Propulsion and Power Research 2016;5(1):22–33

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Propulsion and Power Research

www.sciencedirect.com

ORIGINAL ARTICLE

Nozzle geometry variations on the discharge coefficient

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Received 14 February 2014; accepted 16 November 2015
Available online 12 February 2016

KEYWORDS

Boundary layer;
Compressible flow;
Reynolds-averaged Navier–Stokes (RANS);
Shear layer;
Sonic lines;
Supersonic core

Abstract Numerical works have been conducted to investigate the effect of nozzle geometries on the discharge coefficient. Several contoured converging nozzles with finite radius of curvatures, conically converging nozzles and conical divergent orifices have been employed in this investigation. Each nozzle and orifice has a nominal exit diameter of 12.7×10^{-3} m. A 3rd order MUSCL finite volume method of ANSYS Fluent 13.0 was used to solve the Reynolds-averaged Navier–Stokes equations in simulating turbulent flows through various nozzle inlet geometries. The numerical model was validated through comparison between the numerical results and experimental data. The results obtained show that the nozzle geometry has pronounced effect on the sonic lines and discharge coefficients. The coefficient of discharge was found differ from unity due to the non-uniformity of flow parameters at the nozzle exit and the presence of boundary layer as well.

1. Introduction

Nozzles are found encountering in a wide variety of engineering applications, mainly to generate jets [1–4], flow metering [5–7], and sprays [8,9]. The accurate prediction of the compressible nozzle flows is still challenging for the aerodynamicist, and achieves increasing importance since

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Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

http://dx.doi.org/10.1016/j.jppr.2016.01.002

Nomenclature

a	sound speed (unit: m/s)
A_e	area at nozzle exit (unit: m^2)
C_d	discharge coefficient
C_p	specific heat at constant pressure (unit: J/(kg · K))
D_e	diameter at nozzle exit (unit: m)
D_m	diameter of Mach disk (unit: m)
E	total energy per unit mass (unit: J/kg)
$\boldsymbol{F}$	inviscid flux vectors
$\boldsymbol{G}$	viscous flux vectors
H	total enthalpy per unit mass (unit: J/kg)
$\boldsymbol{H}$	vector for source terms
i	unit vector in the x-direction
j	unit vector in the y-direction
k	unit vector in the z-direction
k	turbulent kinetic energy per unit mass (unit: J/kg)
l_0	location of minimum jet section (unit: m)
L_m	location of Mach disk (unit: m)
L_s	length of supersonic core (unit: m)
$\dot{m}$	mass flow rate (unit: kg/s)
M	Mach number
p	pressure (unit: Pa)
q	heat flux (unit: W/m^2)
$\boldsymbol{Q}$	dependent vector of primary variables
r	radius (unit: m)
R	radius of curvature (unit: m)
Re	Reynolds number
T	temperature (unit: K)
U_r	reference velocity (unit: m/s)
w	electromagnetic energy density (unit: J/m^3)
u_i, u_j	Cartesian mean velocity components (unit: m/s)
v_x, v_y, v_z	Cartesian velocity components in x-, y- and z-directions (unit: m/s)

Greek symbols

β	conic divergent angle (unit: degree)
δ	boundary layer thickness (unit: m)
δ_{sh}	shear layer thickness (unit: m)
γ	ratio of specific heats
μ	dynamic viscosity (unit: Pa · s))
υ	kinematic viscosity (unit: m^2/s)
θ	conic convergent angle (unit: degree)
ρ	density (unit: kg/m^3)
$\Re$	gas constant (unit: J/(kmol · K))
τ	shear stress (unit: Pa)
ω	specific dissipation rate (unit: s^{-1})

Subscripts

0	stagnation point
b	ambient
t	turbulent
x	x-coordinate
y	y-coordinate
x	z-coordinate

the nozzle performance is significantly influenced by its inlet geometry. The flow emanating from nozzle exit serves as the initial conditions for the downstream jet flows. Thus, the studies on nozzle geometric effect are becoming a major interest for compressible and incompressible nozzle flows.

Several works reported information on aerodynamic features of jets and flow with various inlet-boundary conditions and nozzle geometries. Matsuo et al. [10] performed numerical study to investigate the effect of nozzle geometry on the sonic line and characteristics of the supersonic air jets. Two contoured converging nozzles, two conically converging sharp-edged nozzles (45° and 75°) and a sharp-edged orifice were employed in their study. Otobe et al. [11] investigated the near-field structure of highly underexpanded sonic jets using three nozzle geometries (cylindrical straight nozzle, 75° convergence conical nozzle and 45° divergent orifice), and they proposed an empirical relation of diameter of Mach disk in terms of the pressure ratio, regardless of the nozzle geometry. Menon and Skews [12] conducted a numerical study on underexpanded sonic jets issuing from nozzles with contoured inlet, 45° conical inlet and an orifice inlet under a range of pressure ratio between 2 and 10. Hatanaka and Saito [13] conducted experimental and numerical studies to investigate the effect of nozzle geometry on the structure of supersonic free jets for three simple nozzle geometries over a wide range of pressure ratios up to 90. However, most of the above research works concentrated mainly on the shock and Mach characteristics of jets. In another study, Yu et al. [14] performed numerical simulations to investigate the effects of geometry variations on flow through nozzles. Four nozzle configurations were considered in the study: a baseline nozzle and three modified (extended, grooved and ringed) nozzles. The turbulence characteristics of incompressible flow through nozzles at Reynolds number of approximately 50,000 were investigated in their study. Only very few studies have reported, till date, on the performance of nozzle in terms of discharge coefficients. Hebber et al. [15] conducted an analytical study to obtain a simple, explicit and analytical expression for the discharge coefficients of conical convergent nozzle operating under varying pressure ratios. Cruz-Maya et al. [16] performed study to characterize the discharge coefficients in the venturi sonic nozzle considering the viscous and multidimensional effects of the fluid flow as uncoupled phenomenon.

Since the main purpose of this research is to investigate the effect of nozzle geometries on the performance in terms of discharge coefficients, five cylindrical, four conical convergent nozzles and eight conical divergent orifices with varying radius of curvatures, convergent and divergent angles, respectively, have been used. Sonic lines and their inflections were analyzed to examine the effect of flow parameter at nozzle exit on the discharge coefficient. Based upon the computed results, the nozzle geometry has