Effect of Nozzle Internal Shape on Near-Field Characteristics of Transverse Liquid Jet in a Supersonic Crossflow

Chandrasekhar Medipati, S. Deivandren, and R. N. Govardhan

Abstract We experimentally investigated the effect of orifice geometry on the characteristics of a transversely injected liquid jet into a supersonic crossflow. The focus was to highlight the role of orifice inlet shape on the liquid jet penetration and associated bow shock dynamics. It was found that for a given momentum flux ratio, the liquid jet from a sharp-edged nozzle exhibits higher jet penetration and bow shock strength compared to that from a tapered inlet nozzle. High-speed shadowgraphy images show that the observed variation in the jet penetration and bow shock position is due to strong shock wave–boundary layer interaction in the flow. Quantitative measurements of the jet penetration height and shock fluctuations are obtained for both nozzles. The fluctuations of liquid jet injected through the tapered inlet nozzle have significantly higher in the spatial extent compared to that of the sharp-edged nozzle.

Keywords Liquid jet · Bow shock · Shock wave–boundary layer interaction · High-speed shadowgraphy · Momentum flux ratio

1 Introduction

Transverse injection of liquid jet into supersonic crossflow finds its application in Scramjet combustors. In these combustors, the residence of incoming supersonic air in the combustor is extremely limited, and hence, the efficient atomization and mixing of the liquid fuel with the air are very crucial.

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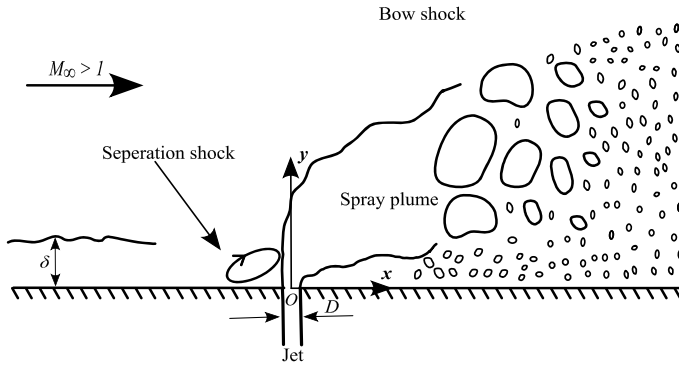Department of Mechanical Engineering, Indian Institute of Science, Bangalore, India

Fig. 1 Schematic of liquid jet into supersonic crossflow

As shown in Fig. 1, the injection of transverse liquid jet into supersonic crossflow results in the formation of 3D bow shock and separation shock, and the interaction between these shocks and the incoming turbulent boundary layer leads to significant shock wave boundary layer interaction. Also, due to the strong exchange of momentum between the crossflow and the jet resulting in atomization of the jet into very fine drops.

2 Literature Review and Objective

The injection of liquid jets in subsonic crossflow has been studied extensively in the recent past. Measurement of penetration of liquid jet into crossflow is an important information for the design of the combustors; hence, large body of literature is focussed on formulation of empirical correlations of spray trajectory. The penetration height and drop size depend strongly on the momentum flux ratio (J) [1] defined as the ratio of momentum flux of the liquid injected to that of the crossflow, exit condition of the liquid jet [2, 3], and the internal shape of the orifice [4]. There have been several initial studies in the supersonic crossflow where the attention is mainly focussed on measurement of penetration heights using shadowgraphy [5, 6] and PDPA [7]. Also, spray characteristics like drop size and its velocity variations are measured using PDPA [7]. Not much attention is given on the effect of the inlet geometry of the orifice on the jet penetration and the shock structures which is very important for the design of efficient supersonic combustors. Our objective of the present study is to experimentally investigate the effect of internal shape (round and sharp edged) of the circular orifice on jet penetration and shock location characteristics, and their unsteadiness when injected into supersonic crossflow keeping the injection location (incoming turbulent boundary layer) and momentum flux ratio between the orifice shapes are same for the entire study.

3 Methodology

All the experiments in the current study are done using the open-circuit blow down wind tunnel at the department of ICER, Indian Institute of science. The tunnel test section cross-section is 15 cm × 15 cm and a length of 1 m. In the entire study, free stream Mach number is kept at 2.5 by maintaining the settling chamber pressure of about 2.8 bar which corresponds to a mass flow rate of 8 kg/s. Both side and top walls of the test section are transparent to provide optical access. Using PIV, the free stream velocity and the turbulence level in the test section were measured and found to be 585 m/s and 1.5% of the free stream velocity, respectively [8].

A high-pressure liquid injection system line is used to deliver liquid into supersonic crossflow. It comprises a liquid chamber, pressure regulator, mass flow metre, flow control valve, pressure gauge, and solenoid valve as shown in Fig. 2. Water is used as the injectant liquid in the entire study. Experiments were conducted with two different nozzle geometries, namely tapered inlet and sharp-edged inlet nozzles, with exit diameters $D = 1$ and 1.2 mm, respectively. In both the cases, the value of L/D is 2. The schematic view of these nozzles is shown in Fig. 3. In the entire study, x, y, and z directions represent streamwise, cross-streamwise, and spanwise directions, respectively.

Both the nozzles were placed at the same streamwise location to ensure that the crossflow turbulent boundary layer thickness approaching the jet would be the same for each ($\delta = 8.85$ mm).
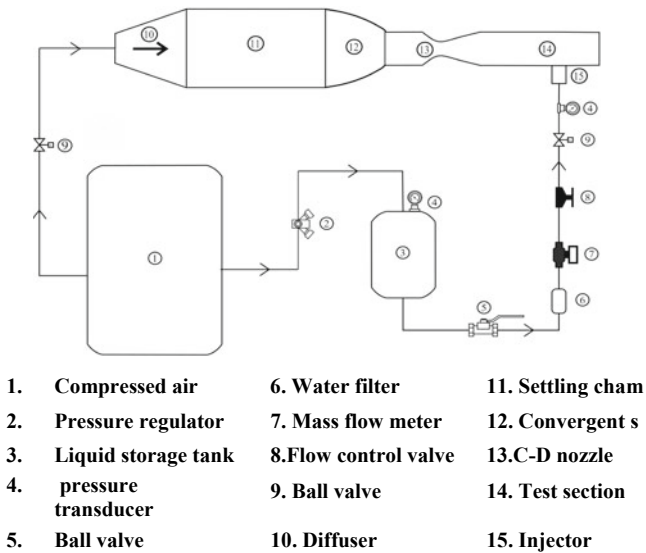
A.   High-Speed Shadowgraphy

1.	Compressed air	6. Water filter	11. Settling cham
2.	Pressure regulator	7. Mass flow meter	12. Convergent s
3.	Liquid storage tank	8.Flow control valve	13.C-D nozzle
4.	pressure transducer	9. Ball valve	14. Test section
5.	Ball valve	10. Diffuser	15. Injector

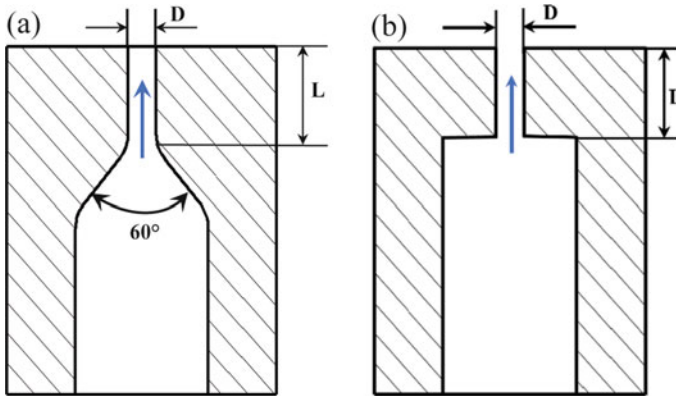**Fig. 2** Schematic of supersonic wind tunnel

Fig. 3 Schematic of **a** tapered inlet nozzle **b** sharp-edged inlet nozzle

High-speed shadowgraphy is employed for the simultaneous visualization of both shock and the windward edge of the jet. It comprises a 150 W halogen lamp (as light source), condenser lens, a spherical concave mirror, and a high speed Photron camera with 105 mm lens as shown in Fig. 4. A collimated light beam is transmitted through the side window (from back) and the density gradients in the flow were captured with a microsecond exposure at 10,000 fps using the high-speed camera through the other side window (front). The narrow field of view of 10 mm × 15 mm close to the injector exit with a pixel resolution of 0.04 mm/pixel is used in the current study. Choosing a narrow field of view along with the high-speed imaging is extremely helpful to understand the near-field characteristics of shock, windward edge, and their interaction and quantify their unsteadiness.

B.   Experimental Details

In the present work, we experimentally study the effect of nozzle internal shape on the interaction between the shock and the windward edge. The important flow parameters used are given in Table 1.
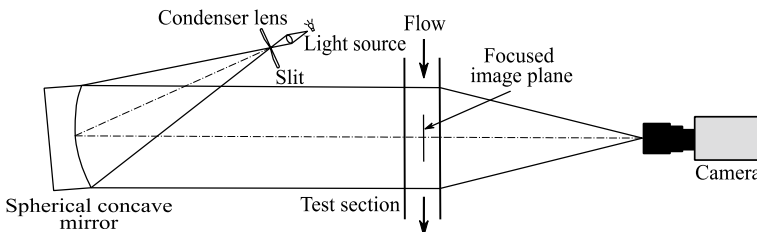

Fig. 4 Schematic of high-speed shadowgraphy

Table 1 Experimental parameters

Parameter	Value
Mach number, $M_\infty = \dfrac{U_\infty}{\sqrt{\gamma RT_\infty}}$	2.5
Momentum flux ratio, $J = \dfrac{\rho_j U_j^2}{\rho_\infty U_\infty^2}$	7
Weber number, $We_\infty = \dfrac{\rho_\infty U_\infty^2 D}{\sigma}$	2403 (1 mm) 2884 (1.2 mm)
Ohnesorge number, $Oh_j = \dfrac{\mu_j}{\sqrt{\rho_j D\sigma}}$	0.001

4 Results and Discussion

4.1 Instantaneous Images

Figures 5 and 6 represent the instantaneous side view temporally correlated images of liquid jet from the tapered nozzle and sharp-edged nozzle, respectively, for $J = 7$. It is evident from these images that the formation of shock structures and the windward edge (mixing layer) as the jet traverses into the crossflow are completely different.

In the present study, the liquid jet injected from the sharp-edged inlet nozzle has the stronger intact liquid column length for about $y/D = 5$ (from the average) with almost no perturbations unlike the tapered case where the liquid jet is coming out with fluctuations. Due to the presence of stronger intact liquid column at the nozzle exit in the sharp-edged nozzle case helps in increasing the penetration of liquid jet into the crossflow. The liquid structures formed in the windward side are almost ten times larger in the sharp-edged case compared to tapered nozzle. Apart from increasing the
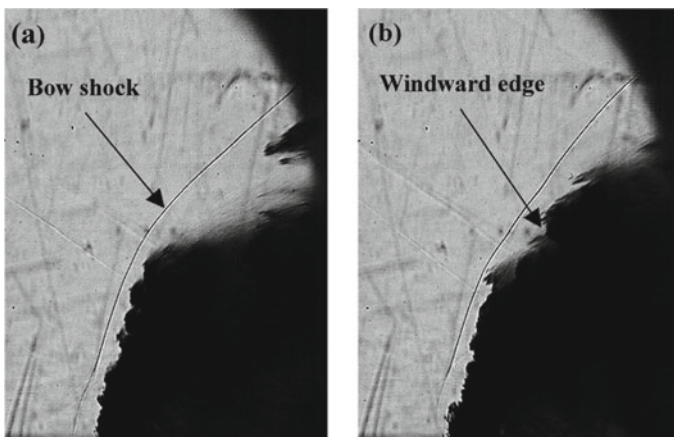

Fig. 5 Instantaneous side view images of tapered inlet nozzle case
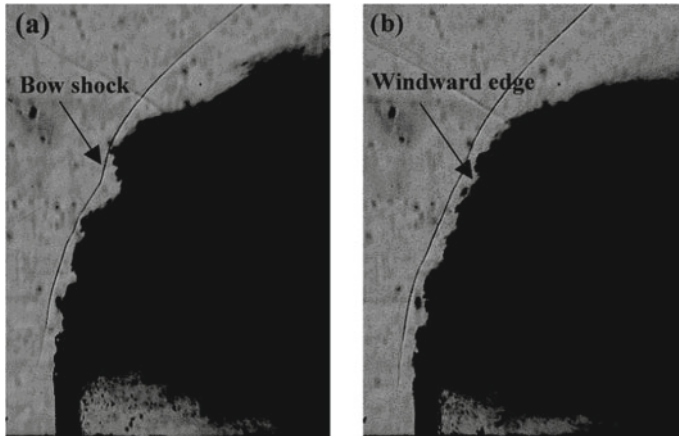
Fig. 6 Instantaneous side view images of sharp-edged inlet nozzle case

penetration, it also leads to increasing the shock strength (due to increase in shock angle).

Increasing the shock strength leads two things: One it helps in increasing the residence time of air in the combustor, and two it also leads to decrease in total pressure. Both are very important factors for the design of combustors.

It was also observed that due to the formation of dense irregular liquid structures in sharp-edged case which leads to the formation of 'bumpy shock' (Fig. 6b), hence the liquid structure near to that will be subjected to complex velocity field unlike the tapered case where the velocity increase in the downstream of the shock is monotonic because of the formation of conventional bow shock (Fig. 6a).

4.2 Ensemble Averaged Results

Using the in-house algorithm developed in MATLAB, both the shock and windward edge locations were traced for each instantaneous image. About 500 instantaneous temporally correlated images were used for quantifying the mean shock and windward edge locations.

Figure 7a and b represent the variation of mean jet penetration height and mean shock location both in the streamwise and cross-streamwise directions. As evidenced in both the figures when the liquid jet is injected through tapered nozzle, there is a significant amount of reduction in mean penetration height and mean cross-streamwise shock location of about 55% and 36%, respectively, for $x/D = 4$ and $J = 7$. It is evident from the instantaneous images (Fig. 6) and the mean locations (Fig. 7) that the nature of the shock structures and windward edge are completely different for both the nozzles studied. Hence, it is important to understand how these are varying about mean with time.

Fig. 7 **a** Mean penetration height **b** mean shock location
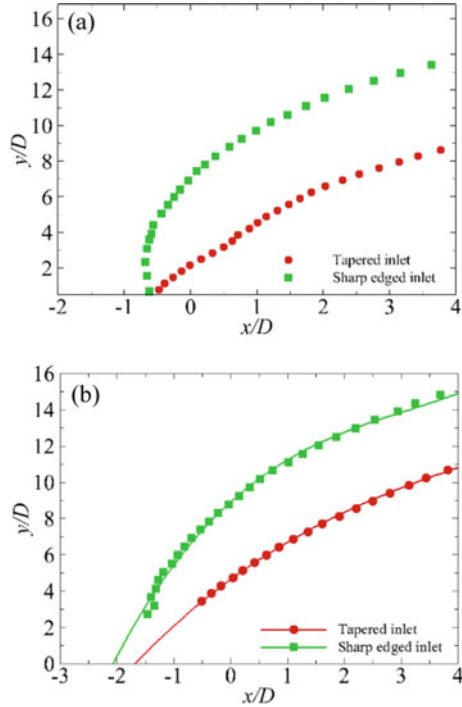
4.3 Unsteady Shock and Jet Motion

Figures 8 and 9 show the variation of the windward edge and shock trajectories between the instants along with their mean locations (shown with thick black line). It is evident from these figures that there is significant amount of fluctuations in shock and jet motion for both the nozzles studied. These fluctuations are due to the presence of significant shock wave boundary layer interactions which is a natural phenomenon that occurs in the high-speed applications [9].

To understand the extent of fluctuations spatially, detailed analysis is being done by choosing a cross-streamwise location (y/D) and tracing the streamwise location of both shock (X_s/D) and windward edge (X_j/D) with time. For presenting, $y/D = 7$ was chosen and the results are shown below.

Figures 10a and b show the spatial extent of fluctuations of streamwise locations of shock and windward edge about their means (indicated with dashed line). It was observed that the spatial extent of fluctuations for both shock and windward edge in the case of tapered and sharp-edged nozzles is $1.7D$, $4D$ and $0.9D$, $1D$, respectively. There is a significant amount of drop in fluctuations in the case of sharp-edged nozzle due to fact that the jet coming out from the sharp-edged nozzle is relatively stronger as stated earlier.

Fig. 8 Instantaneous
a windward edge **b** shock
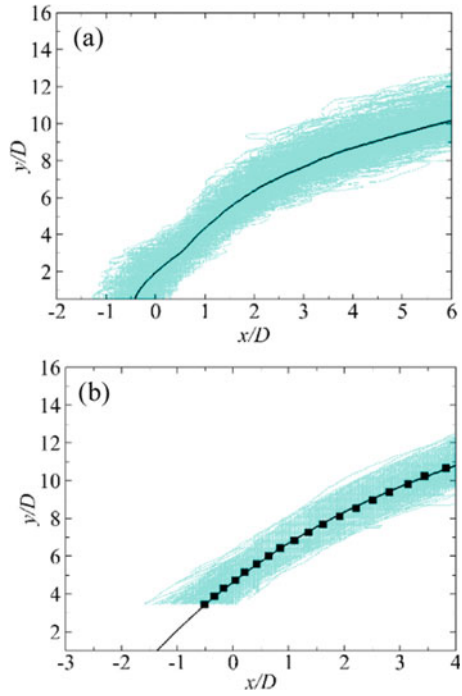locations along with their
mean for tapered nozzle case

Fig. 9 Instantaneous
a windward edge **b** shock
locations along with their
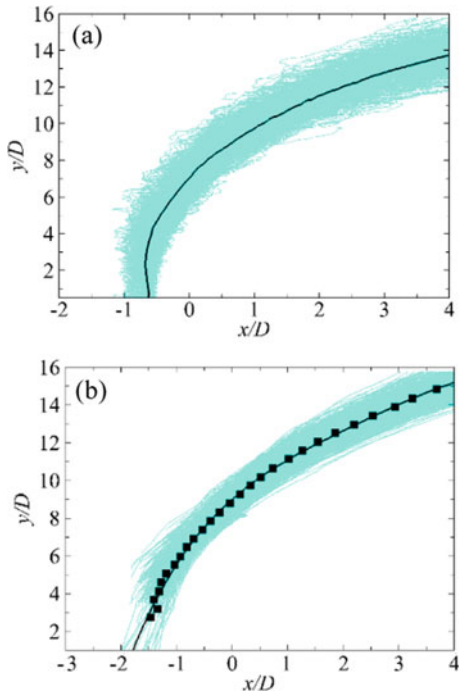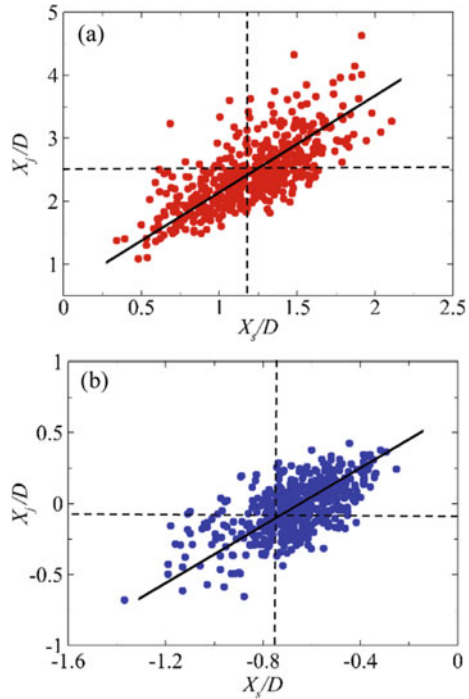mean for sharp nozzle case

Fig. 10 Scatter plot between instantaneous streamwise locations of shock (X_s/D) and windward edge (X_j/D) for **a** tapered nozzle **b** sharp-edged nozzle

Also, it is important note that in both the cases, the correlation analysis between the shock and jet motion was done at the same y/D. It was found that the correlation coefficient is about 0.73 and 0.63 for tapered and sharp-edged nozzles, respectively, which tells that they are strongly correlated. This clearly indicates that when the jet is more upstream (penetration is more), the shock is pushed to more upstream location and vice-versa. This phenomenon can be easily understood by following the thick black (inclined) line as indicated in Figs. 10a and b. Similar analyses were done at different cross-streamwise locations and yielded the similar results.

5 Conclusions

In the present work, we experimentally studied the effect of injector internal shape on liquid jet penetration and bow shock location when injected transversely into supersonic crossflow with a free stream Mach number of $M_\infty = 2.5$. It was observed that the mean penetration height and bow shock locations are higher in the case of sharp-edged nozzle case compared to tapered nozzle for the same J. It was observed that, due to the presence of strong intact liquid column near the jet exit in the case of sharp-edged nozzle is helping it to penetrate more into the crossflow. Also, there is a significant amount of unsteadiness in shock and liquid jet motion is present in both

the cases. It was found that the fluctuations of shock and liquid jet are spread more spatially in the case of tapered injector, since the jet coming out from it is relatively weaker compared to the sharp-edged injector jets. Also, correlation coefficient is quantified between the shock and liquid jet motion and found that they are strongly coupled for the injectors used.

Nomenclature

ρ	Density of the fluid [kg/m^3]
j	Jet
∞	Free stream
s	Shock (°)
U	Velocity [m/s^2]
μ	Dynamic viscosity [N-s/m]
σ	Surface tension [N/m]
D	Orifice diameter [m]
L	Orifice length [m]
γ	Specific heat ratio
R	Gas constant [J/kg-K]
x, y, z	Streamwise, cross-streamwise, and spanwise coordinates [m]

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