Numerical Investigation on Flow Fields of SVC Nozzle with Bypass Injection

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Abstract. Shock vector control (SVC) is one typical fluidic thrust vectoring technology. It has simple working principle and wide working range, but not high enough vector efficiency. In the paper, a bypass injection concept was proposed on the SVC technology to improve the vector efficiency and vector angle. The flow mechanism of SVC nozzle with bypass injection was investigated numerically after the turbulence model was validated by experimental data. The enhanced performance of SVC nozzle was estimated and the influence of critical affecting parameters, bypass injection angle ($\theta_{ad}$) and bypass injection position ($X_{j,ad}$) on vector performance were studied. Results show that, the vector efficiency was increased from 1.21 °/%-$\omega$ to 1.93 °/%-$\omega$ by adopting bypass injection, and the vector angle has an increase by about 58.9%. The vector performance increased with the increase of bypass injection angle when induced shock wave did not interacted with the opposite wall. The better vector performance was achieved with the configuration of the bypass injection slot was upstream of secondary injection slot when SPR is less than 1.0. In wide working ranges, a vector angle of 16°-20°, a vector efficiency larger than 2.0 °/%-$\omega$ were obtained while thrust coefficient of a SVC nozzle kept larger than 0.90.

1. Introduction

Thrust vectoring (TV) is a necessary technology for the 4th or later fighter plane. It provides extra force and moment in three dimensions besides thrust, and helps fighter plane to enhance agility and maneuverability at post-stall regime, to shorten taking off and landing distance and to enlarge the flight envelop etc. [1-2] Generally, there are two types of TV, the mechanical TV and the fluidic TV. The mechanical one is a fully developed technology, which was investigated since 1970s, and has different kinds of forms, including 2D mechanical TV used in F119, axis mechanical TV used in 31f and EJ-200, and three swivel bear nozzle used in F-135 etc. [3-5] However, the complex mechanical structures also bring out higher weight, larger lift cycle costs and gas leakage problem, which motivate researchers around the word to explore new concepts of TV with better performance. That is the fluidic TV. Compared with the mechanical TV, it has a weight reduction by 43%-80%, an improvement of engine thrust-to-weight ratio by 7%-12% and a reduction in nozzle procurement and life cycle costs by 37%-53% [6].

Different fluidic TVs were proposed based on active flow control. In these concepts, a secondary flow was adopted to control the primary flow, and methods including co-flow ejection, counter-flow suction, transverse injection were investigated [7]. Correspondingly, the concept of co-flow, counter-flow, throat shifting (TS), double throat nozzle (DTN) and shock vector control were formed. Among them, the SVC was emphasized due to its suitability on exhaust system with high nozzle pressure ratio. The working principle of SVC is based on transvers jet injected into supersonic primary flow at the
divergent section of nozzle. In the supersonic flow, an induced shock wave forms and deflects the primary flow, therefore the thrust vectoring is achieved [8]. In SVC nozzle, the main side-force for primary flow deflection is the high pressure formed upstream of injection slot and the jet injection moment.

Nowadays, numerical and experimental investigations were conducted, and two aspects of work were focused on. One aspect is the study on the complex flow mechanism and the influence of aerodynamic and geometric parameters on vector performance, including nozzle pressure ratio (NPR), secondary pressure ratio (SPR), nozzle inlet total temperature, secondary inlet total temperature, free stream Ma number, secondary injection position, secondary injection area and secondary injection position [9-11]. In the previous study, critical conclusions were found that the lower NPR brings better vector efficiency; the optimal SPR for largest vector angle exists when the induced shock wave interacts with nozzle lip; better performance is obtained when the secondary injection position moves forwards; and the increase on vector angle can be achieved by 50% when the secondary injection angle is optimised etc. The other aspect is the study on the multi-function thrust vectoring and vector performance optimization. In the work of Chiarelli and Wing, the SVC and Co-flow method were combined and the thrust vectoring with pitch and yaw function was achieved [12-13]. In the work of Giuliano, the investigation on a SVC nozzle with different flow path cross-sections and trailing-edge shapes were conducted at jet exit test facility, and multi-axis thrust vectoring control was obtained [14]. In the work of Federspiel and Anderson, the SVC / throat skewing combined concept and mechanical / fluidic combined concept were proposed, which extended the usage of SVC method and showed that better performance can be achieved by the combinations of different fluidic TV methods [15]. In the previous work, the advantages of SVC nozzles were fully displayed, but the remaining problem, not high enough vector efficiency, also should be considered. Generally, the vector efficiency of SVC nozzle is about 0.8-1.4 °/%/ω , which means about a secondary flow of 14.3% - 25% of primary flow is needed. It has large influence on the working performance of an aero-engine. Therefore, in the paper a concept of SVC with bypass injection was studied to improve the vector performance and to reduce the secondary flow demand. The flow characteristics was investigated, the vector performance of SVC nozzle and SVC nozzle with bypass injection was compared, and the effect of bypass injection angle and bypass injection position on vector performance were conformed.

2. Numerical Approach

2.1. The geometric model
The basic geometric model of a SVC nozzle with bypass injection is a convergent-divergent SVC nozzle, and a bypass flow is introduced from the nozzle convergent section to the nozzle divergent section, seen in Figure 1. There three flows in the nozzle, the primary flow, secondary flow and bypass flow. Consequently, the geometric parameters consist of the three parts.

![Figure 1](image-url)
throat area ($A_b$) is 3890 mm$^2$. The nozzle aspect ratio at nozzle exit is 2.2. For the secondary flow, the injection position ($X_s$) is 0.79, which is the dimensionless distance to the coordinate origin by the length of nozzle divergent section ($L_d$)). The secondary injection area ratio ($A_s/A_b$) is 0.08, which is the dimensionless injection area by nozzle throat area. The secondary injection angle ($\theta$) is 90°. For the bypass flow, the definitions of bypass injection position ($X_{s,ad}$) and bypass injection area ratio ($A_{s,ad}/A_b$) are similar with those of $X_s$ and $A_s/A_b$. In this study, the $X_{s,ad}$ varies from 0.69 to 0.89, which means bypass injection is arranged upstream or downstream of the secondary flow. $A_{s,ad}/A_b$ is 0.08. The bypass injection angle ($\theta_{s,ad}$) is from 90° to 120°.

2.2. Governing equations

The flow characteristics of a SVC nozzle with bypass injection was obtained by solving the compressible form of conservation equations continuity, momentum and energy equations in Cartesian coordinates, shown as follow. A commercial software of Fluent of ANSYS 18.2 was used to conducted the simulation work.

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Momentum:

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla \cdot \mathbf{p} + \nabla \cdot \mathbf{r}_{ij} + \rho g_i + \mathbf{F}_i$$

Energy:

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [\rho \mathbf{u} (E + p)] = \frac{\partial}{\partial x_i} \left[ \frac{\partial (E + p)}{\partial x_i} \right] + \rho T \frac{\partial \rho \mathbf{u}}{\partial x_i} + u_j \left( \tau_{ij,eff} \right)$$

Where $\mathbf{r}_{ij}$ is the shear stress tensor and is defined as follow:

$$\left( \tau_{ij,eff} \right) = \mu_{ij} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] - \frac{2}{3} \mu T \frac{\partial u_i}{\partial x_j} \delta_{ij}$$

The equations solved are the fully three-dimensional compressible Reynolds averaged Navier-Stokes equations, which are discretized in finite volume form on each of the hexahedral control volumes. The second implicit scheme adopted for the time discretization, and the second order upwind scheme is used in the spatial discretization. The implicit density-based algorithm is used to solve the equation, and Roe averaged flux difference splitting (Roe-FDS) is chosen for the flux type.

2.3. The Computational grid

The computational grid of the SVC nozzle with bypass injection is shown in Figure 2. Due to the geometric symmetry of the SVC nozzle, half model was adopted for investigation. The hexahedral meshes were produced all over the computational zones. Meshes near nozzle wall and around secondary injection slot and bypass injection slot were refined, with the $y^+$ about 1.0. The final grid was generated with about 3.2 million cells.

2.4. The validation of turbulence model

The flow fields of the SVC nozzle with bypass injection are featured by jets interactions, flow separation, vortices, shock waves and shear layers etc. Before the numerical simulation, the turbulence model needs to be validated. Several turbulence models, including the S-A model, the SST $k$-$\omega$ model, the SAS model, the realizable $k$-$\varepsilon$ model, and the RNG $k$-$\varepsilon$ model, are chosen and validated by the experimental data from Spaid and Zukoshi[16]. The experiment was conducted at a free stream $Ma$ of 2.61 with the ratio of injected jet total pressure to free stream total pressure of 1.15. Noticeably, the boundary condition is similar to that of the SVC nozzle with bypass injection, thus the best validated turbulence model will be used in the study. The numerical and experimental results of pressure distributions along the nozzle center line are shown in Figure 3.
A: outer inlet, B: Pressure far-field, C: Outlet, D: Symmetric plane, E: nozzle inlet, F: Secondary inlet

Figure 2 The computational grid

![Computational Grid](image)

Figure 3 Turbulence model validated by experimental data

![Turbulence Model](image)

It is seen that the predicted separation position of boundary layer upstream of jet injection slot by the S-A model, the Realizable k-ε model, and the RNG k-ε model did not match the experimental data well, and the predicted peak pressure is about 10% larger than the experimental data while the predicted high pressure zone is about 20% smaller. The SST k-ω model and SAS model predicted separation position and pressure profiles very well, and in the high pressure zone the maximum pressure difference with the experimental data is within 2%. Additionally, the two turbulence models also performed better at predicting pressure distributions downstream of jet injection port. But in the comparison of calculation time, the simulation with the SAS turbulence model took time more than that of the SST k-ω model by about 50-80%. Therefore, The SST k-ω model was proven to be the best choice.

2.5. The Boundary conditions

Pressure inlet boundary is specified for nozzle inlet (E), secondary flow inlet (F) and outer flow inlet (A), shown in Figure 2. On these boundaries the total pressure \( p_s, p_s', p_n \), the total temperature \( T_s, T_s', T_n \) and flow angle are prescribed. Nozzle total pressure and secondary flow total pressure are calculated from NPR and SPR, which vary from 6 to 16 and from 0.6 to 1.5, respectively. The total temperature of nozzle inlet is 800 K, while secondary flow total temperature is obtained from the isentropic relationship between pressure and temperature, shown as follow:

\[
T'_s = T_n \times \left( \frac{P_s'}{P_n} \right)^{\frac{1}{\gamma}}
\]

At outlet boundary (C), static pressure \( P_0 \) is imposed and the other variables were extrapolated from the interior parameters. Symmetry boundary condition is adopted at the center face (D). A free-stream Mach and flow direction are provided for far-field pressure boundary (B). Impermeable, no-slip and adiabatic wall boundaries were applied on the solid wall to ensure zero normal mass, momentum and energy crossing the mesh face at the wall boundary.
3. Results and discussions

3.1. Working principle and flow characteristics of a SVC nozzle with bypass injection

The structure of a SVC nozzle with bypass injection was shown in Figure 4. It is seen that the bypass flow is from the high pressure zone of the nozzle to the diverter section. It is injected into the supersonic flow at nozzle divergent section and assists the secondary flow to control primary flow deflecting. With the bypass injection, the transverse jet penetration depth is enhanced, the strength of induced shock wave becomes stronger, the position of the induced shock wave moves forwards, and the separation zone upstream of injection enlarges, which results in larger high pressure zone on nozzle wall and larger side-force for vectoring. Meanwhile, the bypass injection has tiny influence on secondary flow. So the secondary flow mass keeps unchanged, and the vector angle increases, therefore, the vector efficiency is improved. When a larger vector angle is required, the demanded secondary flow mass of a SVC nozzle with bypass injection is smaller compared with a SVC nozzle, and it has less influence on the performance of an aero-engine.

![Figure 4 The sketch map of working principle of the improved SVC nozzle](image)

The flow characteristics of a SVC nozzle with bypass injection are featured by transvers jets (secondary flow and bypass flow) into the supersonic at nozzle divergent section and the shock wave / boundary layer interactions in a confined space. In this section, the flow characteristics of a SVC nozzle with bypass injection were investigated numerically. The concerned parameters are as follows: the secondary injection area ratio \( \frac{A_s}{A_8} \) and the bypass injection area ratio \( \frac{A_{s,ad}}{A_8} \) are 0.08, respectively; the secondary injection angle \( \theta \) is 90º, which is the same with the bypass injection angle \( \theta_{ad} \); the nozzle pressure ratio \( \text{NPR} \) is 13.88, the nozzle inlet total temperature \( T_{in} \) is 800K; the secondary pressure ratio \( \text{SPR} \) is 1.0, and the secondary injection total temperature \( T_{s} \) is 622 K (according to Eq.5).

For the SVC nozzle with a bypass injection, two under-expanded jets (secondary flow and bypass flow) were injected into the supersonic primary flow. A strong obstacle was generated and an induced shock wave was caused. Correspondingly, there was a strong adverse pressure gradient, which forced the boundary layer upstream of injection slot to separate. Then another shock wave was induced, i.e. the separation shock wave. When the two shock waves interacted, they merged into a “λ” shock wave, seen in Figure 5. It has a stronger shock wave leg and a weaker one. The “λ” shock wave caused unbalanced pressure distributions on nozzle up and down walls, which plays an important role in deflecting primary flow.
The influence of the “λ” shock wave on the flow characteristics of a SVC nozzle with bypass injection is concerned with the acceleration of the primary flow. In one aspect, the acceleration of primary flow made the Ma number distributions upstream of shock waves non-uniform, which varied from 1.80 to 2.40. When primary flow passed through shock waves, the flow mechanical energy losses were different, and the Ma number downstream of shock wave, ranging 1.2 to 1.66, were obtained. In the other aspect, the acceleration and shock wave losses brought non-uniform flow characteristics at nozzle exit plane. And there are typically five different flow losses zones on the exit plane, seen in Figure 5, which is distinguished according to the total pressure recovery coefficient (σ) that is the ratio of local total pressure to the inlet total pressure of nozzle.

Figure 5 Ma number and streamlines distributions on the symmetric plane

In zone-1, small flow loss exits, and σ is about 1.0. It is mainly because that primary flow in this zone did not affected by shock waves. In zone-2 and zone-3, primary flow passed through shock wave main branch and shock wave legs, respectively. The σ in zone-2 is about 0.88, and is a little smaller than σ (0.94) in zone-3. The primary reason is that the primary flow of zone-2 has larger Ma number upstream of shock wave, as is known, when shock angle is the same, the larger Ma number upstream of shock is, the more drastic flow loss there is. Another reason is that the flow of zone-3 passed through two weak shock waves, while the flow of zone-2 passed through a stronger one. Usually, the multi-shock waves can result in less flow loss than that of a stronger one. For the zone-4, the flows are from injected jets (secondary flow and bypass flow) and shear layers between jets and primary flow. The σ is about 0.50, which is comparatively low. The mainly reason is that there are Mach discs in under expanded jets, which are normal shock waves and bring out tremendous flow losses. In zone-5, ambient air flowed into low pressure zone downstream of injection slot, and those low powerful flows filled up the zone, which finally resulted in a much smaller σ of 0.07. Because the flow in zone-5 was

Figure 6 Total pressure recovery coefficient distributions on the exit plane
not from primary flow, the mass averaged $\sigma$ on nozzle exit plane was not suitable for estimating the overall performance of the SVC nozzle with bypass injection. So another parameter, the thrust coefficient ($C_{fg}$) was adopted, and in this case the $C_{fg}$ of was about 0.907. There are complicated vortices in the the SVC nozzle with bypass injection because of the transverse jets into accelerated supersonic primary flow. A pair of counter-rotating span-wise vortices were witnessed upstream of injection slots. The front vortex is formed by the boundary layer separation due to shock waves, named as primary upstream vortex (PUV), which is clockwise and bigger in size, seen in Figure 5. The position and size of it can be identified by limited streamlines distributed on nozzle down wall, seen in Figure 7 (a). The solid line denotes the convergent limited streamlines, which is the boundary separation line. It starts from a saddle point and ends with a nod point, and it is the front boundary of PUV. The following dashed line denotes the divergent limited streamlines, which represents the attachment position of flow separation, and it is the rear boundary of PUV. Additionally, the zone between solid and dashed lines is used to judge the stream-wise size of PUV. The other vortex is an anti-clockwise vortex, named as secondary upstream vortex (SUV), and it is a litter smaller. It is formed due to the entrainment of bypass jet and PUV, and in size it was confined by the attachment line and bypass injection slot. There is also another pair of counter-rotating vortices between bypass injection slot and secondary injection slot. As is analyzed, they were formed mainly by the entrainment of secondary flow and bypass flow. From the divergent limited streamlines (dashed line) between injection slots, it is found that the vortex near secondary jet is larger, because the secondary flow has higher speed and correspondingly the larger entrainment intensity. Besides, there is another divergent limited streamline on nozzle wall downstream of injection slots, marked by dashed line too, which was a sign of attachment of separation flow. In this zone, low pressure was formed due to injected jets, and ambient air flowed around nozzle lip into the zone, resulting in an anti-clockwise lip vortex, at the entrainment of which and secondary injection flow a small vortex was also induced, seen in Figure 5 and Figure 6.

The role of the bypass flow is to enhance the vector performance of a SVC nozzle, e.g. vector angle ($\delta_p$), thrust vector efficiency ($\eta$). A comparison on the vector performance of a SVC nozzle with and without bypass flow was conducted. Results showed that an improved vector angle of 14.28º was achieved with assistant of the bypass flow, which was 58.9% larger than that of a SVC nozzle without bypass flow. Meanwhile a $\eta$ of 1.93%/ω was achieved, which is also much larger than that of a SVC nozzle. Additionally, the bypass flow equivalently increased the flow flux of a nozzle, which changed the working character of an aero-engine, and it was benefit for net thrust. Based on the preliminary results above, it is inferred that the SVC with bypass injection method may offer more desirable option for fluidic thrust technology. Thus in the following sections, to get more understanding of the SVC nozzle with bypass injection, the influence of two critical geometric parameters on the flow characteristics and vector performance were investigated in wide working conditions.

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![Diagram](image.png)

(a) Nozzle down wall
The influence of bypass injection angle on vector performance of a SVC nozzle with bypass injection

The influence of bypass injection angles ($\theta_{ad}$) on the performance of a SVC nozzle with bypass injection was investigated with $X_{j, ad}$ of 0.89 and $A_{ad}$ of 0.08. $\theta_{ad}$ has a varies from 90°, 100°, 110°, 120° to 130°. The bypass injection angle affects the trajectory and jet penetration depth of secondary flow, and alters the separation length upstream of injection slot.

Figure 8 shows the flow characteristics of a SVC nozzle with bypass injection at NPR of 13.88 and SPR of 0.6, 1.0 and 1.5. With the increase of the bypass injection angles, the forward component of bypass flow moment increased, which has larger impact on secondary injection flow and made the peak point of jet trajectory promote, seen figure 8 (e). But it is found that the jet trajectory kept unchanged below the Mach dick. And the height of Mach dick is not suitable to analyse the jet penetration depth and vector performance. Instead, the jet trajectory can indicate the induced shock wave angle and the shock wave strength better. But it is difficult to obtain the relation expressions of the jet trajectory on other aerodynamic and geometric parameters.
Figure 8 The flow characteristics of a SVC nozzle with bypass injection at different bypass injection angles

The pressure differences on nozzle upper and down walls and the vertical component of jets moment determine the side-force and vector angle. Figure 8 (d) shows the pressure distributions on nozzle internal walls at different bypass injection angles. With the increase of bypass injection angle, the influence of secondary flow on primary flow was enhanced, the strength of the induced shock wave increased and the induced shock wave moved forwards, which resulted in the separation point of boundary layer upstream of injection slot moved forwards too. Therefore, the high pressure zone enlarged. The pressure on the wall between secondary injection slot and bypass injection slot increased due to the interaction of the two jets until the $\theta_{sd}$ was 120 °. Additionally, the back pressure of bypass flow also increased with the increase of bypass injection angle, therefore the bypass flow mass had a decrease of about 3%-5%. On the other hand, the vertical component changed by $(1 - \cos (\theta_{sd} - 90))$, due to the increase of bypass injection angle. These two aspects are negative to vector performance, but are minor factors.
The vector efficiency

The thrust coefficient

Figure 9 The vector performance of a SVC nozzle with bypass injection at different bypass injection angles.

The vector angle of a SVC nozzle with bypass injection is shown in Figure 9 (a). At the condition of constant secondary flow mass and little changed bypass flow mass, the vector angle has a increase by 12% when bypass injection angle increased from 90° to 130°. It is concluded that the bypass injection angle is a critical parameter. Under the geometric restrictions, the larger bypass injection is benefit to high vector and vector efficiency. But the design process, the bypass injection angle should be coupled with the secondary pressure ratio. Because at larger secondary pressure ratio (e.g. SPR of 1.5), the induced shock wave interacted with the opposite wall at larger bypass injection angle, which is bad for vector performance.

The secondary flow mass kept unchanged when nozzle pressure ratio and bypass injection angle altered. At SPR of 0.6, 1.0 and 1.5, the corrected secondary mass flow ratio is about 0.044, 0.077, 0.111. Therefore, the vector efficiency has the similar varying principle with vector angle versus the bypass injection angle at different SPRs, seen in Figure 9 (b). Noticeably, the larger SPR is, the larger the vector angle is, but the less vector efficiency. It is also seen that with the corrected secondary flow mass less than 10%, the vector angle of 16° - 20° and vector efficiency higher than 2.0 °/° were achieved by modifying the SPR and bypass injection angle at large working ranges. It can satisfy the thrust vectoring demand of fighter planes and has less influence on the performance of an aero-engine.

The thrust coefficient varying with the bypass injection angle is seen in Figure 9 (c). With the increase of bypass injection angle, the induced shock wave angle increased and came closer to the nozzle lip. More primary flow went through the shock wave, thus larger flow losses generated, and the thrust coefficient decreased. At the NPR of 13.88 and SPR of 1.0, about a decrease by 0.5% was found when bypass injection varied from 90° to 130°.
3.3. The influence of bypass injection position on vector performance of a SVC nozzle with bypass injection

The interactions of bypass injection flow and secondary injection flow have influence on the shock waves and vortices, resulting in the re-distributions of pressure on nozzle walls and the change of vector performance. The strength of jets interactions are the critical factor affecting vector performance, and the distance between the two jets are direct affecting variable. In this section, the influence of bypass injection positions ($X_{j,ad}$) on the performance of a SVC nozzle with bypass injection was investigated with $X$ of 0.79, $\theta_{ad}$ of 90 and $A_{s,ad}$ of 0.08. $X_{j,ad}$ has a varies from 0.69, 0.74, 0.84 to 0.89. The first two bypass injection positions locate upstream of secondary injection slot, and the other two downstream of secondary injection slot.

The flow fields of a SVC nozzle with bypass injection varying with bypass injection positions at NPR of 13.88 and SPR of 1.0 is shown in Figure 10. It is seen that the change on distance between two jets has no influence on the partten of vortices. There are still two pairs of counter-rotation vortices and a lip vortex. But the size of the vortices changed. With the jets distance change, two aspects of flow fields altered, the separation length of boundary layer and the pressure distributions on wall between jets. Comparing the configurations of $X_{j,ad}$ of 0.69 and $X_{j,ad}$ of 0.74, Figure 10 (a) and (b), it is seen when the two jets get closer, the jet penetration depth was enhanced, and the high pressure zone (boundary layer separation length) increased by about 9%. But the entrainment also increased, which made the pressure on walls between the two jet smaller, seen Figure 10 (e). And it is found the pressure drop has larger effect than the high pressure increase, therefore, the vector angle of $X_{j,ad}$ of 0.74 configuration is a little smaller. Comparing the configurations of $X_{j,ad}$ of 0.74 and $X_{j,ad}$ of 0.84, which are upstream of secondary injection slot and downstream of secondary injection slot respectively, Figure 10 (b) and (c), it is seen that boundary layer separation length of the later one is larger, it is mainly because the moment of secondary flow is larger than that of bypass injection. Meanwhile the pressure distribution between the two jets kept almost unchanged. Thus the vector angle of the configurations of $X_{j,ad}$ of 0.84 is larger. With the bypass injection position moving afterwards continually, the jets interaction weakened, and the jet penetration and boundary layer separation length decreased. But the pressure on wall between the jet ascended, which finally made the vector angle increase.
(e) Pressure distributions on nozzle wall (NPR=13.88, SPR=1.0)

Figure 10 The flow characteristics of a SVC nozzle with bypass injection at different bypass injection positions
Figure 11 The vector performance of a SVC nozzle with bypass injection at different bypass injection positions

At other SPR conditions, the vector angle has the similar change principle varying with bypass injection positions, besides the SPR of 1.5 at configurations of $X_{j,ad}$ of 0.89. In Figure 11 (a), It is seen that the bypass injection is not a critical parameter. At wide working conditions, the vector angle changed within 2º when the bypass injection position moved from $X_{j,ad}$ 0.74 to $X_{j,ad}$ 0.89. The vector efficiency and thrust coefficient are shown in Figure 11 (b) and (c). It is seen that the vector efficiency is larger than 1.5 $\% - \omega$ and the thrust coefficient is larger than 0.89 at almost simulation working conditions.

4. Conclusions

In the paper, the SVC nozzle with bypass injection configuration was proposed to improve the vector performance of the fluidic thrust vectoring and to reduce the demand on secondary flow extracted from an aero-engine. The flow mechanism of a SVC nozzle with bypass injection and the influence of bypass injection angle and bypass injection position were investigated numerically. Conclusions are as follow:

1) With the assistant of a bypass injection flow, the vector efficiency are improved largely by about 60%, meanwhile the flow fields get more complex. The induced shock wave and vortices brought larger flow losses.

2) By adopting the bypass injection, the vector angle of 16º - 20º and vector efficiency higher than 2.0 $\% - \omega$ were achieved with the corrected secondary flow mass less than 10%, which is desirable.

3) The bypass injection angle is a critical affecting parameter, which has an obvious influence on vector performance when the injection angle increased.

4) The bypass injection position is not a critical affecting parameter, and a vector angle change is within 2 º, when the position moved from $X_{j,ad}$ 0.74 to $X_{j,ad}$ 0.89.

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