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Experimental investigation of correlation between cellular structure of the flame front and pressure

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A B S T R A C T

The present work experimentally studies the correlation between the cellular structure of a flame front and the pressure of methane/hydrogen/air laminar premixed flame at various equivalence ratios and hydrogen fractions in a spherical combustion chamber. The effects of the equivalence ratio and the hydrogen fraction on the explosion characteristics and evolution of the cellular structure of the flame front of methane/hydrogen/air were determined, and the correlation between cellular structure and pressure was analyzed. The results show that with an increase in the equivalence ratio or the hydrogen fraction, the p_{max} and its time increase monotonously. The mean area of all cells reaches a constant value, which tends to increase with an increase in the hydrogen fraction or the equivalence ratio. The absolute value of growth rate decreases with an increase in the equivalence ratio under 70% hydrogen fraction or with an increase in the added amount of hydrogen. The influence of pressure on the cellular structure decreases in the early stage after the flame edge reaches the quartz window under a certain equivalence ratio. When the flame develops to a certain degree, the influence of pressure on the cellular structure is limited.

1. Introduction

The automobile industry is a predominant sector in national economies and plays an important role in civilization development. In recent years, the traditionally petroleum-based automobile industry has been turning towards clean fuel due to the global energy shortage and environmental pollution In recent years, the traditionally petroleum-based automobile industry has been turning towards clean fuel due to the global energy shortage and environmental pollution [1–6]. Natural gas, a mixture mainly composed of methane, is one potential gaseous fuel, used in automobile engines, but its low burning rate causes obvious problems in engines (such as lower combustion efficiency, higher cyclic variation, longer combustion duration, etc.) [7–9]. In particular, combustion duration, defined as the crack angle ranging from start point to end point of combustion, is an important parameter to evaluate the combustion conditions of engines. In order to achieve more rapid combustion with lower ignition energy, researchers have proposed adding hydrogen into natural gas to improve the efficiency of engines while reducing the produced emissions under engine conditions [10–12]. Therefore, investigations on methane/hydrogen blended fuel have become important research topics in the field of fuel science.

Most of the previous work on methane/hydrogen blended fuel has been focused on the laminar burning velocity in which the effects of fuel concentration and thermal boundaries have been thoroughly considered [13–16]. Other studies have focused on the intrinsic instabilities which are also essential to the combustion process [17–22]. Based on these previous reports, it is known that a premixed flame suffers from the effects of diffusive-thermal and hydrodynamic instabilities which make the flame surface unstable, and turbulization phenomenon would occur in an unstable premixed flame if it was sufficiently large [23,24]. However, almost allthese previous studies and the obtained conclusions were based on the constant pressure condition.

For an expanding flame in limited space, the released energy leads to a remarkable pressure rise which subsequently affects the propagating flame (the sharp change in flame structure is one most obvious representation). It is known from earlier studies [25–31] that, an unstable structure leads to an increase in burning velocity. The increased burning velocity leads to noticeable rise in pressure, which again affects the flame structure. Therefore, it is necessary to the correlation between pressure and cellular structure of the flame.

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Aiming at providing such information, in the present work, a series of laminar premixed flame experiments are carried out on a mixture of methane/hydrogen/air under an initial pressureof 0.1 MPa and an initial temperatureof 300 K in a spherical combustion chamber. The effects of hydrogen fractions (ranging from 50% to 90%) and equivalence ratios (ranging from 0.6 to 1.0) have been considered. The explosive characteristics and the evolution of the cellular structure of the flame after the flame edge reaches the quartz window are studied, and the correlation between the cellular structure and the pressure is analyzed.

2. Experimental setup and procedures

2.1. Experimental setup

In this paper, all the experiments were conducted in a spherical combustion chamber system, including a constant volume chamber with an inner diameter of 380 mm, an intake system, an ignition system, a schlieren system, a high speed camera, and a control and data acquisition system. The diameter of the quartz window is 120 mm. The combustion pressure of the mixture in the chamber was measured by a Kistler 6052c type high transient pressure sensor, mounted in the chamber. A type 5018 charge amplifier and a DPO 3054 digital phosphor oscilloscope were combined with the pressure sensor to display and store pressure data. The flame photos of the mixture were recorded by a FASTCAME SA-X2 high-speed digital camera, with a sampling frequency of 13,500 per second. The mixture was ignited by the electrodes located in the center of the chamber, and to ensure simultaneous acquisition of the pressure and flame photos, a synchronized trigger device was used in the experiment. The volumetric percentage of methane, hydrogen and dry air controlled by the pressure gauge was supplied into the chamber through an inlet valve according to the given equivalence ratio. Ignition was activated after the mixture had been kept for 5 min, in order to ensure mixing uniformity. The combustion products were removed by a vacuum pump after complete combustion, and a nitrogen flow was used to purge the constant combustion chamber in order to eliminate the impact of residual gas on the experiments. A schematic illustration of the experiment setup is shown in Fig. 1.

2.2. Parameter definition

The burning velocity of hydrogen is higher than that of methane, which makes the hydrogen percentage a prominent factor influencing the explosion characteristics of the methane/hydrogen mixture. The hydrogen fraction of the methane/hydrogen mixture is defined as

$$X_{H2} = V_{H2}/(V_{H2} + V_{CH4}) \tag{1}$$

where V_{H2} *and* V_{CH4} represent the volume of H_2 and CH_4 respectively.

In order to better understand the pressure variations in the constant combustion chamber, the pressure curve is divided into three regions. First, a constant pressure stage rises from the initial value and lasts from the ignition to the 1% pressure. Next, a pressure rise stage is identified, starting from the 1% pressure rise and reaching the maximum explosion pressure, and finally the pressure drop stage, which is the region between the maximum explosion pressure and complete combustion (Fig. 2). Since the pressure drop stage is not the key point of this research, only a part of the stage is shown in Fig. 2. The maximum explosion pressure (p_{max}), the maximum rate of pressure rise ($(dp/dt)_{max}$), and the combustion duration (t_d), are the parameters selected to quantify the explosion characteristics of the methane/hydrogen/air mixture. The maximum explosion pressure is simply the maximum value during the combustion process, which directly affects the service life and safety degree of any combustion device. The maximum rate of pressure rise, which can be used to roughly characterize the burning degree, appears in the pressure rise stage. This parameter is strongly affected by the volume of the combustion device. The combustion duration (t_d) can indicate the burning velocity in the combustion device, which is important in terms of combustion control technique. It is set as the time elapsed from the ignition

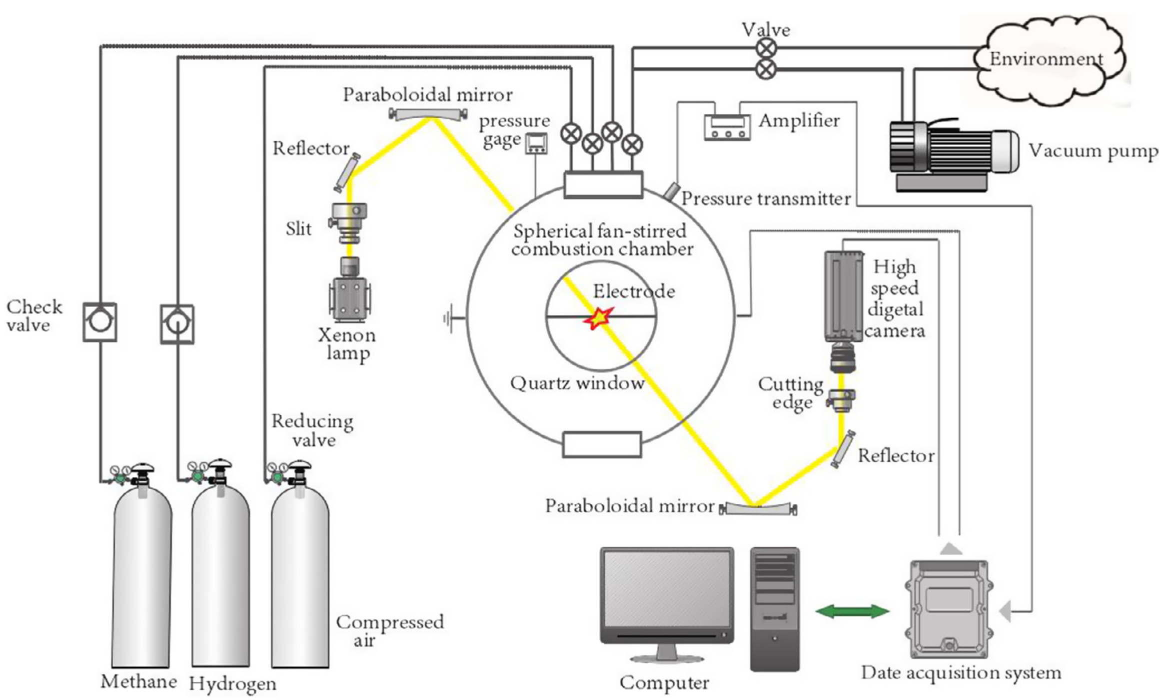

Fig. 1. Schematic of the experiment setup.