PIV measurement of flow characteristic in single-head combustor with triple-stage swirler

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Abstract. The present study investigates the flow field characteristic in a single-head combustor with triple-stage swirled, using particle image velocimetry (PIV). With pure air inlet flow, detailed mean and RMS velocities, turbulent intensity, vortices, Reynolds shear stress are obtained at several longitudinal and cross sections downstream of the swirled in the single-head combustor at flow temperature 300K and inlet combustor pressure 0.49MPa, 0.98MPa. It is seen from the investigation results that strong aerodynamic interactions among different kinds of combustor Eigen structures are existed. Multiple vortices are observed, accompanied with relevant recirculation zones. The effect of swirled is strong, and there are big and regular vortices in the cross sections in the downstream of the swirled 50mm away. The jet effect of main combustion holes and dilution holes is obvious, and the penetration of the jet flows are clearly deep with distinct effect on the flow field structure. It is shown that there are big size recirculation zones in the combustor flow field with high levels of turbulence generated due to triple-stage swirled, main combustion holes and dilution holes of the single-head combustor. It is helpful for promoting rapid mixing and stabilizing flame combustion.

1. Introduction

With the improvement of performance of aero turbine engine, the requirement for fuel atomization, mixing efficiency and flame stability is much rigorous than before, and the swirled stage develops from one to two, even three stages. Accordingly, the inner flow field of turbine engine combustor is quite complicated because of many kinds of aerodynamics structures. In order to understand the complex flow mechanism in turbine engine combustor and provide reference for design of advanced aircraft, the full field distribution of velocity and microscopic structure need to be measured accurately, especially with regard to the study of fuel injection, dilution, ignition, flame stabilization and combustion organization in combustor or afterburner[1-3]. According to the request of aero turbine engine for flame stabilization and efficient mixing fuel with air, kinds of combustor Eigen structures are necessary, such as swirled, main combustion whole, dilution hole with different parameters. As a result, it is difficult to obtain the inner flow field with wide-range velocity, strong rotational and turbulent characteristics [1, 4]. Usually, instantaneous full-field velocity distribution cannot be
obtained through traditional measure technology such as hot wire and pressure probe. Also, only discrete velocity distribution can be measured by laser Doppler velocimetry (LDV) through single point scan method. Benefit from the instantaneous, planar and non-contact nature of PIV [5], it is possible for people to obtain the instantaneous and full-field velocity distribution of complicated inner flow field in the combustor. Up to now, there are a number of successful cases adopting PIV in turbine engine combustor.

Bahrain et al have experimentally studied the swirling flow field in a realistically complicated geometry of a gas turbine combustor [6]. M Scholl et al have successfully applied PIV in highly luminous flames avoiding saturation of the second frame of commonly available double shutter PIV cameras. And the flow field structure of swirled is obtained with the condition of kerosene burning, 0.7MPa and 800K [7]. M Ahmed et al have studied the aerodynamic interactions between the primary air jets and the recirculation zone of a gas turbine combustor model, also the effect for pollutant emissions production such as CO, Knox is discussed [8]. N P Yadav and A Kushiro have presented an experimental investigation of non-reacting flow in a low aspect ratio dump combustor with a tapered exit, especially about effect of swirled on turbulent behavior [9]. The characteristics of swirled flow field, including cold flow field and combustion flow field, in gas turbine combustor with two-stage swirled are studied using PIV by Yan Yingwen et al [10]. In the study, velocity components, fluctuation velocity, Reynolds stress and recirculation zone length are obtained. Influences of geometric parameter of primary hole, arrangement of primary hole, inlet air temperature, and first-stage swirled angle and fuel/air ratio on flow field are investigated respectively. Wang Chinju et al have designed four kinds of triple-stage twirlers, and the corresponding investigation for the combustor flow field is carried out through PIV [4, 11].

The present study investigates the flow field characteristics of a single-head combustor with triple-stage swirled, using PIV technique. With pure air flow under normal temperature at 0.49MPa and 0.98MPa pressure, detailed mean velocities and streamlines, RMS velocities and turbulent intensity (TI), vortices and Reynolds shear stresses are obtained at various cross and longitudinal sections. And the affection for flame stabilization and mixing fuel with air is analyzed and discussed.

2. Experimental details

2.1. Experimental setup

The experimental investigations are conducted at the combustion facility in CARDC. Figure 1 shows the schematic diagram of the experiment system. In order to keep the tracer particles distributing uniformly in the combustor flow, the tracer particles are injected into the main flow about 1m upstream of the inlet of combustor. For the use of camera and laser sheet in PIV measurement, there is a T-branch pipe with quartz glass window at the outlet of combustor.

![Figure 1. Schematic diagram of experiment system.](image)

In the present work, air is fed from an air storage vessel at a maximum pressure of about 20 MP. And then, air passes through a nozzle. Downstream of the nozzle, air flows into the combustor through
triple-stage swirled, main combustion holes, and dilution holes. Leaving from the combustor, air flows up at 45 degrees into the exhaust pipe. For experimenters’ security, there is a special unit for particle gathering. The combustor has two side quartz windows for 116mm×86mm and one rear quartz window for 98mm×72mm.

The test model is shown in Figure 2. It is a rectangular single-head combustor with triple-stage swirled. The model is obtained from a wholly annular combustor by the way that flow velocity is constant. The inner Eigen structures are shown in Figure 3, which include fuel nozzle, triple-stage swirled, main combustion holes, dilution holes and lots of pin holes for air film cooling.

![Figure 2. Test model of combustor.](image1)

![Figure 3. Schematic diagram of characteristic of combustor.](image2)

2.2. Particle image velocimetry

![Figure 4. Schematic diagram of PIV system.](image3)
Figure 5. Schematic diagram of solid micro-particle generator for high pressure using.

Figure 4 shows the schematic diagram of PIV system used in the present work. The PIV system consisted of a frequency-doubled dual-cavity ND: YAG laser, a frame-straddling CCD camera (2048×2048 pixels) and a pulse synchronizer. The laser pulses have the duration of 10 ns and energy of 500 mg at 532 nm with 15Hz repeat frequency. After passing through sheet-forming optics, the laser beam has a height of approximately 100 mm and a thickness of 2 mm inside the combustor. The time separation between the two laser pulses is set to 4 is. Synchronization between the cameras, laser, and image acquisition is accomplished by the pulse synchronizer.

2.3. Tracer particles and seeding

It is clear from the principle of PIV that velocity measurement is based on images of tracer particles suspending in the flow. For the reasons of security and measurement accuracy, firstly the tracer particles have to trace the flow well. Secondly, they need to possess high scattering signal quality. At last, the tracer particles should provide such characteristics as non-toxin, non-cauterization, chemical stability and non-pollution. In experimental investigation, the adding particles should be small enough and have the similar density as fluid so as to trace flow well. However, if diameters of the adding particles are too small, the scattering signal will be poor, which is adverse for particles imaging. Thus, when choosing the tracer particles, all kinds of factors should be taken into account.

In general, choosing tracer particles should obey the following rules. The tracer particle density should be as similar to the fluid as possible. In the premise that the tracer particle can be imaged clearly, its diameter should be small enough. In present study, titanium dioxide (TiO2) powders are chosen for tracer particles. The powder nominal diameter is 0.3 μm, density is 4.26g/cm3, and melting point is 1840 °C with chemical stabilization.

In fact, tracer particles have strong tendency to form agglomerates which are several times larger than the nominal size, especially at the submicron or Nan levels as a result of humidity and prolonged storage. In order to break up agglomerates and obtain uniform particles distribution, a special high pressure particles generator based on principle of cyclone separation is designed. The schematic diagram is shown in Figure 5. When used in different work conditions, the injection pressure of particle-air mixture flow should be higher than that of main flow about 2 MP to ensure particles to be seeded into the combustor successfully.

3. Results and discussions

As mentioned above, there are kinds of Eigen structures in the test combustor model such as triple-stage swirled, main combustion holes and so on. The whole combustor inner flow field has the properties with wide-range velocity, strong rotational and turbulent flow due to the interactions among the swirled, main combustion holes, dilution holes. In order to make sure that the correlation between
particles image A and B is good enough for analysis, the particles displacement during frame straddling time $\Delta t$ should be appropriate, and the displacement off the laser sheet must be as small as possible. Thus, it is difficult to measure the combustor inner flow with highly three-dimensional character by 2D-PIV. And there are lots of other challenges for PIV measurement, such as seeding particles uniformly, pollution of windows, system parameters setting and image post-processing. In the present work, the combustor inner flow field velocities are measured by 2C-2D PIV. The different test conditions are listed in Table 1.

Table 1. Experimental conditions of single-head combustor test.

| Test conditions | Inlet pressure /MP | Inlet temperature /K | Inlet velocity /m•s$^{-1}$ |
|----------------|-------------------|----------------------|--------------------------|
| Middle pressure | 0.49              | 300                  | 13                       |
| High pressure   | 0.98              | 300                  | 13                       |

3.1. 0.49 MP Pressure test condition

Figure 3 shows the coordinates system used in the image processing of the experimental particles image. The positive direction of X axis is same as the inlet flow direction, and the positive direction of Y axis is toward the top of test model vertically, while the positive direction of Z axis points toward side window along radial direction of the swirled. The X, Y and Z axes meet the condition of right-hand rule, and the origin of coordinate’s lies at the outlet center of the swirled. In order to study the flow characteristics in the combustor, flow field velocities in several sections are measured, including longitudinal sections Z1, Z2, Z3 with Z coordinates -24.5mm, 0mm, 24.5mm respectively, and cross sections X1, X2, X3 with X coordinates 50.05mm, 67.2mm, 101.6mm. The real measurement areas are a little different to each other due to differences of system installation and reflection of model.

The result data corresponding to the cross sectional planes X1, X2, X3 downstream of the swirled are plotted together in a 3D cascaded view as shown in Figure 6-Figure 11. The ensemble-averaged velocity vectors and streamlines in several cross-sectional planes at different locations along X axis are shown in Figure 6 and Figure 7. Due to the effect of strong swirl flow, there is a big anticlockwise vortex. The cores of vortex in different planes are off X axis somehow. Along the X axis, the flow field velocities become higher gradually, accompanied with high velocity gradient. In the X3 plane far field downstream of the swirled, the velocities are observed to be having a maximum value of 35 m/s.

In sections X1 and X2, the velocity values in vortex’s left side region are higher than the right side for the reason that the flow direction of the vortex’s left side is from top to bottom, just as similar as the flow direction of the top main combustion hole in longitudinal section Z3. But in the right side region, the velocity values become lower because of inverse flow direction of the top main combustion hole in longitudinal section Z1 relative to the vortex. The velocity values at the bottom are higher obviously than other region due to the bottom center main combustion whole in longitudinal section Z2.

In section X3, the velocity values in vortex’s left side region are lower than the right side for the reason that the flow direction of the vortex’s left side is from top to bottom, just opposite to the flow direction of the bottom dilution hole in longitudinal section Z3. But in the right side region, the velocity values become higher because of similar flow direction of vortex and the bottom dilution hole in longitudinal section Z1. The velocity values in the top region are higher obviously than other region due to the top dilution hole in longitudinal section Z2. Besides, there is a complicated flow structure of irregular vortex in the top-left region due to the effect of the strong swirl flow and the dilution holes in longitudinal section Z2 and near the left side wall.
Figure 6. Mean velocity vector plots in cross sectional planes of 0.49 MP.

Figure 7. Mean velocity streamline plots in cross sectional planes of 0.49 MP.

The turbulent velocity fluctuations are obtained from lots of instantaneous flow field velocities. Through further computations, RMS velocity magnitude (RMS Mag) and TI can be obtained by the following definitions, where $u'$ and $v'$ stand for velocity fluctuations in Z and Y directions respectively, $\bar{u}$ and $\bar{v}$ stand for ensemble-averaged velocity in Z and Y directions respectively.

$$RMS\ Mag = \sqrt{u'^2 + v'^2}$$

$$TI = \sqrt{u'^2 + v'^2} / \sqrt{\bar{u}^2 + \bar{v}^2}$$

The RMS and TI contours obtained are shown in Figure 8 and Figure 9. Velocity fluctuations become stronger gradually along X axis, accompanied with stronger turbulent intensity. The TI is higher than 40% in most regions in each cross section, even close to 20 somewhere. It is shown that there is high turbulent intensity in combustor inner flow, and it is helpful for efficiently mixing fuel with air.
Figure 8. RMS velocity magnitude contour in cross sectional planes of 0.49 MP.

Figure 9. Turbulent intensity contour in cross sectional planes of 0.49 MP.

The mean vortices and Reynolds shear stress ($-u'v'$) contours obtained in various cross sections are shown in Figure 10 and Figure 11. The magnitude of mean vortices is observed to be varying from -2300 to 2300 s$^{-1}$ depending on the direction of circulation. There is negative vortices distribution in some regions along X axis due to effect of main combustion holes and dilution holes, and the swirling flow intensity is obvious strong nearby the center-line of swirled. Also, the turbulent characteristic of swirling flow is presented by Reynolds shear stress. There are higher levels of Reynolds shear stress distribution nearby the main combustion holes and dilution holes in cross sections X2 and X3, where the flow possesses high level of velocity gradient distribution. Thus, in real combustion condition the mixing impact among main combustion whole jet, dilution whole jet and main swirling flow is strong. It is helpful for rapidly, efficiently mixing fuel with air and promoting combustion efficiency.

Figure 10. Mean vortices contour in cross sectional planes of 0.49 MP.
Figure 11. Reynolds shear stress contour in cross sectional planes of 0.49 MP.

The result data corresponding to the longitudinal sectional planes at Z1, Z2, Z3 are plotted together in a 3D cascaded view as shown in Figure 12-Figure 17. The ensemble-averaged velocity vector fields and streamlines in several longitudinal sectional planes at different locations along Z axis under 0.49 MP pressure test condition are shown in Figure 12 and Figure 13. The velocities are observed to be having a maximum value of 70 m/s in different longitudinal sections, and there are higher levels of velocity distribution nearby the main combustion holes and dilution holes. In the center longitudinal section Z2, outlet flow velocity distribution of swirled is symmetric about the center line of swirled? It can be seen clearly that there is tapered swirling flow due to triple-swirled, and two symmetric small vortexes are formed in the top and bottom corners after meeting the main combustion whole backflow, accompanied with two small recirculation zones. Flow velocities of main combustion hole and dilution hole are higher than other regions, and they have deep penetration. There are two big vortexes due to interaction between main combustion whole jet and main swirling flow, together with big recirculation. Located at the outlet of combustor, a vortex is formed after the bottom main combustion whole jet meeting the top dilution whole jet, then flowing out of combustor. In section Z1, a S-shaped flow throughout flow field top and down is observed owe to effect of bottom center main combustion hole jet and swirling flow. The outlet flow velocity distribution of swirled is still symmetric about Y = 0 mm. and two symmetric small vortexes are formed in the top and bottom corners after meeting the S-shaped flow. A big vortex is formed nearby the top main combustion hole because of interaction between the main combustion whole jet and the S-shaped flow. Located at outlet of combustor, main combustion whole jet meets dilution whole jet, then flowing out of combustor downstream.

Also, in section Z3 an anti-S-shaped flow throughout flow field top and down is observed owe to effect of bottom center main combustion whole jet and swirling flow. It is a pity that effective flow field velocities nearby the swirled cannot be measured, as there is strong laser reflection of twirler’s polished surface.

Figure 12. Mean velocity vector plots in longitudinal sectional planes of 0.49 MP.
Figure 13. Mean velocity streamline plots in longitudinal sectional planes of 0.49 MP.

Figure 14. RMS velocity magnitude contour in longitudinal sectional planes of 0.49 MP.

Figure 15. Turbulent intensity contour in longitudinal sectional planes of 0.49 MP.

The RMS and TI contours obtained in various longitudinal sections are shown in Figure 14 and Figure 15. It is seen that there are lower levels of velocity fluctuations nearby regions of $X=40\text{mm}$ due to stable recirculation zone. And there are higher levels of velocity fluctuations nearby main combustion hole and dilution whole jet. The TI is about 20 in some regions in each cross section, even close to 45 somewhere.

The mean vortices and Reynolds shear stress contours obtained in various longitudinal sections are shown in Figure 16 and Figure 17. In sections Z1 and Z3, vortices nearby main combustion holes
appear in pairs, which means that the jets flow forward and backward simultaneously. In section Z2, there are also positive and negative vorticities in pairs, but the positive values is much higher. In the top region of section Z2, negative vorticities are dominant due to swirling flow effect. There are higher levels of Reynolds shear stress distribution nearby the regions of the center of swirled, main combustion holes and dilution holes, which are consistent with the distribution of Reynolds shear stress in cross sections X2 and X3.

![Figure 16. Mean vortices contour in cross sectional planes of 0.49 MP.](image)

![Figure 17. Reynolds shear stress contour in cross sectional planes of 0.49 MP.](image)

### 3.2. 0.98MPa Pressure test condition

In order to compare characteristics of engine combustor in different test conditions, 2D-PIV measurement is carried out for longitudinal section Z2 under combustor inlet pressure of 0.98 MP. The ensemble-averaged velocity vector fields and streamlines in longitudinal section Z2 under 0.98 MP pressure test condition are shown in Figure 18 and Figure 19. Compared with the situation of 0.49MPa pressure condition, there is also a big recirculation zone between swirled and main combustion hole, which lies in the region of X<70mm. And contra-flow can be seen along the center line. The flow field structure is similar as 0.49MPa pressure condition. It is shown that the inlet pressure has little effect on the flow field structure.
4. Conclusion
The present work investigates the flow field characteristics in a single-head combustor with triple-stage swirled by 2D-PIV. With pure air inlet flow, detailed mean and RMS velocities, turbulent intensity, vortices, Reynolds shear stress are obtained at several longitudinal and cross sections downstream of the swirled in the single-head combustor at flow temperature 300K. Complicated three-dimensional flow characteristics with strong swirling flow, multi-jet flow and wide velocity range are observed in the combustor. The test conditions include combustor inlet pressures of 0.49 MP and 0.98 MP under normal temperature.

A high pressure solid particle generator based on cyclone separation principle is designed, and appropriate tracer particles and seeding method are chosen. Then they are applied for PIV measurement of inner flow field of high pressure aero turbine engine combustor successfully. The measurement results show that there are multiple vortices in the inner flow field of the studied combustor, accompanied with relevant recirculation zones. The effect of swirled is strong, and there is big vortex anti-clockwise in cross section. The jet effect of main combustion holes and dilution holes is obvious; the jet flows have deep penetration, and have distinct effect on the flow field structure. Through the present research it is shown that there are big size recirculation zones in the combustor flow field with high levels of turbulence intensity generated due to triple-stage swirled, main combustion holes and dilution holes of the single-head combustor. And the strong aerodynamic
interactions among different kinds of combustor Eigen structures are existed. It is helpful for promoting rapidly mixing fuel with air and stabilizing flame combustion. The flow field structure under 0.98 MP pressure condition is similar as 0.49MPa pressure condition.

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