Effect of notch width-ratio of core lobe to bypass lobe on performance of two-dimensional lobed mixer

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Abstract. Geometrical and numerical simulation models of 2-D lobed mixer with differences of \( \frac{b_h}{b_c} \) were established to study the effects of \( \frac{b_h}{b_c} \) and bypass lobe to thermal mixing efficiency and total pressure recovery coefficient of the mixer. The results show that when the \( \frac{b_h}{b_c} \) range from 0.444 to 1.364, the maximum average non-dimensional streamwise vorticity along flow direction rises as \( \frac{b_h}{b_c} \) increases. The mixer of which thermal mixing efficiency is maximum varies over stream wise and \( \frac{b_h}{b_c} \) of the mixer of which thermal mixing efficiency is maximum increases along the flow direction. Besides, the total pressure recovery coefficient of the lobed mixer ascends as \( \frac{b_h}{b_c} \) increases.

Nomenclature
\[ \begin{align*}
D &= \text{diameter of the lobed mixer, 40 mm} \\
d &= \text{height of 2-D lobe, 40 mm} \\
x, y, z &= \text{coordinates} \\
u, v, w &= \text{velocity three components} \\
U_k &= \text{average velocity of the air at the inlet of the lobed mixer, 20 m/s} \\
\bar{u} &= \text{average velocity of the air at the inlet of the 2-D lobe mixer, 60 m/s} \\
m &= \text{mass flow rare, m/s} \\
T &= \text{total temperature, K} \\
\omega &= \text{non-dimensional streamwise vorticity} \\
\eta &= \text{mixing efficiency} \\
p^* &= \text{total pressure} \\
\sigma &= \text{total recovery coefficient} \\
b &= \text{notch width} \\
\lambda &= \text{width of computational domain} \\
b_h &= \text{width of core lobe} \\
b_c &= \text{width of bypass lobe} \\
m_{\text{mix}} &= \text{mixed or partly mixed flow}
\end{align*} \]

1. Introduction
Lobed mixers, an improved mixing fluid mechanic devices that has corrugated trailing edges, can create large scale streamwise vorticity to realize full mixing in less distance [1-2]. Lobed mixers possess many of advantages such as higher mixing efficiency and excellent stability owing to its special structure. The devices were widely applied to promote aero-engine thrust, reduce infrared radiation of aero-craft, lower jet noise and fuel consumption and improve the performance of reheat combustion chamber [3].

In numerous studies on effective mixing mechanism of lobed mixer since lobed mixer was firstly put forward and applied to aero-engine by Frost in 1966, Paterson [4] proposed the conception of streamwise vorticity and confirmed the existence of streamwise vortices in the flow field behind the
lobe edges in the experimental studies. Meanwhile, Paterson expounded the mechanism how streamwise vortices enhance the mixing between core flow and fan flow. Skebe et al [5] further clarified the conformation of streamwise vortices and derived a formula to calculate the circulation at the trailing edge of the lobed mixer which was used to estimate the incremental coefficient of streamwise vortices to the mixing. Elliott et al [6] concluded that three primary contributors concern to the mixing process in mixing flows: the spanwise vortices which occur in any free shear layers; the increased interfacial contact area due to the convoluted trailing edge; the streamwise vortices generated by the radial velocity difference due to special geometry of the lobed mixer.

Besides the theoretical mechanism studies for lobed mixer, many of engineering researches were carried out to design mixer with better performance. Most researches concentrated on the effects of geometry sizes and inlet conditions to the flow field and performance of lobed mixer. Liu et al [7-8] completed a series of quantitative influence researches of geometry on the performance of lobed mixer through numerical simulations based on RANS. However, the studies about the effects of the $b_h/b_c$ on performance of mixer are not comprehensive enough. Besides, the accuracy of numerical simulation still need to be improved.

In this paper, numerical simulation is carried out on the lobe mixer model with different notch width-ratio of core lobe to bypass lobe to find the influences of $b_h/b_c$ on flow field, thermal mixing efficiency and total pressure recovery coefficient of the mixer. The reasons for which the effects were caused are also explored in this paper.

2. Physical model and numerical method

2.1. Computational method verification

The paper established verifying model (Figure 1) and calculated with the methods in the paper referring to the experiments of Hu [9]. Non-dimensional streamwise vorticity in Hu’s paper is defined as following:

$$ \omega_x = D/U_1 \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) $$

(1)

Figure 2 shows the non-dimensional streamwise vorticity on $x/D=0.5$ of numerical simulation results and Hu’s experiment. Figure 3 shows the non-dimensional maximum streamwise vorticity on different cross plane from numerical simulation and experimental measurement. According to Figure 2, the flow field of numerical simulation is nearly consistent with experimental results. Similarly, the differences of non-dimensional maximum streamwise vorticity on different cross plane between computational and experimental results are also small, less than 6 percent (Figure 3). It means that the computational method applied in the paper could well reflect the flow changes in lobed mixer.

![Figure 1. Geometry model and mesh of verification](image-url)
2.2. Geometry modeling and computational mesh

Considering the plane symmetry structure of two-dimensional lobed mixer, a segment ($\lambda = 29\text{mm}$) containing a whole lobe unit was chosen as computational domain. The geometric dimensions of the
domain were shown in Figure 4. Seven computational models with different notch width-ratio (0.444, 0.529, 0.625, 0.733, 0.857, 1.0, 1.167 and 1.364) of core lobe to bypass lobe were established. Hybrid grid was adopted considering the complicated structure of the lobe. The mesh around the lobes is unstructured tetrahedral cells and the other domain is structured grid as shown in Figure 4. Five-layer prism grid is applied in the walls to adapt to the boundary layer flow. The paper verified the independence of simulation results from mesh and eventually identified the grid number as 1.8 million.

2.3. Computational method and boundary conditions

The numerical simulation is based on 3-dimensional incompressible Reynolds Average Naiver-Stokes equation in steady state for the low inlet velocities (less than 0.3 Mach number). Compared with other turbulent models [10], the computational results of Realizable k-ε turbulent model approach best to the measured results in Hu’s experiment. Standard wall function was selected to solve the boundary layer flow. A finite volume discretization with convention terms discretized using MUSCL was adopted and pressure term discretized applying second upwind scheme. The standard SIMPLE was chosen as solution algorithm. Convergence accuracy of velocity component is 10⁻⁶.

Work medium in two mass flow inlets is air and the state parameters of core flow and bypass flow is shown in table 1. Pressure outlet with atmospheric pressure was selected as outlet boundary condition.

| Table 1. Boundary conditions |
|-----------------------------|
| v (m/s) | T (K) |
| Core flow | 90 | 560 |
| Bypass flow | 30 | 300 |

3. Computation Results and Discussion

3.1. Analyses of flow field

When the airflow passes through the lobe, radial velocity of opposite directions appears nearby sidewalls of the lobe which forms the vortex structure consistent with lowing direction. The vortex structure is called "streamwise vortices" which greatly enhance the mixing between the primary and secondary flows. Non-dimensional streamwise vorticity of 2-D lobed mixer is defined as following:

\[ \omega_x = \frac{d}{d} \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \]  

Figure 5 shows the velocity vector and non-dimensional streamwise vorticity of the lobed mixer model \( \frac{b_h}{b_c} = 1 \) in different cross sections. The development of the streamwise vortices in 2-D lobe mixer is generally similar to that of the circular lobe mixer, but the differences still exist. Fig 5(a) shows that the shape of streamwise vortices in \( x/d=0.2 \) is consistent with the trailing edge of the lobe in general. The velocity vector distribution in Figure 5(a) reveals the opposite component velocity along x direction nearby sidewalls of the lobe. In vicinity of lobe trough and crest, component velocity along y direction are also existing. However, there is no component velocity along y or x direction far away the lobe, which suggests that the effects of lobe are limited. The shape of streamwise vortices in figure 5(b) are no longer parallel to longitudinal portion of the lobe.

At cross-plane of \( x/d=1.25 \), two smaller vortex cores appear in each streamwise vortex and the size of two vortex cores differs greatly because of unequal lobe inclination at top and bottom. When the air flows from \( x/d = 0.625 \) to \( x/d = 1.25 \), the vortices further developed and the component velocity of the airflow along y direction increased. When the air flow past \( x/d = 1.875 \), the vortex begins to decay, the vortex intensity decreases in core and the area influenced by the vortex gradually reduces. At cross-plane of \( x/d = 6.25 \), the streamwise vorticity is very small due to the frictional losses from the mixing between hot and cold air.

Figure 6 shows the changes of average non-dimensional streamwise vorticity of lobed mixer models with different \( \frac{b_h}{b_c} \). When the air flow past the lobe trailing edge, the streamwise vortex
begins to develop and the intensity of the vortex increases gradually and reaches a peak on the cross-plane of $x/d = 1.875$. Subsequently, the vortex dissipates for the mixing of core and bypass airflow. Although the change trends of average non-dimensional streamwise vorticity of different $b_h/b_c$ are similar, the differences of average non-dimensional streamwise vorticity of different $b_h/b_c$ can be observed distinctly in Figure 6. When the $b_h/b_c$ ranges from 0.444 to 1.364, the average non-dimensional streamwise vorticity increases on all cross-planes. However, the augment of the maximum average non-dimensional streamwise vorticity decreases as $b_h/b_c$ increasing. The notch width of core lobe and bypass lobe determines the flow passing through the notch was changed. Only the core and bypass flows passing through the notch are equivalent, the maximum average non-dimensional streamwise vorticity will reach the climax. Thus, it can be inferred that the maximum average non-dimensional streamwise vorticity will reach the climax as $b_h/b_c$ increases to a specific point and will decrease if $b_h/b_c$ further increases.

![Figure 5. Distribution of non-dimensional streamwise vorticity and velocity vector](image)

**Figure 5.** Distribution of non-dimensional streamwise vorticity and velocity vector

3.2. Thermal mixing efficiency
Thermal mixing efficiency is adopted to evaluate the mixing degree of lobed mixer. Among numerous definition of thermal mixing efficiency, a revised formula is selected in the paper, which is defined as following [11]:

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

(3)
Figure 6 Average non-dimensional streamwise vorticity

Figure 7 shows the thermal mixing efficiency distribution of lobed mixer models with different $b_h/b_c$ along flow direction. Thermal mixing efficiency rises quickly in the front of mixer and the rising rate slow down subsequently. As analysed above, the dissipation of streamwise vortex and large velocity gradient perpendicular to flow direction are the main reasons for mixing. When the mixing advances to a certain extent, the streamwise vorticity and velocity gradient inclined. Then, the mixing slows down as shown in Figure 7.

When $x/d<3.125$, the thermal mixing efficiency increases slightly as the $b_h/b_c$ decreases. However, when $x/d>3.125$, the lobed mixer of maximum the thermal mixing efficiency is different in different cross-plane. In order to reveal the effect of the $b_h/b_c$ on thermal mixing efficiency of lobed mixer, the X axis was change to represent $b_h/b_c$ and the distribution of thermal mixing efficiency on different cross-planes was illustrated in Figure 8. The figure shows that the thermal mixing efficiency declines as $b_h/b_c$ increases on cross-plane of $x/d=1.25$ and $x/d=1.825$. On cross-plane of $x/d=2.5$, $3.75$, $5.0$ and $6.25$, the $b_h/b_c$ of lobed mixer model of maximum thermal mixing efficiency are respectively $0.529$, $0.625$, $0.625$ and $0.875$. It means that the $b_h/b_c$ of lobed mixer model of maximum thermal mixing efficiency increases as the lobed mixer lengthens, which provides theoretical foundation to the performance optimization of lobed mixer.

3.3. Total pressure loss

For lobed mixer, the mixing of hot and cold air flow is important reason for total pressure loss. The flow loss is often characterized with total pressure recovery coefficient which is defined as following:

$$\sigma = \frac{\int P_{mix}^* dm/m_{mix}}{\int P_{in}^* dm/m_{in}}$$

The change of $\sigma$ along flow direction is shown in Figure 9. Since the velocity of core flow is larger than the velocity of bypass flow and smaller $b_h/b_c$ means smaller area ratio of core flow and bypass flow, smaller $b_h/b_c$ will expand the velocity gap between core flow and bypass flow which can increase the total pressure loss. Thus, the declination of $\sigma$ slow down and the total pressure loss reduces as $b_h/b_c$ increases. The total pressure recovery coefficient drops more quickly when $x/d<3.125$, the reason is that high velocity gradient and streamwise vorticity lead to larger total pressure loss. Correspondingly, the growth rate of thermal mixing efficiency is bigger when $x/d<3.125$.

4. Conclusion

The paper studied the effect of $b_h/b_c$ (0.444-1.364) on flow field, thermal mixing efficiency and total pressure loss of lobed mixer and obtained some conclusions as following:

1. The mixing process in lobed mixer is dominated by the development of streamwise vortex, which can be influenced by $b_h/b_c$. The average non-dimensional streamwise vorticity ascends as $b_h/b_c$ increases.
2. The lobed mixer of maximum thermal mixing efficiency varies on different cross-plane, in other words, there is optimal $b_h/b_c$ and the optimal $b_h/b_c$ rises when mixing distance lengthens.

3. Total pressure recovery coefficient decreases as $b_h/b_c$ increases.

![Figure 7. Total pressure recovery coefficient](image1)

![Figure 8. Thermal mixing efficiency of different streamwise location](image2)

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