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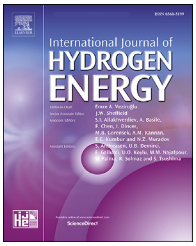

Effect of hydrogen-air mixture diluted with argon/nitrogen/carbon dioxide on combustion processes in confined space

Haiqiao Wei[*], *Zailong Xu*, *Lei Zhou*[**], *Jianfu Zhao*, *Jie Yu*

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

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ABSTRACT

The effects of the dilution with inert gas on different combustion processes in confined space are investigated by utilizing a newly designed constant volume combustion bomb (CVCB) equipped with a perforated plate. Hydrogen-air mixture diluted with argon, nitrogen and carbon oxide of different proportions is employed in the present work. Combustion phenomena were all captured by high-speed Schlieren photography including flame propagation, compression wave formation as well as pressure oscillation. The results show that the dilution of inert gas slows down flame propagation in the combustion chamber. The velocity deficit increases in the order of Ar/N_2/CO_2, which indicates that CO_2 is a better inhibitor of flame propagation than Ar and N_2. The evaluated jet flow accelerates continuously driven by the forward spreading laminar flame and the velocities at different inert gas conditions decrease in the sequence of Ar/N_2/CO_2. No shock wave occurs during the combustion process when inert gases are introduced into the chamber. The amplitude of pressure oscillations decreases with diluted mixture due to the absence of flame-shock interactions. Besides, the peak pressure shows difference among different inert gases.

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Introduction

Recently engine downsizing with supercharging plays an important role in spark ignition (SI) gasoline engines to realize higher thermal efficiency and lower emissions. However, knock/super-knock is an inherent constraint on the performance and efficiency of downsized spark ignition (SI) engines since it limits the maximum compression ratio that can be used with any given fuel [1–4].

It is generally agreed that knock/super-knock is caused by the extremely rapid energy release of the end-gas ahead of the propagating turbulent flame companied with intense pressure oscillations. Essentially, knock/super knock is always relevant to the interactions between flame and shock wave and a rapid chemical energy release [4–6]. Particularly, it was found that super knock originates from pre-ignition and is accompanied by the phenomenon of deflagration to detonation [7–9]. Therefore, comprehensively understanding the interaction mechanism between the flame and shock wave is extremely beneficial for avoiding pressure oscillation and improving the engine performance [10].

Valiev et al. [11] found that gas compression reduces the acceleration rate and the maximum flame tip velocity by

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[*] *Corresponding author*. 92 Weijin Road, Nankai District, Tianjin, PR China.
[**] *Corresponding author*. 92 Weijin Road, Nankai District, Tianjin, PR China.
E-mail addresses: whq@tju.edu.cn (H. Wei), lei.zhou@tju.edu.cn (L. Zhou).

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increasing the initial Mach number, which moderates finger flame acceleration during the early stage of burning. It provides a potential direction for the research on suppressing the flame propagation and detonation development based on real combustible mixture properties. Significant advances [12–19] have been made over the past years in the understanding of mechanism of diluted inert gas on the detonation and flame propagation. Wu et al. [12] investigated the detonation transmission behaviors in acetylene-oxygen-argon mixture in the initiator tube. According to their experimental results, the velocity deficit is observed to be about 10% for low argon diluted mixture, while it reaches 20% for high argon diluted mixture. Zhang et al. [13] experimentally investigated the detonation velocity deficits of $2H_2$-O_2 and $2H_2$-O_2-3Ar mixture in narrow gaps. It could be found that the velocity of $2H_2$-O_2-3Ar mixture is obviously lower than that of $2H_2$-O_2 mixture. Detonation propagations in stoichiometric H_2–O_2 mixture diluted with Ar and N_2 were experimentally investigated by Wang et al. [14]. The results show the velocity decreases and the limiting pressure increases with the increase of the dilution concentration. This indicates that the detonation propagation ability is weakened with the addition of the inert gases in particular N_2. Benedetto et al. investigated the effects of diluents on the explosion behavior of stoichiometric CH_4–O_2 and H_2–O_2 mixtures both experimentally and theoretically [20–23]. In their studies, they reported a detailed analysis of the role played by the addition of a diluent (CO_2, N_2, He, and Ar) on the anomalous behavior. Consequently the less effective diluent has been found to be Ar followed by He, N2, and CO2 in the order listed. It is also proposed that the addition of CO_2 increases the specific heat of the mixture and thus lowers the flame temperature and the combustion rate. All the findings mentioned above provide valuable reference for related researches on diluent inert gas. However, the effects of different diluted inert gases on the turbulent flame propagation and in-cylinder pressure oscillation in confined space have not been comprehensively discussed through optical methodology.

The purpose of the present work is to experimentally investigate the influences of the dilution with different inert gases on a series of combustion processes such as flame propagation, compression wave formation as well as pressure oscillations in confined space. In addition, the effect of flame-shock/acoustic interactions on flame propagation was observed. The experiment was carried out in a newly designed experimental apparatus equipped with a perforated plate. The perforated plate was employed to achieve a high-speed turbulent flame. The experimental results were imaged by high-speed Schlieren photography. We selected a stoichiometric H_2-air mixture as the test fuel because of its high flame tip velocity and the formation of the obvious shock wave ahead of the flame front. The N_2, Ar and CO_2 are employed as the inert gas. Note that in the comparisons of this work, the energy density or equivalence ratio keeps constant.

The paper is organized as follows: the experimental apparatus and procedures are briefly discussed in Section Experimental apparatus and procedures; the effects of the dilution with different inert gases on a series of combustion processes are presented in Section Results and discussion; and finally, main conclusions from this work are drawn in the last section.

Experimental apparatus and procedures

Experimental apparatus

Experiments were carried out in a newly designed constant volume combustion bomb (CVCB) equipped with a high-speed Schlieren photography system, as shown in Fig. 1. The entire experimental system is comprised of a constant volume combustion chamber, a high-speed Schlieren photography system, an image acquisition system, a pressure acquisition system, an intake and exhaust system, a heating system, a high-voltage ignition system, a synchronization controller as well as a perforated plate with hole size of 5 mm and porosity of 12%.

The combustion bomb is an approximately cylindrical cavity with 100-mm inner diameter and 230-mm long and total volume of 2.32 L. Two opposite optical windows made of high-quality quartz glass are mounted in the front and back side of the CVCB, which can provide optical access. The windows are in racetrack-shape of 230 mm in length and 80 mm in width. The optical region is marked in shadow area in Fig. 1 with a length of 150 mm and a width of 80 mm. A perforated plate with hole size of 5 mm and porosity of 12% is installed in the middle of the combustion chamber to generate flame acceleration. The structure of the perforated plate is elucidated in Fig. 1. It is made of a 3 mm thick stainless steel plate. Different numbers of holes are distributed on the plate in rectangular form. At the top and bottom of the CVCB, there is a cluster of electrical heating elements with total power of 2 kW to heat the bomb to the target temperature equably. A closed-loop feedback controller is used to regulate the internal temperature within a deviation of 3 K. This would prevent combustion products from condensing into droplets. The bomb is capable of withstanding a transient pressure less than 10 MPa. As a precaution, an 8 MPa pressure release valve is installed in the chamber against emergency. The spark plug is arranged on the left wall of the combustion chamber. The mixture is ignited using a Bosh R6 ignition plug with extended electrodes by a spark with duration of 0.7 ms. The pressure transducer (Kistler 6113B at 100 kHz) is located on the top of the combustion chamber 30 mm far away from the right wall to record the in-cylinder pressure during the combustion process. The in-cylinder pressure can be acquired on the computer by utilizing the pressure acquisition card. The intake and exhaust system are installed at opposite ends of the chamber for scavenging the exhaust gas. High-speed Schlieren photography technology is employed in this study to capture and record the combustion images. The Schlieren system is arranged in a standard Z configuration to observe the process of flame acceleration and propagation.

Experimental procedures

Initially, the combustion chamber is heated up to the target temperature by the heating system. Stoichiometric H_2-air mixture is obtained according to Dalton's partial pressure law.

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