

Laminar Burning, Combustion and Emission Characteristics of Premixed Methane- Dissociated Methanol-Air Mixtures

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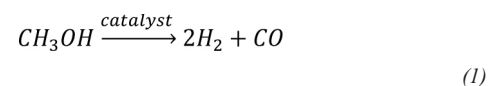
ABSTRACT

This research presents an experimental study of the laminar burning combustion and emission characteristics of premixed methane-dissociated methanol-air mixtures in a constant volume combustion chamber. All experiments were conducted at 3 bar initial pressure and 373K initial temperature. The dissociated methanol fractions were from 20% to 80% with 20% intervals, and the equivalence ratio varied from 0.6 to 1.8 with 0.2 intervals. The images of flame propagation were visualized by using a schlieren system. The combustion pressure data were measured and exhaust emissions were sampled with a portable exhaust gas analyzer. The results show that the unstretched laminar burning velocities increased significantly with dissociated methanol enrichment. The Markstein length decreased with increasing dissociated methanol fraction and decreasing equivalence ratio. The Lewis number decreased with increasing dissociated methanol fraction due to the enhancing of diffusional thermal instability and hydrodynamic instability. The highest maximum combustion pressure was observed when the equivalence ratio was around 1.2 with 80% dissociated methanol added. The ignition delay time decreased with increasing dissociated methanol fraction. As the fraction of dissociated methanol increased in the mixtures, HC and CO₂ decreased but CO and NO_x increased.

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INTRODUCTION

China's rapid economic growth has been accompanied by crude oil based fuel shortage and environmental crisis. So that it is urgently required to find alternative fuels that can be widely used in conventional IC engines with minor modification. Natural gas (the major ingredient is methane) has been a great potential alternative fuel used in conventional IC engines because it's abundant and cost-effective. But compared to gasoline, the lower volumetric heating value and slower burning velocity of methane become the biggest obstacle in application and development of this alternative fuel [1]. To overcome these disadvantages of methane fuel, many researchers have studied the hydrogen as an additive to methane since it has a high flame speed about 6 times faster than the methane flame speed and a high lower heating value about 2 times higher than the methane lower heating value [2][3][4][5]. Despite these advantages, however, hydrogen suffers from its extremely high activity which brings much inconvenience to the hydrogen storage and transportation. Besides, the high cost of production also brings certain difficulty to gain hydrogen as a widely applied alternative fuel.



Methanol also attracts great attention because of many advantages over gasoline such as: (1) Methanol is a renewable energy resource that it can be gained from a lot of materials, such as natural gas, coal and biological [6]; (2) Methanol can be applied in high compression ratio engines due to the higher octane number than gasoline [7]; (3) Methanol is more economical than gasoline on the condition of equivalent fuel heating value [8]. Even so, as an alternative fuel, methanol also has a few disadvantages. It's well known that the vaporization latent heat of methanol fuel is very large, which leads to poor gasification performance and bad low-temperature startup performance. In order to solve these problems, methanol vapor can be reformed into dissociated methanol (DM) through a dissociative reaction as the equation (1) shows, which is a mixture consisting of 66.7% hydrogen and 33.3% carbon monoxide, and then introduced into the intake manifolds for engine operation [9]. Methane-dissociated methanol (MDM) is a kind of promising new alternative fuel which has many advantages such as: (1) The approach of exhaust heat dissociating methanol is a useful method to improve the fuel

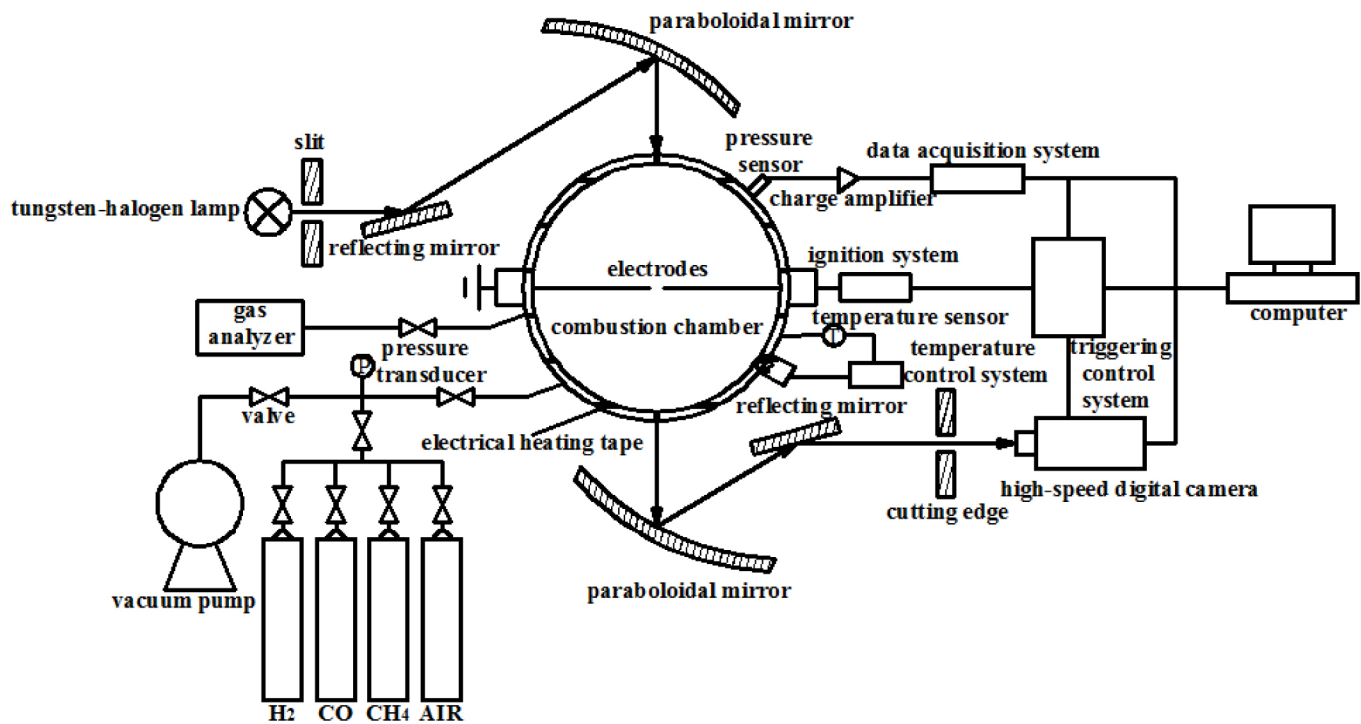


Figure 1. Experimental setup

efficiency of IC engine through recovering the wasted energy of exhaust gas; (2) The combustion characteristics of DM is similar to pure hydrogen due to the high hydrogen fraction in the mixture [10], so it can not only improve the combustion of methane but also solve the problem of hydrogen storage and transportation; (3) The cost of producing DM is much cheaper than hydrogen. However, methane slip is also a big challenge to MDM application on IC engines, and this problem will be the research emphasis of the following work.

Many researchers have studied the laminar burning and flame instabilities of H_2 -CO-air mixtures at different conditions, such as hydrogen fractions, initial pressures and initial temperatures [11][12][13][14]. Vu TM [15] studied the outward propagation and development of surface cellular instabilities of CH_4 (or C_3H_8)/ H_2 /CO-air centrally ignited spherical premixed flames in a constant pressure combustion chamber, the initial pressures were 0.1MPa, 0.2MPa, 0.3MPa, 0.4MPa, and the equivalence ratio were 0.8, 1.0, 1.2, but the CH_4 fraction were only 5%-20%. Lapalme D [16] investigated the impact of syngas (H_2 /CO mixtures) composition on laminar flame speed, the addition of CH_4 reduced the laminar burning velocity. Jie Liu [17] studied the chemical, thermal and diffusion effects of H_2 and CO addition on the characteristics of methane laminar flame numerically by using the CHEMKIN 2.0 code with a modified GRI-Mech 3.0 mechanism. There are relatively few researches about the premixed CH_4 /H₂/CO-air mixtures. The purpose of this research is to understand the laminar burning, combustion and emission characteristics of MDM. It can not only enrich the laminar burning fundamental data of premixed CH_4 /H₂/CO-air mixtures, but also provide the fundamental theory which supports the application of DM in natural gas engines.

EXPERIMENTAL SETUP AND METHOD

In this study, a spherical constant volume combustion chamber were used to analyze the laminar burning, combustion and emission characteristics of premixed MDM-air mixtures at various compositions. Figure 1 shows the schematic diagram of the experimental setup. The experimental system consists of the combustion chamber, the ignition system, the temperature control system, the data acquisition system, the high-speed schlieren photography system, the exhaust gas analysis system, and the triggering control system.

The chamber bore was 350mm and the volume was 22.4L. In order to visualize the flame propagation, two transparent quartz disks with an efficient bore of 100mm and a thickness of 40mm were selected for two sides of this combustion chamber. The centrally located electrodes with a clearance of 1.5mm were used to ignite the mixtures. The spark was produced by a capacitor discharge ignition system. The combustion chamber was wrapped by electrical heating tape to reach the test temperature. The temperature controlling system were equipped to maintain the test temperature in the range of $\pm 5^\circ C$. The combustion pressure data was measured by a piezoelectric pressure sensor (Kistler 6125C) and recorded with a high speed data acquisition system NI USB-6356). Figure 2 shows the schematic diagram of the high-speed schlieren photography system. It consists of a 100W tungsten-halogen lamp, two paraboloidal mirror, two reflecting mirror, and a high-speed digital camera (Phantom V7.3). The flame propagation were recorded by the high-speed digital camera with a frame speed of 10000 frames/s, and the image resolution was 512×512 . Exhaust emissions which included CO_2 , CO, THC, NO_x were sampled using a portable exhaust gas analyzer (AVL DiCom 4000). The trigger of ignition, the start of camera recording and the launch of combustion pressure data collection were synchronized by the triggering control system (ECTEK Calibration System V2).

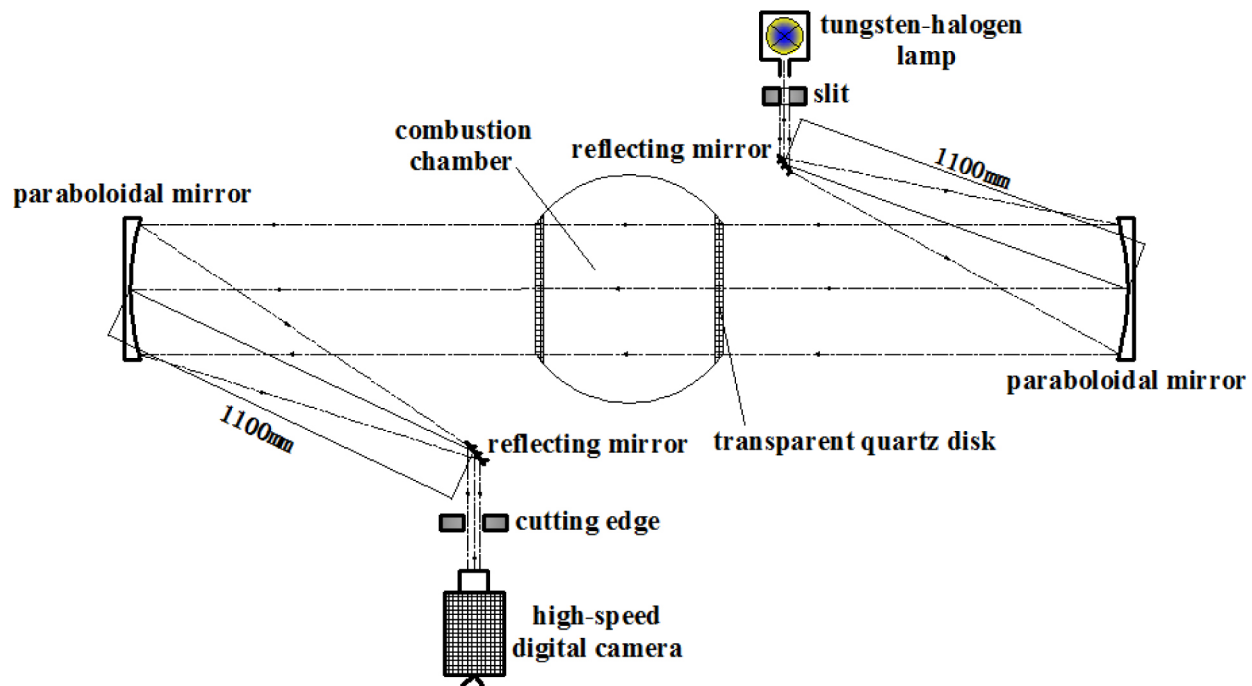


Figure 2. High-speed schlieren photography system

In order to ensure the chamber is heated homogeneously, the chamber will be left for approximately half an hour after heating to the test temperature. A time interval of 5min was awaited after the mixture preparation to ensure the mixture motionless before ignition and avoid the temperature difference between the mixture and the wall of the chamber. After combustion, the chamber was vacuumed and flushed with air to exhaust the remaining gas. The experiment was repeated at least twice to ensure test reliability and the average value was used for analysis. The constituent of DM is simulated by volume using the 66.7% hydrogen and 33.3% carbon monoxide (purity levels: H_2 -99.9%, CO - 99.5%, CH_4 -99.9%). The dry air is simulated by 21% oxygen and 79% nitrogen by volume. To obtain the equivalent ratio of mixture, each component was introduced into the chamber according to its corresponding partial pressure. Table 1 shows the experiment conditions. The DM fraction (α) is defined as the equation (2):.

$$\alpha = \frac{V_{H_2} + V_{CO}}{V_{H_2} + V_{CO} + V_{CH_4}} \quad (2)$$

Table 1. Experiment conditions

DM fraction (α)	0%, 20%, 40%, 60%, 80%
Equivalence ratio (Φ)	0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0
Initial temperature (T_u)	343K
Initial pressure (P_u)	0.3MPa

DATA ANALYSIS

Laminar Burning Velocity and Markstein Length

For an outwardly propagating spherical flame, the stretched flame propagation speed (S_n) is the time rate of change of the flame radius (r_u):

$$S_n = \frac{dr}{dt} \quad (3)$$

Where,

r_u = the radius of the flame in schlieren photograph

t = the time duration after spark ignition

In order to avoid the effect of ignition energy and pressure increase, only the photograph with flame radius between 7mm and 24mm were used in the analysis. Besides, the occurrence of the cellular structure on the flame surface because of the significantly flame speed increasing also need to be considered to the determination of the flame speed.

The flame stretch rate (K) which is influence by the flame propagation and flame bending is defined as the time derivative of the logarithm of the infinitesimal area of the flame surface, it can be calculated using the equation:

$$K = \frac{d(\ln A)}{dt} = \frac{1}{A} \frac{dA}{dt} = \frac{1}{4\pi R^2} \frac{8\pi R dR}{dt} = \frac{2}{R} \frac{dR}{dt} = \frac{2}{R} S_n \quad (4)$$

At the early stage of flame propagation, the unstretched flame propagation speed (S_l) can be obtain from the linear relationship between the stretched flame propagation speed (S_n) and flame stretch rate (K) at $K = 0$ [12][13][14][15], which is the $S_n - K$ curve:

$$S_l - S_n = L_b K \quad (5)$$

