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Turbulent flame propagation with pressure oscillation in the end gas region of confined combustion chamber equipped with different perforated plates

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ABSTRACT

Experiments were conducted in a newly designed constant volume combustion chamber with a perforated plate by varying the initial conditions. Hydrogen–air mixtures were used and the turbulent flame, shock wave, and the processes of flame–shock interactions were tracked via high-speed Schlieren photography. The effects of hole size and porosities on flame and shock wave propagation, intensity of the shock wave and pressure oscillation in closed combustion chamber were analyzed in detail. The effect of interactions between the turbulent flame and reflected shock or acoustic wave on the turbulent flame propagation was comprehensively studied during the present experiment. The results demonstrated that flame front propagation velocity and pressure oscillation strongly depend on the hole size and porosities of the perforated plate. The flame front propagation velocity in the end gas region increases as hole size increases and porosity decreases. The flame front propagation intensity in the end region of a confined space is strongly relevant to two competing effects: the initial turbulent formation and turbulent flame development. The experimental results indicated that an oscillating flame is associated with both the reflected shock wave and the acoustic wave. Meanwhile, different turbulent flame propagations and combustion modes were observed.

1. Introduction

The turbulent flame is one of the most interesting parts of combustion science and industry systems. Due to its huge complexity and nonlinear combustion features, progress in understanding and predicting a turbulent flame is still extremely challenging at present [1–5]. Particularly, in a closed space, such as an internal combustion engine and fire safety area, turbulent flame propagation with induced pressure oscillation is strongly related to energy efficiency, safety, emissions, etc. The understanding of turbulent flame propagation in a confined space is still a vital obstacle for quantitatively understanding and predicting the combustion phenomenon, including the knocking combustion in gasoline engines, the interaction between the flame and shock/acoustic wave, and the deflagration to detonation transition (DDT) [4]. It is well known that flame propagation in a duct filled with obstacles can accelerate to a fast flame [4,6,7]. Therefore, based on previous studies, a newly designed experimental apparatus is used to investigate the turbulent flame propagation process with high-amplitude pressure oscillation in a small confined chamber with perforated plate.

Significant advances have been made over the past years in the understanding of flame propagation at the presence of obstacles [8,9]. A great deal of effort [6–13] has been spent on studying the turbulent flame acceleration mechanism in channels equipped obstacles in recent decades. Bychkov et al. [4] noted that the flame acceleration in long tubes equipped with obstacles is induced by delayed burning between the obstacles. It can generate a powerful jet flow driving an extremely fast flame velocity [4,14]. In addition, the well-known Kelvin–Helmholtz (K–H) and Rayleigh–Taylor (R–T) instabilities also have significant contribution to the flame acceleration when the flame is suddenly accelerated over an obstacle or through a vent. Previous studies have significantly improved our understanding of the flame acceleration process. However, turbulent combustion still remains one of the most intensively studied but least understood phenomena in combustion theory [8,9]. In turbulent flame propagation, it involves two mechanisms of turbulent flames, the turbulent flame self-acceleration mechanism [5,15,16] and interactions between a turbulent flame and shock

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wave or compression wave (acoustic wave) [7,14,17–20]. A common conclusion is that the self-acceleration of a turbulent flame is related to the intensity of hydrodynamic instability as well as that of diffusional-thermal instability with the increase of flame surface. The interactions of reflected shocks with a flame or turbulent flame have been widely used to investigate flame instabilities transition to turbulence, and most recently, the deflagration to detonation transition (DDT) [21]. Furthermore, the transient flame–vortex interaction is the key process in the description of an accelerating flame propagation through obstacles. The resulting flame–vortex interaction intensifies the rate of flame propagation and pressure rise. For instance, Di Sarli et al. [22–27] well and comprehensively investigated the unsteady coupling of the propagating flame and the flow field at the wake of obstacles by means of both particle image velocimetry (PIV) and large eddy simulation (LES). They clearly demonstrated a satisfactory agreement in terms of shape of the accelerating flame propagation, flame arrival times, spatial profile of the flame speed, pressure time history, and velocity vector fields. The flame–vortex or flow interaction finally improved the flame acceleration.

Based on the above theory fundamentals including the flame acceleration and flame–shock interactions, a number of experimental studies [12,13,28-30] have demonstrated the influence of obstacle spacing or scale on the flame propagation process. The work by Ciccarelli and Witt [31] demonstrated that the detonation initiation due to shock reflection is roughly the same for the different blockage ratio (BR) reflector perforated plates tested. But, the work was carried out in a long detonation tube. Another work [30] was performed to study the effect of obstacle size and spacing on the initial stage of flame acceleration in a rough tube. The results presented that for the lower blockage ratio plates, the plate size did not have much effect on the flame acceleration. However, for a higher BR, the plate size had a strong effect on the run up distance corresponding to the spacing of the perforated plates. A serial of further works were conducted by Ciccarelli and coworkers [32,33].

In other work by Na'inna et al. [28], the effects of obstacle scale with the same BR on the flame speed and overpressure were investigated. The obstacle with two flat bars obtained maximum overpressure compared with that with four flat bars. Moreover, several studies regarding the mechanism of detonation attenuation by a porous medium were carried out. A novel mechanism was identified, where each shock reflection from a porous medium gives rise to significant enhancement of the gas reactivity. Recently, similar studies were performed. A flame passing through multiple cylindrical obstacles could generate high speed deflagrations at different obstacle configurations and blockage ratios.

Hall et al. [34] studied the effects of the number and location of solid obstacles on the rate of propagation of turbulent premixed flames. It is found that while the peak overpressure increases with increasing number of grids or baffle plates. After this work, Masri et al. [35] performed a comparative study of turbulent premixed flames propagating past repeated obstacles. They found that for all fuels the peak pressure as well as the rate change of pressure increases with increasing blockage ratio (BR) and with decreasing separation between successive baffles. But, there works more focus on the pressure evolution. Maeda et al. [36] investigated the deflagration-to-detonation transition in a channel with different heights of obstacles. It is found that the initial flame acceleration showed almost the same pattern for different heights of obstacles. But, in the downstream region the flame front velocity for highest height reaches the sound speed. Furthermore, Valiev et al. [37] provided details of the theory and numerical modeling of the flame acceleration for various blockage ratios and various spacing between the obstacles in a channel with one open end and one close end. Gamezo et al. [38] demonstrated the competing effects of high blockage ratio: larger obstacles promote non-uniform flow and they also weaken shocks diffracting over large obstacles. Consequently, the DDT occurrence is affected. Similarly, Goodwin et al. [39] adopted the numerical simulations to investigate the effect of decreasing blockage ratio on DDT in an infinitely long rectangular channel. They pointed out different blockage ratios have different mechanisms and in a certain range the DDT can occur.

Although significant effort has been devoted to the flame acceleration and detonations combustion of a flame propagating through repeated obstacles or porous media, previous experimental studies did not completely address the turbulent flame propagation mechanism with high pressure oscillation in a confined space, especially a controlled turbulent flame. This problem is, of course, of prime importance to the design of engines, such as knock suppression in spark ignition engine. Furthermore, the interaction between a flame and shock wave is always accompanied by acoustic oscillations, which can lead to significant overpressures and pressure oscillations within a confined space [11,40]. However, the amplitude of pressure oscillations or overpressures is very small. For a strong pressure oscillation, it has a strong damaging effect on the device. There is still a lack of detailed studies regarding strong pressure oscillation, which is similar to the knock phenomenon in engines. Overall, the effect of a reflected shock wave on the flame propagation and pressure oscillation in the end region of confined space has not been comprehensively discussed.

The present study focuses on turbulent flame propagation controlled by an perforated plate with different hole sizes and porosities in confined space. The interactions between turbulent flame and compression wave including visible shock wave and invisible acoustic wave are investigated. Meanwhile, the different combustion phenomena and relationships of turbulent flame propagation and pressure oscillation are demonstrated in this work. In this work, a newly designed experimental apparatus equipped with a perforated plate, which employed the technique of fast flame generated by a flame passing through the orifice plate and the theory of self-accelerated turbulent flame, was used. Different intensities of the turbulent flame and shock wave can be generated by effectively controlling the hole sizes and porosities. The interaction between flame front and shock wave was imaged via high-speed Schlieren photography. The effects of a reflected shock wave on the combustion modes and, consequently, on the pressure oscillation were studied in detail. A stoichiometric hydrogen–air mixture was used as the test fuel because of its high flame propagation velocity and the formation of an obvious shock wave ahead of the flame front, which can be used to investigate the interaction of the flame–shock wave. The present study will provide a new insight into not only the knock phenomenon in spark ignition gasoline engines, but also the DDT and pulse detonation phenomenon in engines.

The paper is organized as follows: the experimental setup and conditions are briefly discussed in Section 2. The results and discussion are presented in Section 3, involving the effects of different hole sizes and porosities. In Section 4 the specific combustion modes of normal combustion and reciprocating combustion as well as the analysis of pressure oscillations were shown. Finally, this study's conclusions are presented in the last section.

2. Experimental setup and conditions

2.1. Experimental setup

The experiments apparatus is same with our previous study [41], thus the detailed information is not shown here due to the limited length of paper. The experimental apparatus was composed of the constant volume combustion vessel, the orifice plate, the intake and exhaust pipe system, the ignition system, the heating