Investigation on Flow Characteristics of SVC Nozzles


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ABSTRACT

Shock vectoring control (SVC) is an important method of fluidic thrust vectoring (FTV) for aero-engine exhaust system. It behaves better on nozzle of high pressure ratio, and is considered as an alternative TV technology for a future aero-engine with high thrust-to-weight ratio. In this paper, the flow mechanism and vector performance, including the vector angle ($\delta_p$) and thrust coefficient ($C_{fg}$), of 2D and axisymmetric SVC nozzles were investigated after the validation of turbulence models by experimental data. The influence of aerodynamic parameters, e.g. nozzle pressure ratio (NPR), secondary pressure ratio (SPR) and free-stream Ma number ($M_\infty$) on flow characteristics and vector performance were studied numerically, and results show that unbalanced pressure distributions on nozzle internal walls determine $\delta_p$, while shock waves dominate thrust loss, referring to $C_{fg}$. The "pressure release mechanism" of an axisymmetric SVC nozzle causes vector angle about 16.54% smaller than that of a 2D SVC nozzle at NPR of 6. The induced shock wave interacts with nozzle upper wall at SPR of 1.5, and results in the $\delta_p$ of a 2D SVC nozzle 12% smaller. A new parameter ($F_{y,mod}$) of side-force was redefined for free-stream conditions, taking the pressure distributions on nozzle external walls into account. Results indicate that pressure connection on nozzle external walls of an axisymmetric SVC nozzle causes vector performance better at $M_\infty>0.3$ and the $\delta_p$ is about 11.2% larger at transonic conditions of $M_\infty$ of 0.9 and 1.1.

Keywords: SVC; Transverse injection; Vector performance; Aerodynamic parameters; Flow control.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$A_9/A_8$</td>
<td>nozzle expansion ratio</td>
</tr>
<tr>
<td>$A_{9,A8}$</td>
<td>ratio of secondary injection area to nozzle throat area</td>
</tr>
<tr>
<td>$C_{fg}$</td>
<td>thrust coefficient</td>
</tr>
<tr>
<td>$C_{fg}$</td>
<td>total temperature of nozzle inlet</td>
</tr>
<tr>
<td>$C_{fg}$</td>
<td>total temperature of secondary inlet</td>
</tr>
<tr>
<td>$F_{x}$</td>
<td>thrust along nozzle axis</td>
</tr>
<tr>
<td>$F_{y}$</td>
<td>thrust normal nozzle axis</td>
</tr>
<tr>
<td>$F_{y,mod}$</td>
<td>modified thrust normal nozzle axis</td>
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<tr>
<td>$F_{x,mod}$</td>
<td>width of a 2D SVC nozzle</td>
</tr>
<tr>
<td>$F_{x,mod}$</td>
<td>width of injection slot</td>
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<tr>
<td>$F_{x,mod}$</td>
<td>length of convergent section of nozzle</td>
</tr>
<tr>
<td>$F_{x,mod}$</td>
<td>length of divergent section of nozzle</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>ratio of specific heat</td>
</tr>
<tr>
<td>$L$</td>
<td>length of nozzle</td>
</tr>
<tr>
<td>$L_{sep.}$</td>
<td>length of separation zone upstream of injection slot</td>
</tr>
<tr>
<td>$Y^*$</td>
<td>non-dimensional injection position on divergent section of nozzle</td>
</tr>
<tr>
<td>$y^*$</td>
<td>non-dimensional height of first grid near wall</td>
</tr>
<tr>
<td>$m_n$</td>
<td>mass flow rate of nozzle</td>
</tr>
<tr>
<td>$m_s$</td>
<td>mass flow rate of secondary flow</td>
</tr>
<tr>
<td>$M_\infty$</td>
<td>ambient Mach number</td>
</tr>
<tr>
<td>NPR</td>
<td>nozzle pressure ratio</td>
</tr>
<tr>
<td>NPRD</td>
<td>designed nozzle pressure ratio</td>
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<tr>
<td>$P_0$</td>
<td>ambient static pressure</td>
</tr>
<tr>
<td>$P_0^*$</td>
<td>total pressure of outer flow field</td>
</tr>
<tr>
<td>$P_{n}^*$</td>
<td>total pressure of nozzle exit plane</td>
</tr>
<tr>
<td>$P_{n}^*$</td>
<td>total pressure of nozzle inlet</td>
</tr>
<tr>
<td>$P_{s}^*$</td>
<td>total pressure of secondary inlet</td>
</tr>
<tr>
<td>$P_{s}^*$</td>
<td>total pressure of secondary inlet</td>
</tr>
<tr>
<td>$R$</td>
<td>ideal gas constant</td>
</tr>
<tr>
<td>SPR</td>
<td>secondary pressure ratio</td>
</tr>
<tr>
<td>SVC</td>
<td>shock vectoring control</td>
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</table>

$T_{s}$ | ambient static temperature |
$T_{n}^*$ | total temperature of nozzle inlet |
$T_{s}^*$ | total temperature of outer flow-field |
$W$ | thrust vectoring |
$W_s$ | width of a 2D SVC nozzle |
$X_{c}$ | length of convergent section of nozzle |
$X_{D}$ | length of divergent section of nozzle |
$\beta$ | nozzle divergent angle |
$\theta$ | secondary injection angle |
$\theta$ | angle between Y direction and normal direction of nozzle outer wall |
$\delta_{p}$ | Thrust vector angle, |
$\tau$ | ratio of secondary flow total temperature to nozzle inlet total temperature |
$\omega$ | ratio of secondary mass flow rate to nozzle mass flow rate |
$\omega^*$ | corrected flow ratio of secondary flow to primary flow |
1. INTRODUCTION

Thrust vectoring (TV) technology offers enormous benefits to a fighter plane, e.g. enhancing agility and maneuverability at post-stall regime, improving survival rate and combat efficiency, shortening take-off and landing distance, and increasing stealth ability (Sehra, et al. 2004; Terrier, et al. 2003; Scharnhorst, 2013). It is becoming an absolutely necessary demand for a 4th and later fighter plane. Generally, there are two types of TV: mechanical TV and fluidic TV. Compared with the former one, fluidic TV has simpler structure, lower weight, and quicker vectoring response (Mason, et al. 2004). As reported by Deere (2003), using fluidic TV, 43-80% weight reduction, 7-12% improvement of engine thrust-to-weight ratio, and 37-53% reduction in nozzle procurement and life cycle costs was obtained. Therefore, fluidic TV technology is considered as an alternative TV technology for exhaust system of a future aero-engine and has been investigated worldwide.

Many concepts of fluidic TV have been proposed and investigated since 1990s, including co-flow TV, counter-flow TV, throat skewing (TS) TV, dual throat nozzle (DTN) TV and shock vectoring control (SVC) TV (Shih, et al. 1999; Deere, 2000; GU, et al. 2015 ). Wing (1994) studied a co-flow TV, based on the “Coanda effect”, on a convergent-divergent nozzle. A vector angle ($\delta$) of 8.7º was obtained at NPR of 2.0, and a conclusion that the method was invalid when NPR was larger than 4.0 was drawn. In the later investigations of Saghaﬁ (2006) and HEO (2012), the co-flow TV method was adopted on a subsonic primary flow and a supersonic primary flow. They studied the flow mechanism of co-flow TV numerically and experimentally, and achieved a $\delta_p$ of 20º at NPR of 1.3 and 10º at NPR of 3.0, respectively. Styrkoski and Krothapalli (1993) proposed “Counter-flow” TV which is characterized by counter flow and counter shear layer. The working principle, parameters affecting rules and usage range for subsonic and supersonic primary flows were identified, and the thrust vectoring efficiency of a $\delta_p$ of 8º per 1% suction secondary flow was obtained. Shi (2013) investigated jet attachment and control method numerically, and founded that a hysteresis phenomenon existed in the control course. Later, LIU (2014) concluded Ma number has magniﬁcent inﬂuence on vector performance of a counter ﬂow nozzle. In previous studies, it was also pointed out that problems e.g. the jet detachment control and efﬁcient vacuum device restrict the usage of the method and are still needed to be solved. The idea of “throat skewing” method is manipulating sonic line using secondary injections at throat and divergent section to achieve primary ﬂow deﬂecting. Catt and Miller (1995, 1999, 2001) investigated flow characteristics of a TS nozzle, obtained a $\delta_h$ of 8º, a thrust coefﬁcient ($C_p$) of 0.94 and a vector efﬁciency of 1.7-2.0º/% (that is vector angle of 1.7º-2.0º with per 1% secondary ﬂow) at low NPR, but as studied by Zhang (2012), the vector performance of TS method is lower than SVC method at higher NPR (NPR>6.24). The DTN TV involves a convergent-divergent nozzle (Deere, et al. 2005; Bellandi, et al. 2009). A vector angle is generated by injecting secondary ﬂow upstream of throat which causes ﬂow separation in the recessed cavity between the two geometric minimum areas. An efﬁcient method to improve the thrust vectoring efﬁciency of a DTN was studied by GU (2015). The dynamic response of a DTN in open and closed-loop control was investigated numerically by Ferlauto (2016). As studied, this TV method works better at low and middle NPR conditions. The SVC method works as follow: injecting high pressure secondary ﬂow into supersonic ﬂow at a nozzle divergent section, inducing an oblique shock wave and generating side-force on nozzle walls to achieve thrust vectoring (Hamed, et al. 1997). The SVC method is characterized by transverse injection and shock / boundary layer interaction. Complex shock waves, vortices and shear layers are involved, and parameters e.g. shock wave structures, jet trajectory, injection penetration and ﬂow separation types are focused and CHAI (2012) provided ﬁtting formulas of jet trajectory with injection conﬁgurations and momentum ratio of secondary ﬂow to primary ﬂow. Zukoski (1964) proposed a blunt body theory in the study of injection penetration. The effect of secondary injection in supersonic ﬂow is similar as a blunt body with a front surface of quarter sphere, and the penetration depth is the sphere radius. Counter rotating vortices upstream of injection slot and closed or open separation downstream of injection were witnessed inside a SVC nozzle. The restriction of nozzle walls and the effect of negative pressure gradient deforms shock surface and causes the interaction between a bow shock and nozzle wall at some conditions. Waiithe and Deere (2003) showed that an SVC nozzle has vector efﬁciency of 0.8 %%-2.2 % and $C_p$ of 0.86-0.94. Zhang (2012) concluded that SVC method is more suitable for large designed pressure ratio nozzle and a SVC nozzle could be an option for the exhaust system of a future aero-engine with high thrust-to-weight ratio. Due to the important advantages mentioned above, the SVC method was selected as the topic of the research.

Presently, two aspects of research work have been conducted on SVC method numerically and experimentally. One aspect is the study of complex ﬂow mechanism and the inﬂuence of aerodynamic and geometric parameters, including NPR, SPR, secondary injection position, secondary injection angle, and inlet gases thermodynamic properties, on vector performance (Deere, 2000; Shi, et al. 2013, Zmijanovic, et al. 2014, HE, et al. 2017, Zmijanovic, et al. 2012). They concluded that better thrust vectoring performance was obtained when the injection position moved afterward. An SVC nozzle with two injection slots performed better than an SVC nozzle with single slot at low pressure ratio, $\delta_p$
improves by 50% with the increase of injection angle, thrust vectoring effectiveness decreases with increase of free stream Ma number, and gas molar mass has great effect on jet penetration and vector performance. The other aspect is multi-axis thrust vectoring exploration. Chiarelli and Wing (1993, 1994) combined SVC method and Coanda blowing method and achieved the thrust vectoring with pitch and yaw function. Giuliano (1994) conducted investigation on convergent-divergent nozzles with different flow path cross-sections and trailing-edge shapes at jet exit test facility and obtained multi-axis thrust vectoring control. Federspiel and Anderson (1995, 1997) investigated SVC/throat skewing combined concept and mechanical/fluidic concept and extended the usage of SVC method. In the perspective of design and application of an SVC nozzle, previous work provides useful conclusions and guidance.

In this paper, a practical comparison of a 2D SVC nozzle and an axisymmetric SVC nozzle was conducted, which would be helpful when choosing the SVC type for an aircraft. A series of quantitative research on the investigation of the differences of flow characteristics and vector performance between two types of SVC nozzles were carried out numerically, based on solving 3D Reynolds-averaged Navier–Stokes equations. Basic flow mechanism and the influence of critical aerodynamic parameters, including NPR, SPR and $M_\infty$, were investigated. The vector angle and thrust coefficient were compared to evaluate performance differences. Especially, for the study of effect of $M_\infty$, a new reasonable definition of side-force was proposed, taking the pressure distributions on nozzle outer wall into account. This work aims to improve understanding on an SVC nozzle.

2. NUMERICAL APPROACH

2.1 SVC Geometric Models

2D and axisymmetric SVC nozzles were investigated with same characteristic sizes, including nozzle inlet area ($A_7$), nozzle throat area ($A_8$), nozzle discharge area ($A_9$), nozzle convergent section length ($X_C$), nozzle divergent section length ($X_D$), nozzle length ($L$), secondary injection angle ($\theta$), secondary injection position ($X_J$) and secondary injection area ($A_s$), which are shown in Fig. 1 and Table 1. And for the two types of SVC nozzles, the designed nozzle pressure ratio (NPRD) is 13.88, while nozzle exit Ma number is 2.37. As seen in Fig. 1, the secondary injection slot of a 2D SVC nozzle has the same span-width with nozzle, and the injection slot of an axisymmetric SVC has a circular angle ($\omega$) of 90°.

![Fig. 1. Sketch of SVC nozzles.](image)

<table>
<thead>
<tr>
<th>Character parameters of SVC nozzles</th>
<th>$A_7/A_8$</th>
<th>$X_D/L$</th>
<th>NPRD</th>
<th>$A_9/A_8$</th>
<th>$X_C/X_D$</th>
<th>$\theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.33</td>
<td>0.829</td>
<td>13.88</td>
<td>0.0934</td>
<td>0.688</td>
<td>90</td>
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</table>

2.2 Governing Equations

The numerical simulations have been carried out using Fluent of ANSYS 14.0. The flow characteristics were obtained by solving the compressible form of conservation equations continuity, momentum and energy equations in Cartesian coordinates, shown as follow:

Continuity:

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0$$  \hspace{1cm} (1)

Momentum:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}((\rho u_i u_j) ) = \frac{\partial P}{\partial x_j} + \frac{\partial \tau_{ij} }{\partial x_i} + \rho g_i + F_i$$  \hspace{1cm} (2)

Energy:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_j}([u_j (\rho E + p)] = \frac{\partial}{\partial x_j} \left\{ (\alpha + C_{Pm}) \frac{\partial T}{\partial x_j} + u_j (\tau_{ij})_{\text{eff}} \right\}$$  \hspace{1cm} (3)

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

$$ (\tau_{ij})_{\text{eff}} = \mu_{\text{eff}} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu_{\text{eff}} \frac{\partial \delta}{\partial x_i}$$  \hspace{1cm} (4)

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. Second order upwind scheme is used in the spatial discretization, and second implicit scheme adopted for the time. The implicit density-based algorithm is chosen for the flux type.

2.3 Turbulence Model and Computational Grid

An SVC nozzle features transverse injection, and the applicability of turbulence model varies with working conditions, e.g. free stream Ma number, momentum ratio of secondary flow to primary flow et al. (Sriram, et al. 2004). In the section, experimental data of a 2D SVC nozzle from Deere (2000) was used to check the validation of turbulence models; the Spalart-Allmaras (S-A), Realizable $\kappa$-$\varepsilon$ and shear stress transport (SST) $\kappa$-$\omega$ turbulence models were considered; and the predicted pressure distributions on nozzle wall are shown in Fig. 2. Compared with experimental data, the position of pressure abrupt increase (separation position of boundary layer upstream of injection slot) from S-A and Realizable $\kappa$-$\varepsilon$ turbulence models lays behind experiment data, while SST $\kappa$-$\omega$ model offers well fitted results, and the error in separation position is less than 0.5%. Moreover, in high pressure zone upstream of injection slot and low pressure zone downstream of injection slot, SST $\kappa$-$\omega$ model behaves better, and the predicted error is within 2%. Therefore, the SST $\kappa$-$\omega$ turbulence model with the compressible effect is selected for the study.

Then, a study on grid independence of the two SVC nozzles was conducted. Only half geometric models were used due to the symmetry of SVC nozzles, seen in Fig. 3. To satisfy the requirement of SST $\kappa$-$\omega$ turbulence model on $y^+$ less than 5, the height of first grid above walls was carefully arranged. Totally, six grids were considered. They are 2.0 million, 2.8 million and 4.0 million cells for a 2D SVC nozzle and 1.5 million, 2.3 million and 3.4 million cells for an axisymmetric SVC nozzle, respectively. The flow characteristics were focused on at the simulation condition of NPR of 13.88, SPR of 1.0 and free stream Ma number of 0.05. Pressure distributions along center line on nozzle down wall are shown in Fig. 4. The position and pressure are non-dimensionalized by length of nozzle divergent section and nozzle inlet total pressure, respectively. It is seen that for the two SVC nozzles the predicted results using coarse grid (grid #1 and grid #4) deviate a little from that of other grids. And results using middle grid (grid #2 and grid #3) and fine grid (grid #5 and grid #5) almost the same. It is concluded that results would not show differences when cell number exceed 2.8 million and 2.3 million for the two SVC nozzles respectively. Taking the calculation accuracy and time cost into account, the middle grids (grid #2 and grid #5) were selected to carry out the research work in this paper.

2.4 Boundary Conditions

Pressure inlet boundary is specified for nozzle inlet, secondary injection inlet and outer flow field inlet shown in Fig. 3, of which the total pressure ($p_0^*$, $p_s^*$, $p_n^*$), total temperature ($T_0^*$, $T_s^*$, $T_n^*$) and flow angle are prescribed. Nozzle pressure ratio varies from 6-16 while secondary pressure ratio has a range of 0.6, 0.8, 1.0, 1.2, and 1.5. 800 K is set for
nozzle inlet total temperature, while Eq. (5) offers the total temperature of secondary inlet.

\[ T_{n_2}^* = T_0 = \left( \frac{P_n^*}{P_0} \right)^{K-1} \]  

(5)

On the outlet boundary, the static pressure \( P_{st} \) is imposed and the other variables are extrapolated from the interior. Symmetry boundary conditions are adopted at the center face. On pressure-far-field boundary, static pressure, free-stream \( M_\infty \) (0.05, 0.3, 0.5, 0.7, 0.9, 1.1 and 1.3) and flow direction are provided. Interior boundary including the nozzle exit and the secondary injection exit are monitored. Impermeable, no-slip and adiabatic wall boundaries are applied on the solid walls to ensure zero normal flux of mass, momentum and energy crossing the mesh face that lapped with the wall boundary.

\[ \delta_p = \tan^{-1} \left( \frac{F_x}{F_y} \right) \]  

(6)

In the Eq. (6), \( F_x \) and \( F_y \) are components of thrust in X and Y direction respectively, and they are calculated from momentum equation, and in detail they are in Eq. (7) and Eq. (8).

\[ F_x = \int \rho v_x v_x dA \]  

(7)

\[ F_y = \int \rho v_y v_x dA \]  

(8)

Thrust coefficient is defined as the ratio of actual thrust to ideal thrust, seen in Eq. (9).

\[ C_{fg} = \frac{F_{fg nozzle}}{F_{fg nozzle} + F_{fg sec.}} \]  

(9)

where \( F_{fg nozzle} \) is the actual thrust of a nozzle and is calculated by equation of \( F_{fg nozzle} = F_{1 nozzle}^2 + F_{2 nozzle}^2 \). \( F_{fg nozzle} \) and \( F_{fg sec.} \) are the ideal thrust of primary flow and secondary flow, and they are obtained in Eq. (10) and Eq. (11), respectively:

\[ F_{1 nozzle} = m_{n_1} \frac{2KR}{K-1} \left[ T_0^* \left( 1 - \left( \frac{P_0}{P_n^*} \right)^{K-1} \right) \right] \]  

(10)

\[ F_{1 sec.} = m_{s_1} \frac{2KR}{K-1} \left[ T_0^* \left( 1 - \left( \frac{P_0}{P_s^*} \right)^{K-1} \right) \right] \]  

(11)

where \( \kappa \) is the ratio of specific heat.

Additionally, another critical parameter \( \omega \sqrt{\tau} \) named as corrected flow ratio of secondary flow is defined (in Eq. (12)); it represents the momentum ratio of secondary flow to primary flow, and is critical to the separation length upstream of injection port and jet trajectory. Because the secondary flow is extracted from high pressure components of an aero-engine, there is a restriction on secondary flow rate. Generally, the value of \( \omega \sqrt{\tau} \) should be within 0.15.

\[ \omega \sqrt{\tau} = \frac{m_{s_1} \sqrt{T_s}}{m_{n_1} \sqrt{T_n}} \]  

(12)

where \( \omega \) is the ratio of secondary mass flow rate to nozzle mass flow rate, and \( \tau \) is the ratio of secondary flow total temperature to nozzle inlet total temperature.

3. Results and Discussion

3.1 Flow Mechanism of SVC Nozzles

Flow characteristics (on symmetric plane) of a 2D SVC nozzle are shown in Fig. 5. When high pressure secondary flow is injected into supersonic primary flow of nozzle divergent section, strong interactions between injected jet and primary flow occur. A quasi-two-dimensional oblique shock wave, rooting from supersonic flow of boundary layer, is induced. The strength and angle of oblique shock wave are mainly affected by jet penetrating
depth which denotes jet disturbance degree and is associated with nozzle geometric parameters and corrected flow ratio of secondary flow ($\omega_{\text{ref}}$). High pressure rise caused by induced shock wave brings out strong positive pressure gradient for local flow nearby nozzle wall, thickening boundary layer and even making boundary layer to separate. Then a cuneiform-like separation zone before injection slot is formed, and it interacts with induced shock wave, resulting in a $\lambda^*$ shock wave system. Also shown in Fig. 4, the $Ma$ number before $\lambda^*$ shock wave is about 1.80-2.25, while that after $\lambda^*$ shock wave is about 0.60-2.00. In one aspect, the shock wave loss here is the dominating loss source for an SVC nozzle, and it can cause a large reduction for nozzle thrust coefficient ($C_{th}$). In another aspect, the $\lambda^*$ shock wave leads to unbalanced pressure distributions on nozzle upper and lower walls (Fig. 6) and provides side-force for primary flow deflecting. Commonly the unbalanced pressure zone characterized is by length of high pressure zone ($L_{\text{sep}}$) upstream of injection slot, which can illustrate vector performance of an SVC nozzle; and as is investigated, $L_{\text{sep}}$ is mainly associated with $\omega_{\text{ref}}$. From analysis on data of different working conditions, an approximate fitting equation can be obtained as follow.

$$L_{\text{sep}} / W_e = 7.493 + 2.234 \omega_{\text{ref}} + 2.7596 (\omega_{\text{ref}})^2$$  \hspace{1em} (13)

Fig. 5. Flow field on the symmetric plane of a 2D SVC nozzle (NPR=13.88, SPR=1.0).

Besides, upstream and downstream of injection slot, complex flow separating and vortex system exist. A pair of counter-rotating vortices can be witnessed upstream of injection slot; they are formed by boundary layer separation and jet entrainment, respectively. And the dividing line of the two vortices lays on the position of peak pressure (seen in Fig. 6). Open or close separation appears downstream of injection slot under different working conditions; when $\omega_{\text{ref}}$ is less than 0.088, injected jet reattaches nozzle lower wall, there is a close separation bubble. Otherwise, open separation would show up, and ambient air out of an SVC nozzle will be entrained into the separation zone. Also flow unsteadiness can be caused by open separation; the jet trajectory, shock wave position, pressure distribution and vector angle will be affected. Results show that, from fast Fourier transform (FFT) of monitored pressure, maximal pressure amplitude of 4.05 kPa is obtained; and for the vector angle, a fluctuation within 2% is observed.

Though, a 2D SVC nozzle is characterized by two dimensional flow pattern, three dimensional effects are also clear near side walls. Figure 6 shows the longitude pressure distribution of different span-wise position (Z direction); the X coordinate is non-dimensionalized by nozzle divergent section length ($L_D$), while the Y coordinate is non-dimensionalized by total pressure of nozzle inlet. As can be seen, the boundary layer separation positions of $z/W$ of 0.01 and 0.02 are slight ahead of others*, but when $z/W$ is larger than 0.025, the separation positions of boundary layer are coincident. The three dimensional effect is associated with the merger of boundary layers on side wall and lower wall of an SVC nozzle. And this causes the low energy zone to increase, which weakens the resistance ability of boundary layer on positive pressure gradient. Thus flow near sidewall separates earlier. The turbulent kinetic distribution of different X sections shows the influence of shock wave on sidewall, seen in Fig. 7; it can represents the increase on thickness of boundary layer on sidewall, which also brings out flow loss. Additionally, at the corner of sidewall

![Fig. 6. Pressure distributions on nozzle lower wall of different z positions (NPR=13.88, SPR=1.0).](image)

![Fig. 7. Turbulent kinetic energy distributions on different sections (NPR=13.88, SPR=1.0).](image)
and lower wall, another three dimensional effect can be seen. A stream-wise vortex (seen in Fig. 7) is caused by high pressure from jet and low pressure from separated flow downstream of injection slot. It affects the diffusion of nozzle exhausting gas which has high temperature and high species concentration, and eventually reduces the infrared radiation intensity of SVC nozzle by 35%-50% at some high observation angles.

Meanwhile low speed flow goes around injection slot into low pressure zone after injection slot, forming a Y direction vortex (seen in Fig. 9 (a) and (b)); it plays a role of balancing pressure distributions, in another word, it connects the high pressure zone upstream of injection slot and low pressure zone downstream of injection slot, and this is also called “pressure release mechanism” which affects vector performance under some working conditions and causes differences from a 2D SVC nozzle.

As for an axisymmetric SVC nozzle, the basic working principle is similar with a 2D SVC nozzle, however, the flow characteristics are dominated by three dimensional flow pattern, and they are seen in Fig. 8 which show the Ma number distributions on different X sections (x/XD = 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0); the shock wave is a curved surface which can be identified by discontinuity of flow-field on X sections, while the separation line of boundary layer is a spatial curved line (convergent limited streamline seen in Fig. 9 (a)). Moreover, compared with a 2D SVC nozzle, the secondary injection slot of an axisymmetric SVC nozzle is not restricted by nozzle walls in span-wise direction, and it changes the configurations of vortices, especially for those near injection slot. As can be seen in Figs. 8 and 9, positive gradient between high pressure zone upstream of injection slot and low pressure zone downstream of injection slot accelerates local flow and induces vortices. The labeled local high speed flow (in Figs. 8 (c), (d) and (e)) is from separated boundary layer upstream of injection slot and outer layer of boundary layer, goes by injection slot and develops into flow with stream-wise vortex (in Fig. 9 (c) ) and it is also benefits for the reduction of infrared radiation intensity of an SVC nozzle.

3.2 Influence of NPR on Vector Performance of SVC Nozzles

The influence of nozzle pressure ratio (NPR) on vector performance is due to the variation of nozzle wall pressure distributions caused by shock wave and flow separation. Generally, under different working conditions, the high pressure zone upstream of injection slot and low pressure zone downstream of injection slot are two main affecting zones. When NPR varies, the corrected flow ratio of secondary flow ($\omega \sqrt{F}$) keeps almost unchanged
(the variation of $\omega_\tau$ is within 1%). According to Eq. (9), the zone of high pressure upstream of injection slot is also unchanged. However, for the low pressure zone downstream of injection slot, static pressure on nozzle wall, which is non-dimensionalized by nozzle inlet total pressure, shows obvious variation, seen in Fig. 10; with the decrease of NPR, the local non-dimensional wall pressure increases from about 0.06 to 0.14, and this makes the efficient non-dimensional side-fore to ascend, resulting in higher vector angle ($\delta_p$). Seen in Fig. 11, comparing the $\delta_p$ of different NPR conditions, about 85.71% and 56.20% increase in $\delta_p$ are obtained when NPR decreases from 16 to 6 for a 2D SVC nozzle and an axisymmetric SVC nozzle respectively.

![Fig. 10. Pressure distributions on down wall of a 2D SVC nozzle.](a) NPR=6 (b) NPR=16]

For the flow loss of SVC nozzles, it includes shock wave loss, separation loss and friction loss, among which shock wave loss dominates. From Fig. 11, it can be seen, the thrust coefficients ($C_{fg}$) of two SVC nozzles are about from 0.910 to 0.932; the maximal $C_{fg}$ of 0.931 and 0.932 are achieved at NPR of 10 and 13.88 respectively for 2D and axisymmetric SVC nozzles. And this is related with the induced shock wave, for a 2D SVC nozzle, it increases static pressure of primary flow and counteracts the thrust loss caused by over-expansion partly, which is not obvious for an axisymmetric SVC nozzle. Therefore, the maximal $C_{fg}$ of a 2D SVC nozzle is obtained at over-expansion condition, while that of an axisymmetric SVC nozzle is achieved at designed pressure condition. When NPR is less than 10, the $C_{fg}$ of a 2D SVC nozzle is larger; at NPR of 6 and 8, the increment are 1% and 0.5% respectively. But when NPR is larger than 10, the $C_{fg}$ of a 2D SVC nozzle is smaller by 1.3% and 0.6% for NPR of 13.88 and 16 respectively.

### 3.3 Influence of SPR on Vector Performance of SVC Nozzles

With the increase of secondary pressure ratio (SPR), the corrected flow ratio of secondary flow ($\omega_\tau$) and momentum ratio of secondary flow to primary flow ascend, which enhances the interactions between injected jet and primary flow and enlarges the jet penetration depth. Therefore, the angle of shock wave increases, the position of shock wave moves forwards, and it makes the boundary layer separating zone (the high pressure zone) upstream of injection slot to increase and results in larger side-fore for primary flow deflecting. Fig.12 (a) and (b) shows the limited streamline and pressure distribution wall of an axisymmetric SVC nozzle; it can be seen that the high pressure zone caused by induced shock wave grows substantially from SPR of 0.6 to 1.5, correspondingly the vector angle ($\delta_p$) grows from 5.04º to 12.16º. It is concluded that the SPR is a key
controlling parameter for SVC nozzles.

Comparing the thrust coefficient ($C_\theta$) of the two SVC nozzles, it is obtained in Fig. 13, the $C_\theta$ of an axisymmetric SVC nozzle is always higher than that of 2D SVC nozzle; at smaller SPRs of 0.6 and 0.8, the differences between them are about 0.3%; while SPR are 1.0, 1.2 and 1.5, the differences are 1.17%, 0.89% and 0.76% respectively. The larger shock wave loss of a 2D SVC nozzle is the main affecting reason. As is discussed in last passage, the shock wave is more close to upper wall of 2D SVC nozzle, and more primary flow go through it, therefore larger loss is generated. So a conclusion can be drawn that at designed nozzle pressure condition or nozzle under-expansion conditions, the performance of axisymmetric SVC nozzle is better than that of 2D SVC nozzle over wide range of SPRs.

![Figure 12](image1.png)

**Fig. 12. Limited streamlines and pressure distributions on SVC nozzle wall (NPR=13.88).**

Shown in Fig.13, the variation of $\delta_p$ with different SPRs under designed nozzle pressure ratio (NPR0 of 13.88), the difference between $\delta_p$ of a 2D and an axisymmetric SVC nozzle is within 1% when SPR is less than 1.0; however when SPR increases from 1.0 to 1.5, $\delta_p$ of the two SVC nozzles become to 10.84° and 12.16° respectively, and the $\delta_p$ of a 2D SVC nozzle is 12% less than that of an axisymmetric SVC nozzle. This is mainly because of the spatial position of induced shock wave; for a 2D SVC nozzle, when SPR is larger than 1.0, the induced shock wave gradually comes close to the upper wall of nozzle, and interacts with it at SPR of 1.5. Seen in Fig.12 (c), the induced shock wave causes closed separation of boundary layer on upper wall, makes local non-dimensional pressure to increase abruptly from 0.10 to about 0.26, and finally reduces the total side-fore of primary flow, weakening the augment of $\delta_p$ obviously. But for an axisymmetric SVC nozzle, at the condition of SPR of 1.5, although the high pressure zone goes beyond the center line (dashed line in Fig. 12 (b)) to the upper zone, its influence on side-fore and vector performance is gentle, so is it on $\delta_p$.

3.4 Influence of Free Stream $M_\infty$ Number on Vector Performance of SVC Nozzle

Free stream $M_\infty$ number has effects on subsonic zones of nozzle internal flows, e.g. separation zone downstream of injection slot and boundary layer on nozzle upper wall, and has effect on pressure distributions of nozzle outer wall. As is investigated, the former factor can be neglected, while the later one changes total side-fore of SVC nozzle and varies with $M_\infty$. In order to estimate influence of $M_\infty$ on vector performance of SVC nozzles, the side-force ($F_y$) should be redefined. Taking the unbalanced pressure on nozzle outer wall into account, the modified side-force $F_{y,\text{modi}}$ is calculated as follow:

$$ F_{y,\text{modi}} = \int_{\delta_p}^{9} \rho v y_j dA + \int_{10}^{\delta_p} (\rho - p_0) \cos \Theta dA \tag{14} $$

In the secondary term of Eq. (10), 9 and 10 represent the position of nozzle exit and the position of maximal section of nozzle outer wall respectively, and $\Theta$ is angle between Y direction and the normal direction of nozzle outer wall.

When $M_\infty$ is larger than 0.5, flow separation on
nozzle outer wall appears, seen in Fig. 14, and separation zone is larger on upper wall than that on lower wall; this is due to the impact of free stream and primary flow, which also causes larger pressure on upper wall than that on lower wall. Therefore the unbalanced pressure on nozzle outer wall is generated, and eventually it weakens the total side-force and vector performance of SVC nozzles. Additionally, with the increase \( M_\infty \), separation zone on nozzle outer wall enlarges and achieves maximal value at transonic condition of \( M_\infty \) of 0.9 and 1.3, seen in Figs. 14(b), (c), (f) and (g), consequently, the largest decrease on vector angles (\( \delta_p \)) can be witnessed; compared the condition of \( M_\infty \) exceeds 1.1, the maximal difference on \( \delta_p \) between 2D and axisymmetric SVC nozzles is obtained, and it is about 11.2\%. Thrust coefficient (\( C_{fg} \)) of SVC nozzles represents the nozzle internal performance, so the unmodified side-force is still used to calculate actual thrust of SVC nozzles. Seen in Fig. 15, the variation of \( C_{fg} \) with \( M_\infty \) is within 0.2\% and the \( C_{fg} \) of an axisymmetric SVC nozzle is about 0.8\% than that of a 2D SVC nozzle. And in summary, the axisymmetric SVC nozzle has better vector performance than 2D SVC nozzle under different \( M_\infty \) conditions.

Vector performance comparisons of two SVC nozzles are shown in Fig. 15. It is clear that \( M_\infty \) has the same affecting principle on \( \delta_p \), but the affecting level is different. This is caused by the configurations of nozzle outer walls; for a 2D SVC nozzle, the rectangular section can prevent the connection of the high pressure on upper wall and low pressure on lower wall, therefore larger separation zones and larger unbalanced pressure distributions are formed, seen in Fig. 14, and the decrease on \( \delta_p \) is more obvious. Noticeably, at \( M_\infty \) of 1.1, the maximal difference on \( \delta_p \) between 2D and axisymmetric SVC nozzles is obtained, and it is about 11.2\%.

Thrust coefficient (\( C_{fg} \)) of SVC nozzles represents the nozzle internal performance, so the unmodified side-force is still used to calculate actual thrust of SVC nozzles. Seen in Fig. 15, the variation of \( C_{fg} \) with \( M_\infty \) is within 0.2\% and the \( C_{fg} \) of an axisymmetric SVC nozzle is about 0.8\% than that of a 2D SVC nozzle. And in summary, the axisymmetric SVC nozzle has better vector performance than 2D SVC nozzle under different \( M_\infty \) conditions.

In this paper, flow characteristics and vector performance of different SVC nozzles were studied based on CFD. The accuracy of simulation results was guaranteed by comparing predicted results from the chosen numerical method with experimental results of Deere’s work (2000) at a selected condition. At wide range working conditions of critical parameters, e.g. NPR, SPR, \( Ma \) number, the predicted results on vector performance and thrust coefficient by a chosen turbulence model may have a little different from experimental results, due to the simulation ability on flow separation under negative pressure gradient and shock wave / boundary layer interactions. But we believe the deviation would not have significant influences on quantitative results and qualitative regularity, and the judgment could be confirmed by the later experimental work.

4. CONCLUSION

The flow characteristics and vector performance (vector angle and thrust coefficient) comparison on
2D and axisymmetric SVC nozzles were investigated numerically. The affecting factors including nozzle pressure ratio (NPR), secondary pressure ratio (SPR) and free stream Ma number ($M_{\infty}$) were considered, and conclusions can be drawn as follow.

1) The unbalanced pressure distribution on nozzle walls induced by secondary injection is the dominating factor for primary flow deflecting, while the shock wave is responsible for thrust loss which is about a reduction of 6%-12% on thrust coefficient. Compared with flow characteristics a 2D SVC nozzle, free restriction of the injection slot of an axisymmetric SVC nozzle changes the configurations of vortices and caused the pressure release between high pressure zone upstream of injection slot and low pressure zone downstream of injection slot.

2) Under smaller NPR, the pressure release mechanism of an axisymmetric SVC nozzle causes vector angle ($\delta_p$) smaller, and it is about 16.5% less than that of a 2D SVC nozzle at NPR of 6, while there is tiny difference $\delta_p$ at NPR of 13.88 and 16. When SPR exceeds 1.2, the induced shock wave interacts with the upper wall of a 2D SVC nozzle and results in 12% smaller of $\delta_p$ than that of an axisymmetric SVC nozzle at SPR of 1.5; meanwhile the thrust coefficient ($C_{fg}$) of a 2D SVC nozzle is smaller within 1.2%.

The unbalanced pressure distribution on SVC nozzle outer walls caused by free stream weakens vector performance, and its influence on a 2D SVC nozzle is more obvious, especially under transonic condition of $M_{\infty}$ of 0.9 and 1.1, at which condition the $\delta_p$ of a 2D SVC nozzle is 11.2% smaller than that of an axisymmetric SVC nozzle; the variation of $C_{fg}$ with $M_{\infty}$ is within 0.2%, and the $C_{fg}$ of an axisymmetric SVC nozzle is about 0.8% larger than that of a 2D SVC nozzle.

Other research work would be carried out in the future, e.g. investigation of the comparison on afterbody penalty, installment performance and infrared radiation characters for 2D and axisymmetric SVC nozzles, which could help to understand the comprehensive performance of this kind of fluidic thrust vectoring technology.

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