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Further investigation on the enhancement of flame speed in vortex ring combustion

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Abstract

Enhancement of flame speed in vortex ring combustion has been investigated experimentally. The flame speed and the maximum tangential velocity for each vortex ring were simultaneously measured with a PIV system and a high speed camera. To vary the extent of the enhancement, methane/hydrogen mixtures were used. Furthermore, rich mixtures were used as a source of vortex ring so that the situation of the experiment and the results could be applied more directly to practical use. Results have confirmed that enhancement of flame speed does occur in vortex ring combustion of rich methane/hydrogen mixtures in air. The extent of the enhancement becomes larger as the hydrogen content is increased. The flame speed reaches about twice as high as the maximum tangential velocity for pure hydrogen. Based on momentum conservation across the flame, a simple equation on the ratio of the flame speed to the maximum tangential velocity has been obtained, which has shown that the flame speed enhancement can be explained successfully by considering the spherically expanding type premixed combustion behind the flame. The pressure rise of a spherically expanding type premixed flame can explain the flame speed enhancement observed in the present rich methane/hydrogen vortex ring combustion.

Keywords: Vortex; Vortex ring; Flame speed; Vortex bursting; Flame propagation

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1. Introduction

A unique phenomenon in flame–vortex interaction is a rapid flame movement along a vortex axis [1,2]. The mechanism is truly of aerodynamic origin [3], and hence, completely different from the premixed flame propagation.

In these past decades, many experimental, theoretical, and numerical studies have been made on this subject [4–17] and it is now generally accepted that the flame speed is almost equal to the maximum tangential velocity in the vortex [18]. In vortex ring combustion of rich hydrogen/air mixtures, however, the flame speed becomes much higher than the maximum tangential velocity if the combustion occurs in the open air atmosphere [19]. For rich conditions, with an increase of the equivalence ratio, the flame speed increases and approaches the value predicted by Chomiak [3] as

$$V_{\mathrm{f}} = V_{\theta\max}\sqrt{\frac{\rho_{\mathrm{u}}}{\rho_{\mathrm{b}}}} \qquad (1)$$

in which V_{f} is the flame speed, $V_{\theta\max}$ is the maximum tangential velocity of the vortex, ρ_{u} and ρ_{b}

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are the densities of the unburned and burned gases, respectively [see Fig. 5 of Ref. [19], Fig. 38 of Ref. [18]]. In the case of lean or stoichiometric mixtures or in an inert nitrogen atmosphere, the flame speed is almost equal to or below the maximum tangential velocity [19]. Thus, the secondary combustion between the excess fuel and the ambient air is suspected to enhance the flame speed.

This enhancement seems useful from a practical viewpoint, because it may shorten the combustion time in practical combustors. Therefore, the phenomenon should be studied in more detail. In the previous study [19], however, determination of the maximum tangential velocity was not so rigorously made; first, the maximum tangential velocity was determined with a LDV system, and next, using an averaged relationship between the maximum tangential velocity and the translational velocity of the vortex ring, the maximum tangential velocity was estimated. Thus, rigorously speaking, the enhancement itself has not yet been confirmed.

In this study, the flame speed enhancement is further investigated with attention to the following three points. First, simultaneous measurements have been made with use of a PIV system and a high-speed video camera, which yields the flame speed and the maximum tangential velocity for each vortex ring. Second, to clarify the mechanism, mixtures of methane and hydrogen are used as fuel. Because such enhancement could never be observed in methane, whereas it does occur in rich hydrogen/air mixtures, the extent of the enhancement can be varied by changing the hydrogen content in the methane/hydrogen mixture. Third, to make the present experiments relevant to practical combustors such as the direct injection gasoline engine or the fuel-sprayed diesel engine, very fuel-rich mixtures are used as a source for generating vortex rings. Although pure fuel is much better in practical use, the flame speed in the vortex ring combustion of pure fuel reported is low [20] and a location for ignition seems to be quite limited in space. Thus, rich fuel/air mixtures are used as the source of vortex ring in this study.

2. Experimental

Figure 1 illustrates the experimental setup. It consists of a vortex ring generating system, a PIV measurement system, a high-speed video system, and an ignition system. In the previous study [19], the cylinder and piston diameter was 100 mm, but in this study, a larger cylinder and piston diameter of 160 mm was used to generate vortex rings. Methane, hydrogen, and air were supplied from cylinders. The flow rates of these gases were measured with orifice flow meters, and a mixture of methane, hydrogen, and air was fed to the cylinder. The hydrogen molar fraction in the methane/hydrogen fuel is defined as $\alpha \equiv [H_2]/([CH_4] + [H_2])$, in which $[CH_4]$ and $[H_2]$ are the supplying flow rates of methane and hydrogen, respectively.

When the piston moved rapidly from left to right, the shutter opened, and a vortex ring was forwarded into the open air. The vortex strength (the maximum tangential velocity) was varied by changing the driving pressure to the piston and also by changing the orifice plate with different orifice diameter D_o. In this work, three plates of $D_o = 40$, 50, and 60 mm were used. The piston stroke and the driving pressure were fixed at 10 mm and 0.6 MPa, respectively. The maximum tangential velocities available were from 5 to 15 m/s. A different point from the previous vortex generator is that the shutter is placed just inside of the orifice, whereas the shutter was located downstream of the orifice; hence, the ambient air is entrained into the vortex at its early stage. This entrainment improves the ignitability of the vortex ring of very fuel-rich mixtures.

Flow velocity profiles were measured by means of a PIV system (TSI Inc.), which was composed of a double-pulsed Nd:YAG laser (15 Hz, 120 mJ at 532 nm), a high-resolution CCD camera (1280 × 1024 pixels, 10-bit grayscale), a host computer, and a tracer particle supply apparatus. To measure the tangential velocity profiles in the vortex ring, the laser sheets were directed to the vortex ring along the X–Y plane, i.e., with the sheets containing the cylinder centerline, as shown in Fig. 1.

Measurements of flame speed were implemented through direct photography with a high-speed video camera (Kodak HS-4540) enhanced by an image intensifier (NAC ILS-3). The photographing speed was fixed at 4500 frames/s.

A spark ignition system for gasoline engines was used to ignite the vortex ring. The electrodes were set at 350 mm away from the orifice. A digital pulse generator was used to synchronize the PIV system, the high-speed video system, the igniter, and the electromagnetic valve for the compressed air to the piston. The CCD camera of the PIV system was focused on an area just upstream the electrode, while the whole combustion process was recorded by the high speed video camera from the direction opposite the X-axis, as shown in Fig. 1.

3. Results

3.1. PIV measurements

Figure 2 shows the typical velocity vector profiles of a cold vortex ring. In this figure, the vortex ring moves from the left to the right. It is seen that a pair of very narrow core is formed.