Effect of Axisymmetric Sonic Nozzle Geometry on Characteristics of Supersonic Air Jet

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The effect of nozzle geometry on sonic line and characteristics of supersonic air jet was studied. Computational fluid dynamics was applied in this study. The axisymmetric nozzle geometries investigated were two different contour converging nozzles, two different conically converging sharp-edged nozzles and a sharp-edged orifice. The results show that the supersonic jet structure, sonic line and streamlines in supersonic jet are strongly influenced by the nozzle geometry, and the total pressure loss increases with the increase of Mach disk diameter. The present numerical simulation is an effective tool to evaluate compressible flows in supersonic air jet.

Keywords: compressible flow, supersonic jet, non-equilibrium condensation, simulation.


Introduction

Supersonic free jet has long received much interest from researchers since it has had many potential applications for aeronautical and mechanical industries, and it has also been of importance in academic aspects, as well. Much effort has been devoted to the major characteristic features of the supersonic jet\textsuperscript{1-6}. According to these previous works, the under-expanded supersonic jet is specified by its barrel shock structure, Mach disk location, jet boundary configuration, velocity decay and supersonic length, etc., which are usually determined by the jet pressure ratios.

The Mach disk is a distinctive characteristics of the near field shock wave structure in free jet issued from sonic or supersonic nozzles. From the previous investigations of the Mach disk, empirical relationships between the stagnation to ambient pressure ratio and Mach disk diameter and location for different gases, gas-particle flows and reacting gas flows were established experimentally\textsuperscript{7-11}. It was clarified from these results that the Mach disk diameter was strongly affected by the nozzle geometry. It is considered that this is caused by the distortion of sonic line due to nozzle geometry.

However, there is little detailed information on the sonic line.

In the present study, a computational fluid dynamics work is applied to clarify the effect of nozzle geometry on the sonic line and characteristics of the supersonic air jet. The axisymmetric nozzle geometries investigated are two different contoured converging nozzles, two different conically converging sharp-edged nozzles and a sharp-edged orifice. Furthermore, the computational results are compared with the previous experimental ones.

CFD Analysis

Governing equations

The governing equations are the unsteady compressible Navier-Stokes equations written in an axisymmetric coordinate system $(x, y)$ ($y$: radial distance from the center line) as follows;

\begin{equation}
\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = \frac{1}{Re} \left( \frac{\partial R}{\partial x} + \frac{\partial S}{\partial y} \right) + \frac{1}{y} H
\end{equation}

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Nomenclature

\begin{align*}
C_c & \quad \text{Coefficient of contraction (-)} \\
c_p & \quad \text{Specific heat at constant pressure (J/kg°C)} \\
D & \quad \text{Diameter (m)} \\
E,F & \quad \text{Numerical flux (-)} \\
E_s & \quad \text{Total energy per unit volume (J/m³)} \\
H,Q & \quad \text{Source term (-)} \\
L & \quad \text{Length (m)} \\
p & \quad \text{Static pressure (Pa)} \\
R,S & \quad \text{Viscous term (-)} \\
T & \quad \text{Temperature (K)} \\
U & \quad \text{Conservation mass term (-)}
\end{align*}

where,

\begin{align*}
U &= \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ E_s \\ \end{bmatrix}, \quad E = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ \end{bmatrix}, \quad F = \begin{bmatrix} \rho v \\ \rho v u \\ \rho v^2 + p \\ \end{bmatrix}, \\
R &= \begin{bmatrix} \tau_{xx} \\ \tau_{xy} \\ \tau_{yy} \\ \end{bmatrix}, \quad S = \begin{bmatrix} 0 \\ \tau_{yx} \\ \tau_{yy} \\ \end{bmatrix}, \quad H = \begin{bmatrix} -\rho v \\ -\rho uv \\ -\rho v^2 \\ \end{bmatrix} (2)
\end{align*}

where,

\begin{align*}
E_s &= \rho C_p T + \frac{1}{2} \rho (u^2 + v^2) (3) \\
p &= G \left[ E_s - \frac{1}{2} \rho (u^2 + v^2) \right] (4)
\end{align*}

\begin{equation}
G = \gamma - 1
\end{equation}

\begin{equation}
\alpha = ur_{xx} + vr_{yx} + k \frac{\partial T}{\partial x}, \quad \beta = ur_{xy} + vr_{yy} + k \frac{\partial T}{\partial y}
\end{equation}

where \( \tau_{xx}, \tau_{xy}, \tau_{yx} \) and \( \tau_{yy} \) are components of viscous shear stress. \( k \) is thermal conductivity.

The governing equation systems that are non-dimensionalized with reference values at the inlet conditions upstream of the nozzle are mapped from the physical plane into a computational plane of a general transform. To close the governing equations, Baldwin-Lomax model\(^{12}\) is employed in computations. A third-order TVD (Total Variation Diminishing) finite difference scheme with MUSCL\(^{13}\) is used to discretize the spatial derivatives, and a second order-central difference scheme for the viscous terms, and a second-order fractional step is employed for time integration.

Fig.1 Details of models