International Journal of Heat and Fluid Flow 46 (2014) 70–83

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Characteristics of overexpanded nozzle flows in imposed oscillating condition

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ARTICLE INFO

Article history:
Received 23 October 2013
Received in revised form 6 January 2014
Accepted 6 January 2014
Available online 31 January 2014

Keywords:
Supersonic nozzle
Overexpanded flow
Shock waves
Mach stem
Shock separation

ABSTRACT

A computation study is performed to investigate the effect of imposed oscillation of nozzle pressure ratio (NPR) on the flow structure in a two-dimensional, non-axisymmetric supersonic converging–diverging nozzle. In this study, the overexpanded flow conditions are considered which are dominated by the shock-induced boundary-layer interaction and corresponding free shock separation. The computational results are well validated with the available experimental measurements. Results showed that the internal flow structure of the nozzle is dependent on the process of change of pressure ratio during the oscillation. Distinct flow structures are observed during increasing and decreasing processes of the change of pressure ratio even when the nozzle is at the same NPR. Irreversible behaviors in the locations of free shock separation, Mach stem, and the strength of Mach stem are observed at the same NPRs during this oscillation. However, the nozzle thrust performance does not show the same order of irreversibility as in the cases of shock structures. Further, the effect of oscillation frequency is explored on this irreversible behavior.

1. Introduction

The research on flow through a supersonic converging–diverging nozzle is of great importance in many advanced engineering applications, especially in the aeronautical and aerospace industries. When a supersonic nozzle operates at pressure ratios below its design point (over-expanded), shock waves form inside the nozzle. In these cases, shock waves interact with the boundary layer and as a consequence flow separation occurs (Gatski et al., 2013). However, this separation often grouped into two primary categories namely-free shock separation (FSS) and restricted shock separation (RSS) (Frey and Hagemann, 1999; Hadjadj and Onofri, 2009). In FSS, the separation region downstream of the shock fails to reattach for the remaining length of the nozzle. However, the RSS is characterized by a small separation region or "bubble" which exists immediately downstream of the shock wave. In this region, the mean flow circulates and separates or tilts away from the wall before the flow reattaches and continues down the length of the nozzle as an attached boundary layer.

The compressible flow systems can undergo pulsating conditions which are observed in many real field applications such as in airblast nozzle (injector), Rijke tube burners (McIntosh and Rylands, 1996) and so on. Strasse (2011) investigated the characteristics of the three-stream coaxial airblast nozzle which is used to generate an atomized fuel stream for a large-scale reactor. A pulsatile spray pattern was captured in the experiments and computations with frequencies between 75 Hz and 600 Hz. Depending on the frequencies, three distinct flow patterns was observed namely- spray sheds at outer air/film interface, spray sheds at the inner air/film interface and the bulk flapping of annular liquid film. Further, similar pulsating condition is observed in the interaction of compressible jets in supersonic cross-flow (Semlitsch et al., 2013). In the inviscid computation of Semlitsch et al. (2013), it was documented that the shock pattern is greatly influenced by the jets and flow field becomes pulsating with dominating frequency of 266 Hz (Strouhal-number of 0.5).

The complex unsteady shock behavior in a simple over-expanded planar nozzle has been studied by Johnson and Papamoschou (2010). The experiments have revealed a large asymmetry in the two-dimensional shock structure as well as in the region of separation downstream of the shock. Large scale unsteadiness of the shock wave was also present. To better understand the flow physics of asymmetric nozzle flows, Xiao et al. (2009) performed an unsteady Reynolds-averaged Navier–Stokes calculation on the same geometry. Agreement in the mean shock location, pressure profile, and exit velocity profile was surprisingly good in 2D solutions. Several turbulence models were tested which produced slightly different results and all were able to capture the shock wave asymmetry. Further, in the experiments of Papamoschou et al. (2009), the shock was in lambda structure on one side wall and unsteady. However, there was no evidence of resonant tones.

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0142-727X/$ - see front matter © 2014 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.01.001

Nomenclature

A	area, m^2
a_0	speed of sound, m/s
E	total energy, kJ
F	nozzle thrust, kN
FSS	free shock separation
f	frequency of NPR oscillation, Hz
h_t	half-height at nozzle throat, m
k	turbulent kinetic energy, m^2/s^2
M	Mach number
$\dot{m}$	mass flow rate, kg/s
NPR	nozzle pressure ratio
p	static pressure, kPa
p_{01}	inlet total pressure, kPa
p_b	back pressure, kPa
R	universal gas constant, J/kg K
RSS	restricted shock separation
SBLI	shock-boundary layer interaction
T	time period of NPR oscillation, ms/temperature (K)
t	time, s
T_{01}	inlet total temperature, K
u	x-velocity component, m/s
v	y-velocity component, m/s
x	location in x-direction, m
y	location in y-direction, m

Greek symbols

ε	turbulence dissipation rate, $m^{2/}s^3$
ρ	density, kg/m^3
γ	specific heat ratio
μ	viscosity, Pa s
τ	viscous stress tensor
ω	specific dissipation rate, s^{-1}

Subscripts

e	exit
eff	effective
i	ideal
IS	incident shock wave
MS	Mach stem
s	shock wave
t	throat/turbulent

Time-resolved wall pressure measurements indicated that the shock oscillates in a piston-like manner and most of the energy of the oscillations is at low frequency.

Recently, a mechanism for unsteady separation and shock motion in over-expanded planar nozzles has been identified by Olson and Lele (2013) using numerical simulation and a reduced order model. A series of calculations have been conducted to elucidate the effects of Reynolds number, nozzle geometry, and shock strength on this unsteadiness. It was found that the higher Mach number shock waves produce larger oscillations. However, the incoming boundary layers that are at higher Reynolds numbers produce oscillations with smaller amplitudes. The frequency is primarily dependent on the distance from the mean shock location to the exit of the nozzle and the shock Mach number. Further, the results suggested that the mechanism for the unsteadiness is a feedback loop between the separated shear layer and the shock wave.

Beside these, the response of a transonic channel flow when the shock-wave is subjected to a periodic motion at a well defined frequency was investigated by Bur et al. (2006). Two component laser Doppler velocimeter probing was carried out for a shock oscillation frequency of 40 Hz. Phase-averaged field results enabled both the wave propagation in the core flow and the response of the boundary layer subjected to an oscillating shock wave. It was concluded that in the shock oscillation region, no phase lag was observed between velocities in the core flow and in the boundary layers whereas a significant one has appeared in the downstream subsonic region. An experimental study of force oscillation on normal shock wave in a parallel-walled duct has been conducted by Bruce and Babinsky (2008). The frequencies were varied from 16 Hz to 90 Hz. Normal shocks have been observed to undergo oscillatory motion in response to an imposed varying pressure ratio. It concludes that the mechanism by which shocks respond to back pressure variations was due to change their relative strength by moving so that their relative Mach number matches the pressure jump. These changes in relative shock strength can lead to changes in the extent of boundary layer separation and SBLI structure.

However, in recent years, hysteresis phenomena in fluid flow systems drew attention for their great variety of industrial and engineering applications. Ben-Dor et al. (2003) performed a numerical simulation to investigation the flow-Mach-number-induced hysteresis phenomenon in the shock-on-shock interaction of conical shock waves. The specific geometry of the curvilinear cone was chosen in order to promote the RR $\leftrightarrow$ MR (Regular Reflection $\leftrightarrow$ Mach Reflection) transition. The upstream Mach number is varied from 2.5 to 5.0. As a results, a multiplicity of hysteresis loops was observed. It was concluded that there are flow Mach number ranges in which four different wave configurations, three inviscid and one viscous can be obtained for identical flow conditions. The different wave configurations for identical flow Mach numbers were associated with different pressure distributions. This study further complements an earlier study by Ben-Dor et al. (2001) in which an angle of-incidence-induced hysteresis was investigated. In the experiments, the angle of interaction between the two conical shock waves was altered continuously by moving the curvilinear cone along the axis of symmetry and as a result both the RR $\to$ MR and the MR $\to$ RR transitions were observed and recorded. This viscous dependent hysteresis loop was also obtained numerically by Burstchell et al. (2001) in their Navier–Stokes simulations. In case of planar overexpanded jets, the similar hysteresis behavior was observed by Hadjadj et al. (2004). The dependencies of the flow pattern, and the pressure distribution, inside an air intake on the variations of flight speed of a supersonic/hypersonic aircraft should be accounted for in the designing of intakes and flight conditions for supersonic and hypersonic vehicles. Onofri and Nasuti (2001) first related the hysteresis phenomenon in the RR $\leftrightarrow$ MR transition to the performance of air intakes. However, their numerical study was performed using a two-dimensional geometry, which resembles actual supersonic air intakes. Moreover, Shimshi et al. (2011) performed a viscous simulation to investigate the flow in overexpanded nozzles of planar and tapered shapes at different nozzle pressure ratio (NPR). The simulation reveals complex changes in the flow structure as the ratio between the ambient and the stagnation pressures is increased and decreased. Further, the simulation in planar nozzles showed the existence of a hysteresis process in the transition from regular to Mach and from Mach to regular reflections inside an ideal nozzle. However, such a process did not appear in tapered nozzles. Moreover, the transient side-load phenomena in a rocket nozzle during start-up process was investigated by Lijo et al. (2010). In this case, a hysteresis phenomena of shock structure from FSS to RSS was observed.