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Effects of plate slits on flame acceleration of premixed methane/air in a closed tube

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The paper aims at revealing the interaction of various numbers of premixed methane/air jet flames in a closed duct. In the experiment, a high-speed video camera and pressure transducers are used to study the flame structure and pressure dynamics. In the numerical simulations, large eddy simulation (LES) with Power-Law combustion model is employed to investigate the interaction between the moving flame and vortices induced by the thin plate. The results demonstrate that the flame propagation for all plate configurations can be divided into four typical stages, i.e. hemispherical flame, finger-shaped flame, jet flame and bidirectional propagation flame. For three plate configurations, the jet flames merge together under the effect of the vortices, and the more slits with the same blockage ratio (BR) do not mean the stronger deflagration. It is observed that the peaks of flame tip speed and pressure growth rate decrease with the increase of the number of slits. The sub-grid scale combustion model, Power-Law model, coupled with sub-grid scale viscosity model, dynamic Smagorinsky-Lilly eddy viscosity model can well reproduce the flame propagation. By analyzing the numeric flow structure, the flame propagation mechanism of premixed methane/air flame propagation in a tube with various slits can be explained in the view of pure hydrodynamics.

1. Introduction

The flame acceleration in a confined space has much practical utilization ranging from explosion safety to the development of pulse detonation engines (PDEs) [1]. It is hoped that a detonation wave can be initiated by accelerating the flame propagation in a small device [2], and the combustion channel mounted with a plate possessing slits to generate free jet flames may be an effective choice. The coupling of the moving flame and the vortex induced by a thin plate will disturb the flame and increase its surface area, in turn, the pressure growth rate [3–5]. Therefore, the profound comprehension of the flame-vortex mechanism is essential for industrial safety.

Over the past years, significant efforts have been devoted to understand the effects of obstructions on premixed flame propagation in explosion combustion chambers. Masri et al. [6] confirmed that the thin plate with square cross-sections results in the fastest flame acceleration followed by circular and triangular cross-sections, and the flame speed increases with increasing BR. Yu et al. [7] revealed the triangular hollow-square thin plate leads to the highest flame turbulence intensity, flame propagating velocity, and explosion overpressure, followed by the square hollow-square thin plate, whereas the circular hollow-square thin plate results in the lowest values. Hall et al. [8] pointed out that the peak overpressure will reach a limit with increasing thin plate number and higher overpressures are obtained when the thin plates are stacked closer. Di Sarli et al. [9] investigated the vortex structure behind the obstacle using the particle image velocity method (PIV), and suggested that the large-scale vortex plays the dominant role in the evolution of the flame structure along the path.

However, it is difficult to understand the accurate mechanism of flame propagation only by the experimental method. Thanks to the growing computational performance of parallel computers, large eddy simulation is becoming a standard tool modeling the flame dynamics in an obstructed chamber owing to the improved prediction of turbulence and the flame-vortex interaction, with respect to the classical RANS methods. Nevertheless, LES does not resolve the flame front on the computational grid when the premixed flame thickness is smaller

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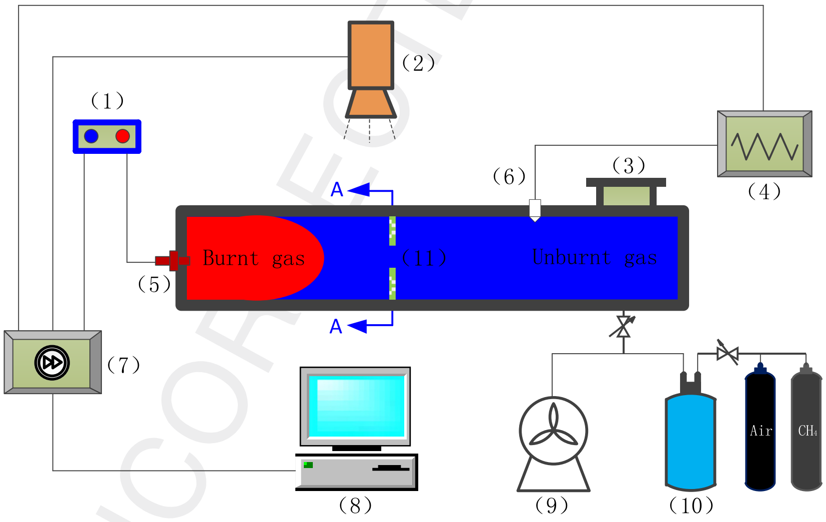
than the grid size used. To overcome this difficulty, various SGS combustion models, such as power-law flame wrinkling model, flame surface density model (FSD) and turbulent flame speed closure model (TFC), have been developed and validated to model the flame-vortex interaction. Xu et al. [10] simulated premixed methane/air deflagration in an obstructed chamber using the TFC model and satisfactory agreements between the experimental data and numerical predictions were achieved. The flame surface density model (FSD) was performed by Johansen and Ciccarelli [11] to model premixed flame propagation through the obstacles. Recently, Charlette et al. [12] proposed a power-law flame wrinkling model for premixed turbulent combustion. Di Sarli et al. [13] compared the prediction ability of different SGS combustion models, and the numerical results demonstrate that the power-law flame wrinkling model provides satisfactory predictions in terms of flame speed and pressure peak and corresponding time.

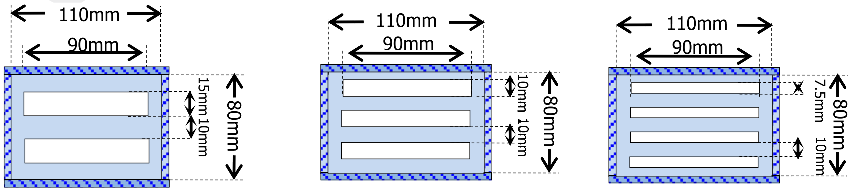
The aim of this paper is to investigate the effect of slits embedded in a thin plate with the same BR on premixed methane/air flame. Firstly, experiments are carried out to examine the flame dynamics for stoichiometric methane/air mixture. Then the power-law wrinkling combustion model coupled with dynamic Smagorinsky-Lilly eddy viscosity model is performed to reveal the vortex structures of flow field.

2. Experimental apparatus

Experiments were performed in a constant volume combustion channel shown in Fig. 1 (a). The long channel is consisted of a high-speed photography system, a pressure recording system, a gas mixing system, a high-voltage ignition system and a synchronization controller. The combustion vessel is a closed rectangular duct 80 mm × 110 mm by 500 mm long, and the two lateral panels of the duct are constructed of quartz glass for allowing optical access, while the upper and lower walls are made of stainless steel. As shown in Fig. 1(b), three 4 mm-thick different kinds of thin plates are equipped at 210 mm from the ignition electrode respectively in the three set of tests, and the thin plates BR are equal to 0.7. A discharge vent is set up close to the right end of duct for safety. The three set of tests are performed using stoichiometric methane-air, which was prepared by mixing 99.9999% pure methane and dry air in a separate gas mixing device. The residual gas left by last test was evacuated by a vacuum pump before methane-air is fed into the duct through an isolating valve. A discharge vent set up close to the right end of duct was sealed by a thin PVC membrane ruptured during deflagration of flame. The combustible mixture is allowed to become quiescent by incorporating a short time delay (approximately 60 s) into the gas filling sequence before ignition. The mixture is ignited by high-energy igniter located at the center of the left end of the chamber with energy in the range of 3–20 J. The change of flame shapes and position is recorded by high-speed camera which was operated at 960 frames per second. A PCB piezoelectric pressure transducer (model 112A05) mounted at 420 mm (6) from the ignition point in horizontal direction respectively is used to record the pressure value in the duct.



(a) Experimental apparatus



(b) A-A section

Fig. 1. Schematic diagram of the experimental apparatus: (1) spark igniter; (2) high-speed video camera; (3) discharge vent; (4) data recorder; (5) ignition electrode; (6) pressure transducer; (7) synchronization controller; (8) computer; (9) vacuum pump; (10) gas mixing device; (11) thin plate.

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