Characteristics of Flow Field and Flame Propagation in a Vortex Ring

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Introduction

The characteristics of flame propagation in a vortex core and the interaction between the vortex and the flame are very important for understanding turbulent combustion(1), for modeling the combustion in a spark-ignition engine(2), and for realizing stable combustion of very lean mixtures(3) and very high-intensity of combustion(4). It is pointed out that the flame speed in the vortex ring is significantly related to the maximum rotating velocity in the vortex ring(5~9). However, the relationship between the flame speed and the maximum rotating velocity is hardly examined because it is very difficult to measure the rotating velocity in the vortex ring. So far the flow field in the vortex ring was measured by the hot wire anemometer(7,10). However, there are some problems on the characteristics of response of the probe and disturbance of the flow field by inserting the probe in this method. The structure of the vortex ring complicates due to the conditions that the vortex ring is formed. Therefore, it is necessary to measure simultaneously the profile of the rotating velocity, the moving velocity, the diameter of the vortex core and the flame speed in the vortex ring in order to examine exactly the relationship between the flame speed and the maximum rotating velocity. In this study, the characteristics of flow field in the vortex ring are examined in detail using a particle image velocimetery (PIV) and the relationship between the flame speed and the maximum rotating velocity in the vortex ring is discussed.

Experimental Apparatus

Figure 1 shows the layout of the experimental apparatus. The flow field in the vortex ring was measured by analyzing the PIV images which were taken using the laser and CCD camera. The vaporized small particles of silicon oil were used as a tracer in order to take the PIV images. Shadowgraphs with a camera speed of 4500 frames/s were taken in order to obtain the flame speed in a vortex ring. Methane was used as the fuel. Since the electromagnetic valve, the electric spark igniter, the high-speed video camera, the laser and CCD camera are operating by the timing controller, the moving velocity, the profile of the rotating velocity, the flame speed and the diameters of the vortex core and the vortex ring can be simultaneously obtained in this system.

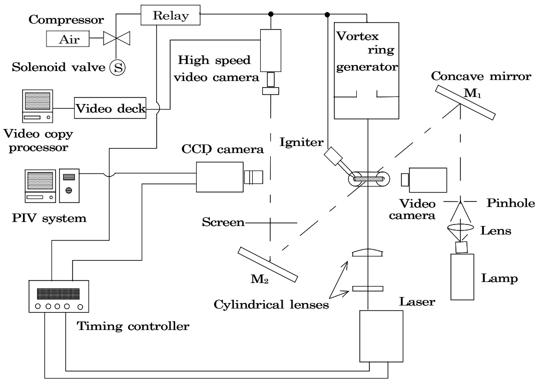
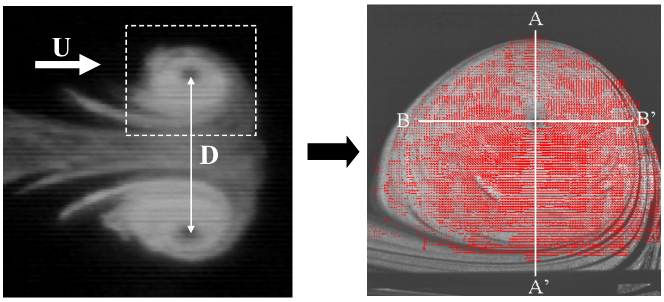


Fig.1 Layout of experimental apparatus



(a) Visualized vortex ring

(b) PIV image

Fig.2 Visualized vortex ring and PIV image

Experimental Results and Discussion

Characteristics of flow field in a vortex ring

Figure 2 shows the visualized vortex ring and the PIV image. The vortex core and the wake region can be seen in Fig. 2. The vortex ring moves downstream simultaneously releasing the vortex in the wake region. The Reynolds number $Re = UD/\nu$, which depends on the moving velocity U, the diameter D of the vortex ring and the kinematic viscosity ν, is 25,639. It is pointed out that the vortex ring undergoes a transition from the laminar to the turbulent regime at Re = 600(11). It seems that the vortex ring shown in Fig. 2 is in the regime of high turbulence. The upper side vortex of the paring vortex was taken as the PIV image in order to get high resolution, as shown in Fig. 2-(b). The velocity vectors shown in the PIV image are the compound vectors of the rotating velocity and the moving velocity. Thus, we must separate the compound velocity into both the rotating velocity and the moving velocity from the PIV image.

The circle marks (○) in Fig. 3 show the velocity profile at the vertical section (A-A') shown in Fig. 2. Abscissa in Fig. 3 describes the radial distance from the center of the vortex. First, the velocity profile was corrected on base of the assumption that the maximum rotating velocities in the positive and negative regions of r are equal each other. The results obtained from the above method are shown by the dark circle marks (●) in Fig. 3. Second, the direction of the rotating velocity are the same as that of the moving velocity in the region of $r \geq 0$ so that the compound velocity V is given by $V = V_\theta + U$ in this region. On the other hand, since the direction of the rotating velocity opposes to that of the moving velocity in the region of $r < 0$, the compound velocity is given by $V = V_\theta - U$ in this region. Therefore, the moving velocity is given by $U = ((V_\theta + U) - (V_\theta - U))/2$. The rotating velocity was obtained using the compound velocity V and the moving velocity U. The results obtained by the second method are shown by the square marks (□) in Fig. 3. The profile of the rotating velocity V_θ obtained by the first method is good agreement with that obtained by the second method. The difference between velocities described by the circle marks (○) and those given by the drake circles marks (●) and the square marks (□) is the moving velocity U.

Figure 4 shows comparison the moving velocities U obtained from the PIV image using the second method described above with those U_v obtained from the visualized image using the smoke from a joss stick. The moving velocities U obtained from the PIV image is good agreement with those (U_v) obtained from the visualized image. Not only the maximum rotating velocity and the diameter of the vortex core but also the moving velocity of the vortex ring can be obtained from the PIV images.

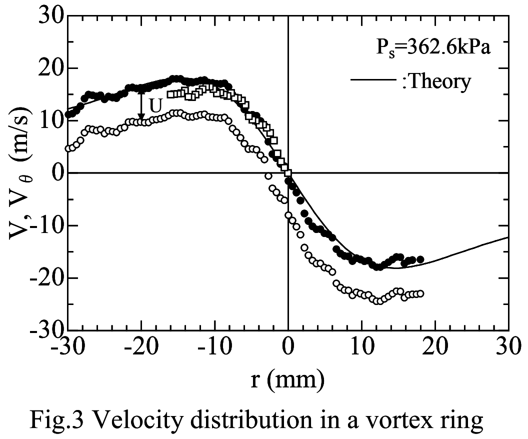


Fig.3 Velocity distribution in a vortex ring

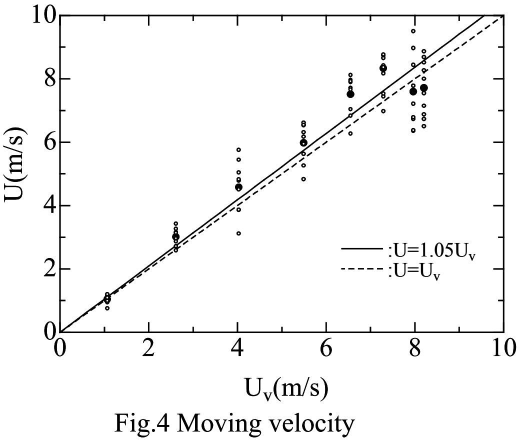


Fig.4 Moving velocity

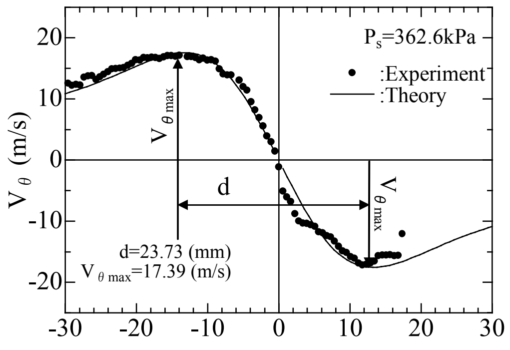
Figure 5 gives the profile of the rotating velocity at the vertical (A-A') and the horizontal (B-B') sections shown in Fig. 2. The profile and the maximum value of the rotating velocity at the vertical section are different from those at the horizontal section. The profiles of the rotating velocity, however, at each section are good agreement with that of Burger's vortex. It is valid that the profile of the rotating velocity at the model of flame propagation in the vortex tube is assumed by that of Burger's vortex.

Figure 6 shows relationship between the moving velocity U and the diameter d of the vortex core. The core diameter d is increased with increasing U. The core diameters obtained from the velocity profile at the vertical section are different from those obtained from the velocity profile at the horizontal section because the shape of the vortex is not symmetric with respect to the center of the vortex, as shown in Fig. 2. The ratios d/D of the diameter of the vortex core to that of the vortex ring are about 21.0 ~ 33.7 %.

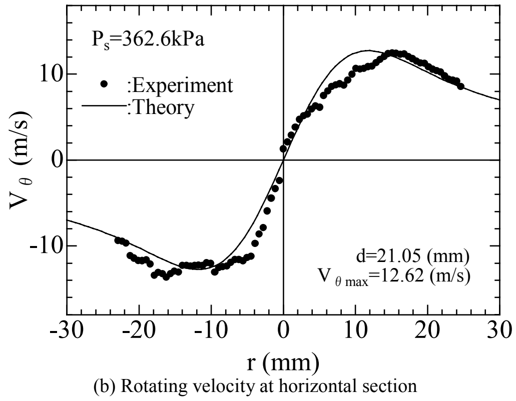
Figure 7 shows relationship between the moving velocity and the maximum rotating velocity $V_{\theta\,\max}$. The maximum rotating velocity $V_{\theta\,\max}$ is linearly increased with an increase in the moving velocity U. The experimental results are not agreement with the theoretical one by Lamb(12) ,but are good agreement with that by Tung and Ting(13).

Characteristics of flame propagation in a vortex ring

Figure 8 shows relationship between the maximum rotating velocity $V_{\theta\,\max}$ and the flame speed V_f. The maximum rotating velocity $V_{\theta\,\max}$ and the flame speed V_f shown in Fig. 8 were simultaneously measured. There are small scatters of V_f when $V_{\theta\,\max}$ is small, but are large scatters of V_f when $V_{\theta\,\max}$ is large. The experimental results in the cases of the equivalence ratios $\phi = 0.98$ and 1.20 are agreement with the theoretical results by Ishizuka(7).



(a) Rotating velocity at vertical section



(b) Rotating velocity at horizontal section

Fig.5 Rotating velocity in a vortex ring

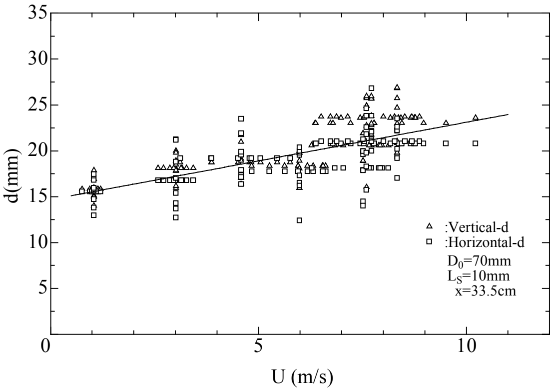


Fig.6 Relationship between moving velocity and core diameter

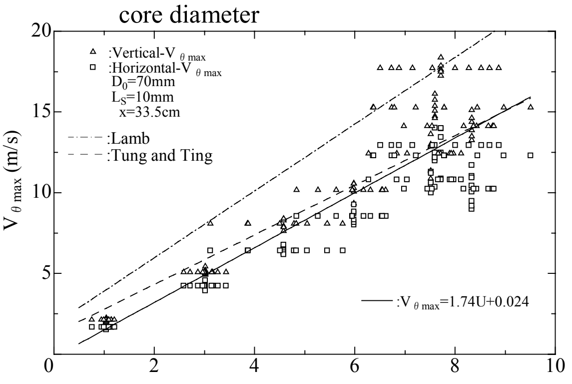


Fig.7 Relationship between moving velocity and maximum rotating velocity

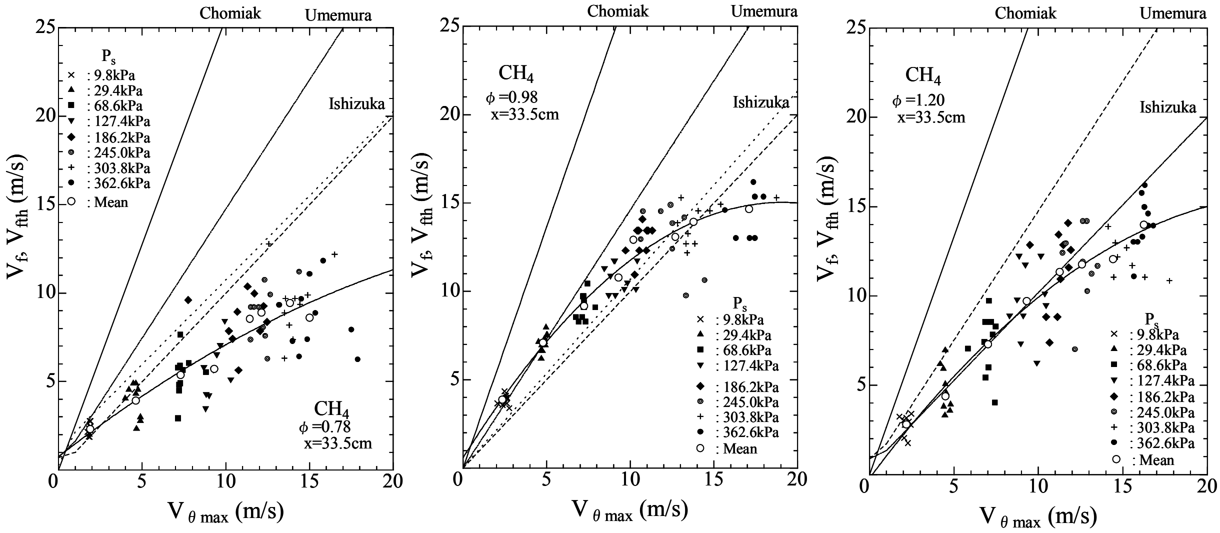


Fig.8 Relationship between flame speed and maximum rotating velocity

However, the result of $\phi = 0.78$ is not agreement with all theoretical results by Chomiak$^{(5)}$, Umemura ea al.$^{(6)}$ and Ishizuka$^{(7)}$. The difference between the experimental and the theoretical results becomes large with increasing the maximum rotating velocity and becoming lean in the mixture.

Conclusions

(1) The profile of the rotating velocity in the vortex ring is good agreement with that of Burger's vortex. The method that the moving velocity of the vortex ring can be obtained from the PIV images is proposed.

(2) Relationship between the moving velocity and the maximum rotating velocity in the vortex ring can be predicted by the theoretical equation by Tung and Ting.

(3) The model of flame propagation in the vortex tube proposed previously cannot predict accurately the flame speed in the cases in which the maximum rotating velocity becomes large and the mixture is lean.

References

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