Effect of inlet pre-whirl on two-dimensional lobed mixer performance

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Abstract. The temperature field downstream the lobed mixer under different pre-whirl conditions was studied by numerical method. The influence of pre-whirl on the mixing performance and total pressure loss was summarized. The results show that large-scale streamwise vortices generated by the lobe structure are the key to the rapid mixing of core and bypass airflow. The inlet pre-whirl will strengthen the interaction between streamwise vortices, thus accelerating the mixing of core and bypass airflow. The mixing efficiency and total pressure loss of the lobed mixer increase with the inlet pre-whirl.

1. Introduction
The mixer is a mechanical device that mixes two streams of air of different pressures, temperatures and velocities. Among the many types of mixers, the lobed mixer can generate large-scale streamwise vortices that differ from other mixers because of the trailing edge presents a periodic petaloid shape. These streamwise vortices significantly enhance the performance of the mixer and accelerate the mixing between core and bypass airflow. Therefore, lobed mixers have obvious advantages over conventional annular mixers.

Many scholars have studied the mixing mechanism of lobed mixers since the lobed mixer was proposed. Povinelli et al. [1] found that large-scale secondary flow generated by radial pressure difference exists downstream of the lobe and the secondary flow is an important reason why the lobed mixer can enhance mixing. Anderson et al. [2] identified the existence of the secondary flow experimentally and proposed that the secondary flow forms a very strong vortex system, which dominates the flow mixing downstream of the lobe. Manning et al. [3] defined the shear vortex which is produced by velocity difference between primary and secondary flows as an orthogonal vortex and proposed that the orthogonal vortex plays a major role in mixing of flat-plate jets at velocity ratios greater than 1. Belovich et al. [4] then conducted a more in-depth study of the interaction between the streamwise vortex and the orthogonal vortex.

As mentioned above, the generation of the streamwise vortex caused by the special shape of the lobe is the key to the efficient mixing of the lobed mixer. Some scholars have studied the influence of the lobe geometry on the mixing effect of the lobed mixer. Skebe, Mao et al. [5] [6] studied the performance of lobed mixers with outlet shapes of arches, triangles and sinusoids, respectively, experimentally. Wu [7] et al. studied the influence of notch width-ratio of core lobe to bypass lobe on performance of lobed mixer. However, the flow of these studies was along the axis of the lobed mixer.
In the actual afterburner of a turbofan aero-engine, since the low-pressure turbo has a certain outlet airflow angle, the incoming flow from the low-pressure turbo enters the mixer with a certain inlet pre-whirl. Therefore, this paper will focus on the influence of inlet pre-whirl on the mixing performance of the lobed mixer using a numerical simulation method.

2. Numerical Method

Geometry Model. Considering the symmetry of geometry, a complete lobe region was chosen as the computational domain. The core and bypass culverts are all rectangular channels. The lobe height is H, the bypass culvert height is 1.5H, the core culvert height is 3H, and the length of the lobe trailing edge to the computational domain exit is 6.25H. The computational domain is illustrated in Figure 1.

![Figure 1. Geometry dimension of computational domain](image)

Computational Mesh. Considering the complex lobe geometry, hybrid meshes were applied to the computational domain. Unstructured grids were adopted around lobe, and structured grids were adopted for other domain. In addition, prism grids were applied in the upper and lower walls and lobed wall to adapt to the boundary layer flow. After verifying grid independence, the number of grids in this paper was determined to be 1.8 million.

Computational Method. Due to the limitations of computer memory and computing speed, RANS model was selected. Nathan J. C, et al. [8] applied different turbulence models to simulate the lobe jets and compared them to the experimental results measured with the DP-SPIV method by Hu et al. [9] It can be inferred that the Realizable k-ε model can more accurately predict the mixing of primary and secondary flows in the lobed mixer compared to the standard k-ε model, the SST k-ω model and the standard k-ω model. Therefore, the Realizable k-ε model was finally chosen to simulate the fluid mixing downstream the lobed mixer. The standard wall function was chosen as the processing method of near-wall flow. The SIMPLE algorithm was chosen as the coupling method between velocity and pressure. In order to improve the calculation accuracy, the convection terms were discretized with the second-order upwind scheme.

Boundary Conditions. The stationary wall conditions were applied to the upper and lower wall of the computational domain and the lobe wall. Periodic boundary conditions are applied to the left and right sides of the computational domain. Outlet boundary condition is pressure outlet with atmospheric pressure. The inlet boundary condition is velocity boundary and parameters of the core and bypass flows are \( V=90\text{m/s}, T=560\text{K} \) and \( V=30\text{m/s}, T=300\text{K} \), respectively.

Based on the issue to be concerned, the pre-whirling flow field was modeled using an inlet flow at an deflection angle to the axis of lobed mixer of 0°, 5°, 10°, 20° and 30°, respectively.

3. Computation Results and Discussion

3.1. The analyses of temperature field without pre-whirl
Figure 2. The temperature distributions of different flow cross-section

The temperature distributions of different flow cross-section downstream the lobed mixer without pre-whirl are shown in Figure 2. Obviously, the shear layer roughly remains consistent with the lobe trailing edge shape at \( x/H = 0.625 \), as shown in figure 2 (a), although it has been deformed and expanded to some extent. The explanation for this phenomenon is that the streamwise vortices have not been fully developed and the orthogonal vortices have not been crushed. The strength of the streamwise vortices then increases with the development of the flow. According to the literature [7], it is known that the large-scale streamwise vortices have formed at \( x/H = 2.5 \). This is why the shear layer distorts in Figure 2 (b). In this stage, the shear layers corresponding to the adjacent vertical sidewall of the lobe are no longer a strip-shaped structures but rotate in the opposite directions and squeeze each other under the action of streamwise vortices. It is obvious in Figure 2 (c) that there is no large-scale vortices structure in the temperature field and the temperature in the center of the mixing zone are nearly completely mixed at \( x/H = 4.375 \). When the fluid arrives at \( x/H = 6.25 \), the effect of streamwise vortices on heat exchange has been very weak. The temperature inside the mixing zone have been generally uniform and the radial height of the mixing zone eventually reaches the 2H as shown in Figure 2 (d).

3.2. The analyses of temperature field with pre-whirl

(a) pre-whirl=5° (b) pre-whirl=10°
Figure 3. The temperature distributions at x/H=0.625, 1.875, 3.75, and 6.25

When the inlet pre-whirl were 5°, 10°, 20° and 30° respectively, the temperature distributions in the 4 axial cross-sections downstream lobed mixer are shown in Figure 3. It can be clearly found that the inlet pre-whirl has a great influence on the temperature field downstream of the lobe, and this effect becomes more pronounced with the increase of the flow distance and pre-whirl angle. At x/H=0.625, the temperature distribution at pre-whirl angle of 5° is similar to no pre-whirl. When the pre-whirl angle increases to 10°, the mixing zone corresponding to the trough begins to shift anticlockwise, and when the pre-whirl angle continues to increase to 30°, the airflow from the adjacent lobes begins to enter the mixing zone and the vortices created by adjacent lobes also interfere more quickly with each other. It can be explained that as the airflow pre-whirl increases, the airflow through the lobe retains a larger tangential velocity. Large-scale streamwise vortices have appeared at x/H =1.875. However, the streamwise vortices are no longer symmetrical about the central axis. Because the streamwise vortices are affected by the tangential velocity component, their positions cannot be stable in the Y direction, and have the tendency to move to the right as whole. The larger the inlet pre-whirl, the more obvious the tendency to move to the right. At x/H=3.75, the streamwise vortices have also been deformed and broken into smaller vortices, even though the pre-whirl angle is only 5°. With the pre-whirl angle increases, the confusion of the temperature field structure is more obvious. When the airflow arrives at x/h =6.25, the temperature of the zone affected by the streamwise vortex is close to the fully mixed temperature, and the influence of the streamwise vortex on the mixing process has decreased greatly.

3.3. Influence of inlet pre-whirl on the thermal mixing efficiency

The thermal mixing efficiency is adopted to evaluate the mixing effect of lobed mixer, which is defined as following:

$$\eta_T = 1 - \frac{\int (T - T_{\text{mix}})^2 dm}{m_h T_h^2 + m_c T_c^2 - m_{\text{mix}} T_{\text{mix}}^2}$$

The plot of the thermal mixing efficiency of lobed mixer along the flow direction is shown in Figure 4. It is obviously that the thermal mixing efficiency has a decreasing slope under the different pre-whirl conditions. In addition, it is also found that the thermal mixing efficiency is greater as the inlet pre-whirl increases. When the pre-whirl angle is less than 10°, the effect of inlet pre-whirl on the mixing is not obvious, but when the pre-whirl angle increases to 20°, the thermal mixing efficiency increases significantly.

According to the above analysis of the effect of inlet pre-whirl on the temperature field, it is known that pre-whirl accelerates the mixing process between cold and hot airflow mainly by increasing the average vorticity along the flow direction. The increase of the vortices strength is the primary reason that the pre-whirl enhances the thermal mixing efficiency of the lobed mixer.
3.4. Influence of inlet pre-whirl on the total pressure loss

The total pressure recovery coefficient is adopted to characterize the flow loss of lobed mixer, which is defined as following:

$$\sigma = \frac{\int P_{\text{mix}}^* \, dm}{\int P_{\text{in}}^* \, dm}$$

The curve of the total pressure recovery coefficient along the flow direction under different pre-whirl conditions is shown in Figure 5. At x/H=0, the total pressure loss has begun to increase with the pre-whirl angle, which is mainly caused by the pre-whirl increasing the pressure difference between the adjacent vertical sidewalls of the lobe. If the pressure on one side wall is too low, flow separation will appear and the flow loss will increase. In general, the flow loss increases with the inlet pre-whirl angle and flow-direction distance.

Total pressure loss and mixing efficiency are closely related, because the mixing process is an entropy increasing process. The increase in pre-whirl leads to dissipation and fragmentation of the streamwise vortices earlier, which increases the total pressure loss while increasing mixing efficiency.

4. Conclusions

In this paper, by comparing the work performance of the lobed mixer under different pre-whirl conditions, the following conclusions are obtained:

1. The inlet pre-whirl causes a pair of vortices corresponding to the adjacent vertical walls of the lobe migrating, and accelerates the dissipation and fragmentation of the streamwise vortices downstream of the lobed mixer.
2. The inlet pre-whirl does not affect the tendency of mixing efficiency of lobed mixer along the flow direction, but the mixing efficiency of the same flow cross-section increases with the pre-whirl.
3. The total pressure loss increases as the pre-whirl angle increases.

Acknowledgments

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