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Investigations of Three-dimensional Flow Characteristics in a Liquid Ramjet Combustor Using the PIV Method

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Abstract: Three-dimensional flow characteristics in a liquid fuel ramjet combustor were investigated using the PIV method. The combustor had two rectangular inlets that form a 90-degree angle with each other, with intake angles of 30 degrees. Three guide vanes were installed in each rectangular inlet to improve flow stability. The experiments were performed in a water tunnel test with the same Reynolds number as Mach 0.3 at the inlet. PIV software was developed to measure the characteristics of the flow field in the combustor. Accuracy of the developed PIV program was verified with a rotating disk experiment and standard data. The experimental results showed that the two main streams from the rectangular intakes collided near the plane of symmetry and generated two large longitudinal vortices, which was in agreement with three dimensional computational results. A large and complex three-dimensional recirculating flow was measured behind the intakes.

Keywords: ramjet, combustor, PIV, vortex, recirculation.

1. Introduction

Advantages of the liquid ramjet engine are that it reduces the size and weight of a launching site and increases the flight distance due to a direct inhalation of air and an oxidizer from the atmosphere (Kubota and Kuwahara, 1996). Recent attention has focused on the integrated liquid ramjet engine whose combustor is utilized as a booster instead of using a subsidiary booster to achieve the required ram air. The objective of the combustor design of the liquid ramjet engine is to maintain stable and efficient combustion with (Eriksson et al., 1993; Ristori et al., 1999) a variation in the intake flow field according to various flight conditions. The combustion regime in the combustor can be categorized into the areas of stabilizing and propagating the flame. The design of the combustor is required to obtain the structure of stabilizing the flame, which is executed by forming the recirculation areas within the combustor.

In this study, the three-dimensional flow field characteristics of the ramjet engine combustor were investigated to determine the configuration and size of the recirculation zone. To achieve this purpose, PIV software was developed to measure the characteristics of the complex flow field in the combustor and the accuracy of the developed PIV program was verified.

2. Experiments

Several configurations of the test sections of the combustor were manufactured to determine the optimum design of the liquid ramjet engine. Figure 1 shows one of the test sections with the two intakes of the rectangular duct

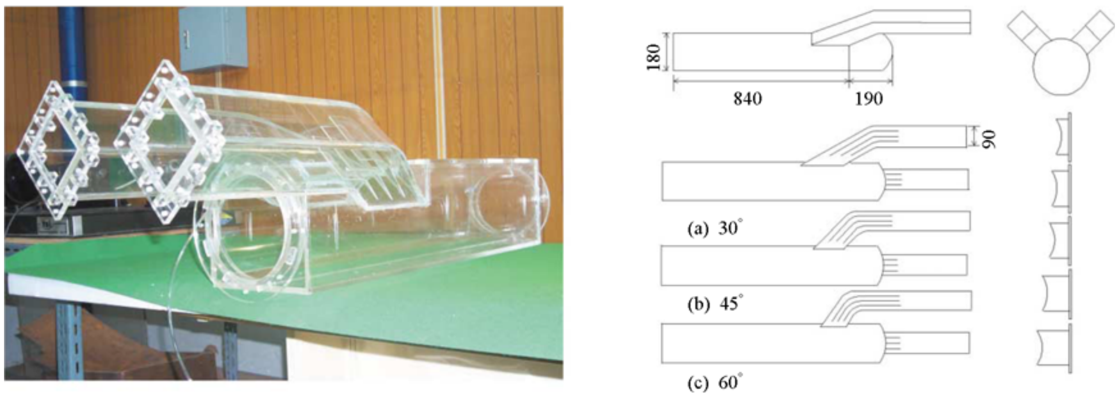

Fig. 1. Photograph of the test section and the combustor configurations with different intake angles and dome sizes.

forming a 90 degree angle with each other. The tested angles of the air intakes were 30°, 45° and 60°. Each of the test sections was changed to accommodate the sizes of the recirculation zones. Thus the characteristics of the flows corresponding to the various recirculation zones were examined. Additionally, 3-guiding vanes, 2 mm thick, were installed at the intersection of the air intakes and combustor to stabilize the fluid flow. The experiments were performed in a water tunnel test with the same Reynolds number as Mach 0.3 at the inlet.

PIV software was developed based on the correlation method (Adrian, 1988, 1991, 1997; Raffel et al., 1998; Prasad et al., 1992; Westerweel, 1993). The verification of the PIV software was performed using two benchmarks. For the first benchmark, particles were put on a circular plate as shown in Fig. 2 and rotated with a constant velocity of rotation. Measurements of the particles' velocities through the PIV method in Fig. 3 are compared to the theoretical velocities. The maximum error falls within 0.7 percent.

Fig. 2. Rotating disk for accuracy test of PIV S/W.

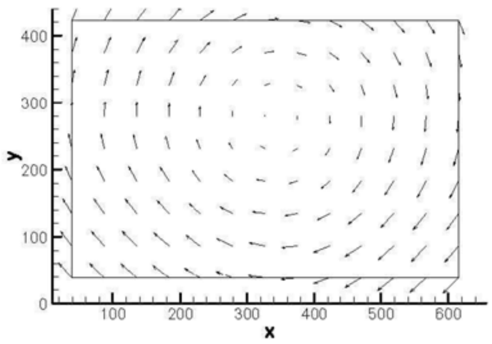

Fig. 3. Predicted velocity vectors for rotating disk.

The standard data and image data of two-dimensional wall shear flow obtained from the Japan Flow Visualization Association (Hu et al., 1998) were used as the second benchmark. The standard data and image data represent the quantitative velocity vectors and the pictures taken by a CCD camera, respectively. Figure 4 shows the velocity vector provided by standard data while Figure 5 shows the predicted velocity vector from the standard image data.

The range of errors falls within 1.8%, which is large compared with the errors of the first benchmark. This is due to a small interrogation area (16×16 pixel). Other factors may be the sizes of the particles and the displacement of the maximum particle.

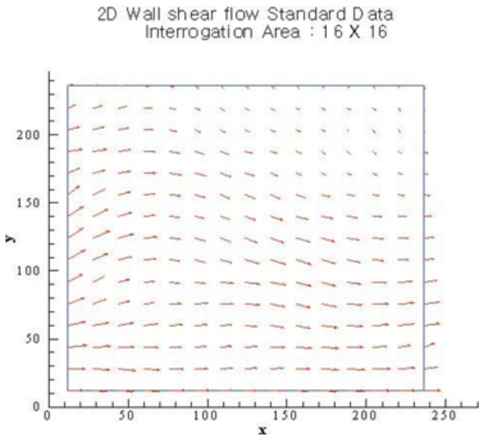

Fig. 4. Velocity vectors of standard data.

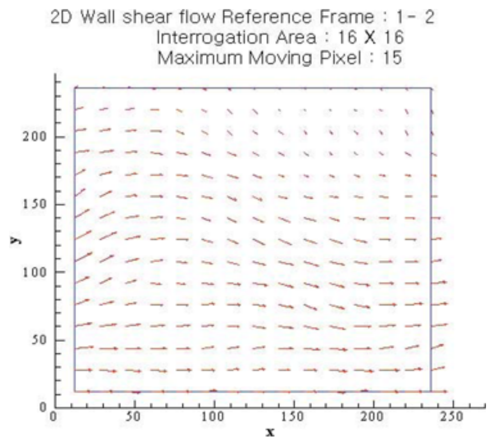

Fig. 5. Predicted vectors from standard image data.

The schematic of the experimental apparatus is shown in Fig. 6. The fluid is introduced to the open tank from the closed tank by the pump. The flow control valve established between the closed tank and the pump plays a role in controlling the amount of flow, with the closed tank reducing the oscillation in the pump. The fluid is introduced from the closed tank, through the test section and to the open tank. A duct, 700 mm long, is set between the closed tank and the test section to obtain uniformity of the fluid. The by-pass valve and the manometer are set up at the positions of 5 and 4 to control the speed of flow and to measure the amount of flow, respectively. The measurements of pressure are performed at the two locations of the intake and the four locations of the combustor.

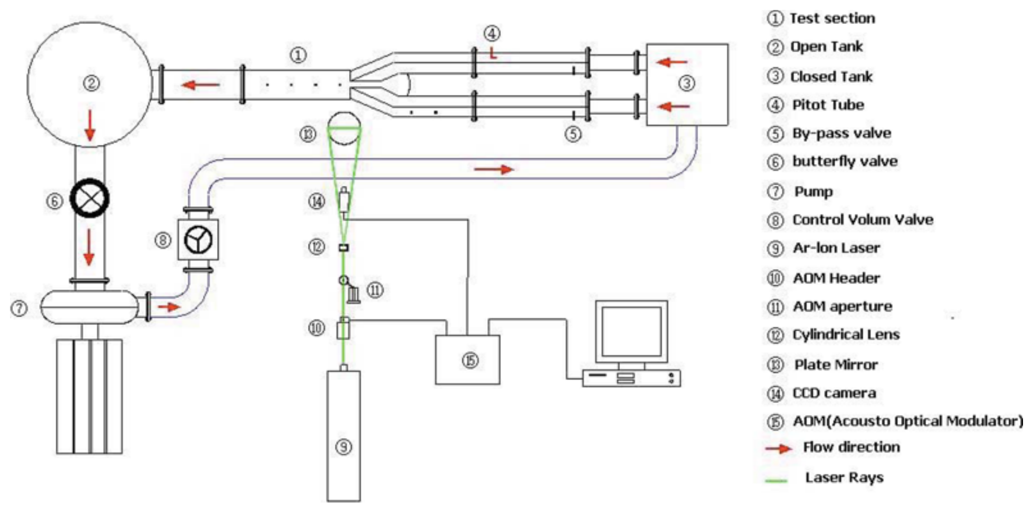

Fig. 6. Schematic diagram of experimental apparatus.

An Ar-Ion laser is utilized as a light source of the PIV system to measure velocity. The light is divided into pulse light and direct light through an AOM header, the pulse light being diffused by an aperture. The plane light through the cylindrical lens is controlled by a plate mirror. The picture is taken by a CCD camera when the flow particles pass through the light. The photograph is converted from an analog image to a digital image by a frame grabber. The digital image is mapped into the velocity vector, utilizing the PIV software.

3. Results and Discussion

Figure 7 shows the location and range of the measurements in the ramjet combustor by PIV. The range of measurements covers the areas from the end of the dome to the position of 956 mm while the measurements are executed at the sections of 0 mm, 30 mm and 60 mm from the symmetric section.

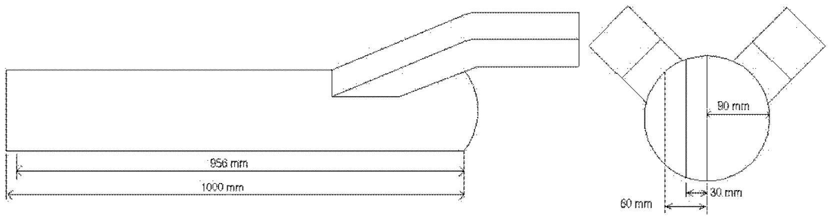

Fig. 7. Range and sections of measurement in the ramjet combustor.

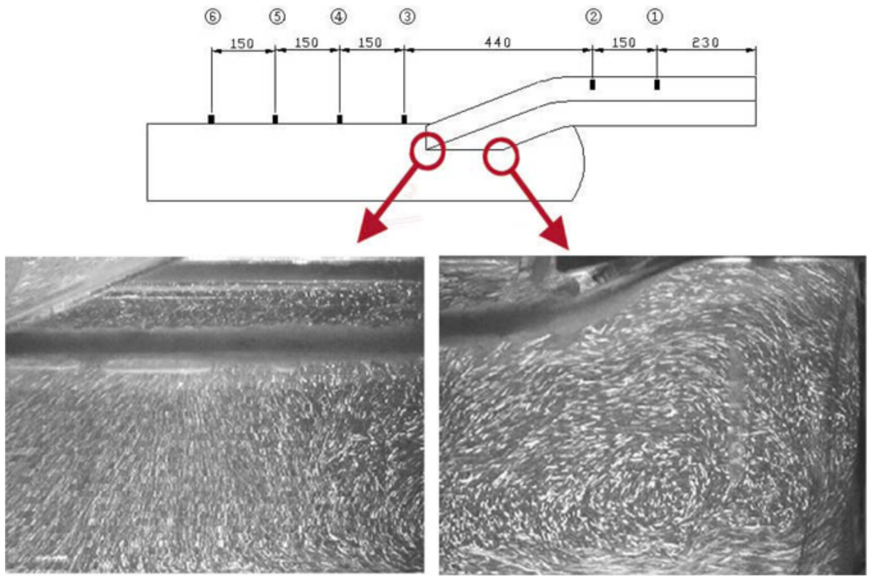

Fig. 8. CCD images of streaklines near the contact area with an intake and combustor and recirculation zone.

The CCD images of streaklines near the contact area with an intake and combustor are shown in Fig. 8. Traces of particles present the characteristics of the flow in the combustor. The CCD image of the recirculation zone indicates the recirculating flow patterns which affect the stability of the flame. It is observed that the trajectories form large swirling flows.

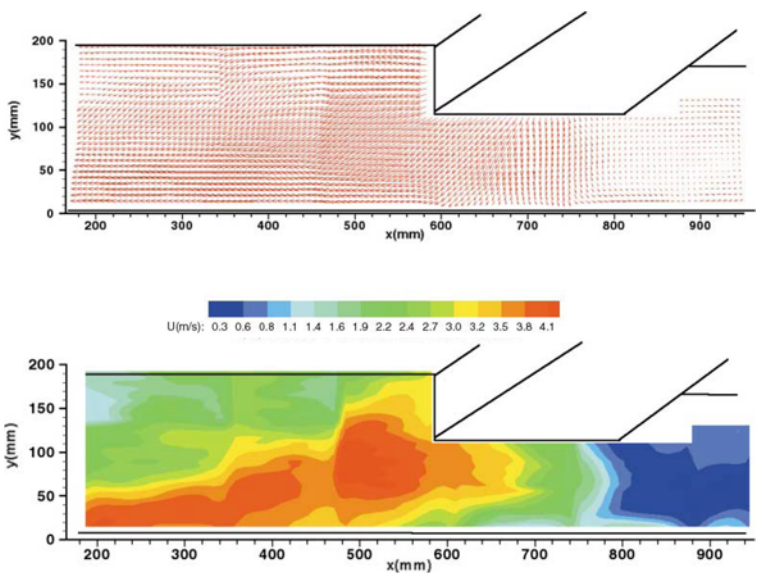

Fig. 9. Velocity vectors, traces and contour of U-velocity at the plane of the symmetric section (z = 0).

Figure 9 presents the velocity vectors and particle trajectories of U-velocity at the symmetric section. One stream flows through the intakes into the combustor in a slanted direction and bounces off at the bottom of the combustor, thus proceeding into the outlet. At the same time, the other stream flows to the end of the dome, thus forming the recirculation zones. The stream from the upper part of the intake in the combustor passes along the wall and falls down into the lower wall of the combustor.

The flow characteristics at the symmetric section demonstrate that the fluid comes out of the intakes, passes along the angle of the intake and leaves the combustor through the outlet. The measurements of flow characteristics are executed at the positions 30 mm and 60 mm from the plane of symmetric section to observe the three-dimensional characteristics. Figure 10 shows the velocity vectors at the locations of 30 mm (top) and 60 mm (bottom) from the plane of the symmetric section, respectively. It is observed that the direction of velocity moves to the low wall and to the upper wall at the locations of 30 mm and 60 mm from the symmetric section, respectively. This is explained by the fact the flows introduced from the right and left intakes collide with each other, thus forming symmetrically large vortices which may be significantly affected by the angles of the intake. These flow patterns can be schematically drawn as in Fig. 11.

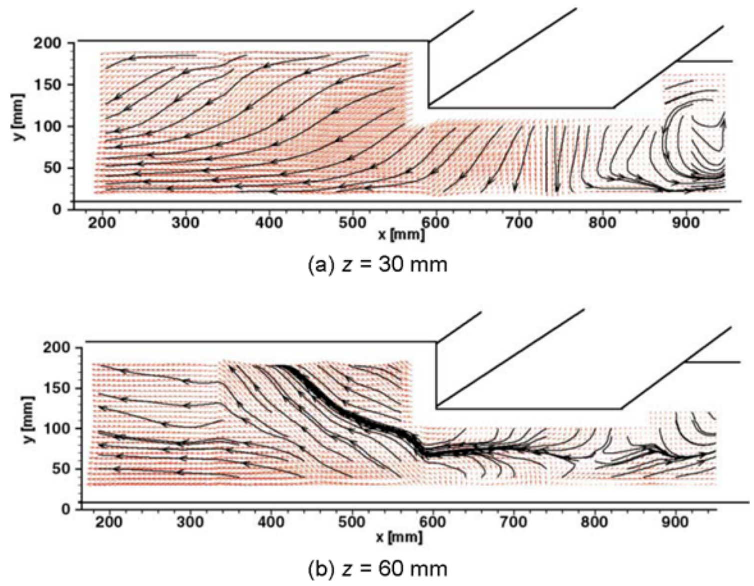

Fig. 10. Velocity vector at 30 and 60 mm from the plane of symmetry.

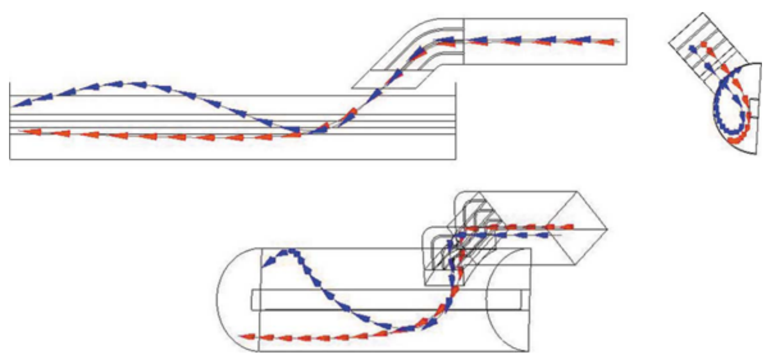

Fig. 11. Schematic flow patterns in the ramjet combustor.

Figure 12 shows the velocity vectors and contours with a variation in inlet angles. As the inlet angle increases, the region of low velocity is moved to an upper and backward position in the dome and considerably reduced. The inlet angle of 30 degree is the most suitable angle as a flame holder in our experimental ranges since one of main roles of the dome is a flame stabilizer in reducing velocity by recirculation.

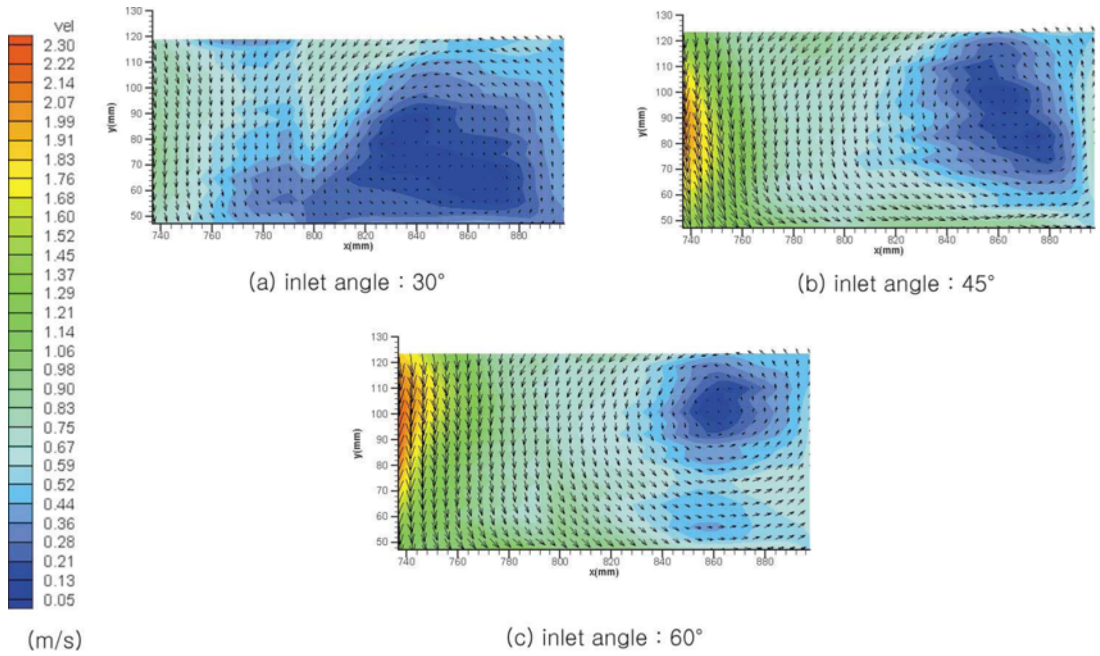

Fig. 12. Velocity vectors and velocity contours with a variation in inlet angles.

4. Conclusions

Three-dimensional flow characteristics in a liquid fuel ramjet combustor were investigated using the PIV method. The combustor has two rectangular inlets that form a 90 degree angle with each other, with intake angles of 30 degree. Three guide vanes were installed in each rectangular inlet and experiments were performed in a water tunnel test with the same Reynolds number as Mach 0.3 at the inlet. PIV software was developed and the accuracy of the developed PIV program was verified using two benchmarks.

The characteristics of the internal flows of the combustor are large swirling flows which appear symmetric with respect to the symmetric section. This is attributed to the fact that the flows introduced from the right and left intakes collide with each other, thus forming symmetrically large vortices. A large and complex three-dimensional recirculating flow was measured behind the intakes. An inlet angle of 30 degrees is the most suitable angle as a frame holder in the performed experimental ranges.

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