPa, MJ/m^3

[10]. As IC engines operate under high pressures, further experimental studies are needed to obtain laminar burning velocities and Markstein lengths at elevated pressures. To the best of our knowledge, such data is not available in literature yet.

Besides, some researches have been conducted to obtain the turbulent burning velocities of methane/air mixtures [13–15]. Peters [16] proposed that turbulent flames can be divided into several flame regimes according to the turbulent fluctuation velocity, the laminar flame speed and some relevant length scales. Erik's experiment showed that premixed combustion of SI engine is in the wrinkled and corrugated flamelet regime [17]. Vivek measured the turbulent burning velocities of methane/air and ethylene/air planar flames in the weakly wrinkled regime [18]. His research found that the ratio of turbulent burning velocity to laminar burning velocity was maintained in the range of 3 ~ 4 when the ratio of rms turbulent velocity to laminar burning velocity reduced to 0.2. The turbulent burning velocities of CH_4/diluent/air flame were measured by S.S. Shy [19] at the equivalence ratios of 0.7 and 1.4. They use N_2 and CO_2 gases to alter the degree of radiation losses from small to large. But their results do not extend much below $u'/u_l = 4$. So far, very few experimental studies on the turbulent combustion characteristics of coalbed methane/air mixtures in weak turbulence are available, especially for $u'/u_l < 0.1$.

This study is to observe the spherically propagating laminar and turbulent flames and obtain the turbulent burning velocities of coalbed methane/air mixtures in the weakly wrinkled regime, as well as the laminar burning velocities and the Markstein lengths in a constant volume combustion bomb by using a high-speed schlieren photography system. The experimental study was performed at rms (root-mean-square) turbulent velocities ranging from 0.03 m/s to 0.1 m/s, N_2 volumetric fractions from 0.0% to 10%, equivalence ratios from 0.8 to 1.2, pressures from 0.1 MPa to 0.3 MPa and an initial temperature of 298 K.

2. Experimental setup

2.1. Constant volume combustion bomb

In Fig. 1, the experimental setup includes a constant volume combustion bomb, a premixed tank, an ignition system, a data acquisition system, as well as a high-speed schlieren photography system which comprises a light source, two reflective mirrors, two parabolic mirrors and a high speed digital camera.

The combustion bomb is a cylindrical type with 100 mm in diameter and 240 mm in length. Two circular sides of the bomb are covered by quartz glasses with the thickness of 50 mm. The fuel/air mixtures are ignited by a couple of electrodes centrally located in the combustion bomb with the ignition energy of 80 mJ. The combustion pressure is recorded by using the Kistler 6061B pressure transducer.

Turbulence is generated in this constant volume combustion bomb by a jet aerator in the left of Fig. 2. The jet aerator is installed in the inner wall of the combustion bomb as shown in the right of Fig. 2, which is 6 cm in diameter with the injection pressure of 0.6 MPa. The diameters of the four jet holes are 2.5 mm. The angle between the injection direction and the plane of jet aerator is 45°. The injection direction points to the ignition position.

2.2. Turbulence field measurement

The test bench of turbulence field measurement is shown in Fig. 3. This measurement system includes a constant volume combustion bomb, a hot-wire anemometer, a gas supply system and a data acquisition system. After injection, the turbulent velocity is measured in x-, y- and z-directions by using a 3-component hot wire probe. The measuring point is set in the ignition position. The turbulent fluctuating velocities in three directions versus the time after injection are shown in Fig. 4.

2.3. Schlieren flame photography and image processing

The spherically expanding flame photos are recorded by the high speed schlieren photography system. The flame propagation is captured by a RedLake MotionPro X4 Plus high speed digital camera operating with the speed of 5000 frames per second. The image processing technique is employed to capture the flame front to calculate the flame mean radius. The flame front is automatically detected by a proprietary Matlab program based on the schlieren flame photographs. Fig. 5 shows the original schlieren flame image of turbulent flame and the corresponding flame front reconstructed by Matlab program. In Fig. 5(b), the burned gas area is white, while the remainder is black. The flame area is then determined by counting the number of pixels in the burned area.

This area is regarded as the equality of the circle area with the mean flame radius so that it is used to calculate the mean flame radius.