Effect of Hydraulic Diameter on Potential Core Decay of Supersonic Jets

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Abstract: *Various studies dealing with decay characteristics of circular and noncircular supersonic jets were conducted by previous researchers. But in these studies due emphasis was not given to the hydraulic diameter (D_h), shape factor (ζ) & the nozzle lip parameters which have significant impact on the characteristics of noncircular supersonic jet. In this study, it has been shown that these parameters played a significant role on supersonic core decay characteristics [2, 3, 6] of the jet. The scope of this study included supersonic core length (L_c), decay pattern, due to noncircular shaped nozzle. In the literature, the supersonic jet characterization and the related experimental correlation are available for optimum expansion conditions whereas for other expansion (under and over) conditions the experimental correlation is barely available. While investigating experimentally, new empirical relations were obtained which were the improved forms of earlier correlations for supersonic core length [4]. For experiments, six different types of nozzles (circular, hexagon, square, triangular, elliptical and rectangular) with the same exit to throat area ratio, convergent length and divergent length were used. The results obtained from the experimentally developed correlations were coherent with numerical results, experimental data and flow visualization.*

Key Words: *Non-circular jet, Potential core, Exit-geometry, Hydraulic diameter, Decay characteristics, Jet mixing.*

1. INTRODUCTION

The jet dissipates its properties as the efflux fluid approaches the condition of environment. The regain or decay process of jet characteristics happen due to mixing process, mass entrainment, corner vortex [1], [8] and surrounding conditions. In this study, the noncircular supersonic jet characteristics were emphasized in comparison with circular shaped exit geometry. Many researchers have studied the flow characteristics of the noncircular supersonic jets [2, 3] and the results have been reported in the literature.

However, in these studies, due emphasis has not been given to the hydraulic diameter and nozzle exit geometry parameters.

In this study, it has been shown that these two parameters play an significant role on the shock cell structure [7], supersonic core length, axis switching phenomenon and mixing characteristics of the jet with the ambient air.

Experiments were carried out on nozzles with six different exit geometry shapes to study their impact on supersonic jet characteristics. Numerical simulations [5] and Schlieren flow visualization study were performed.

2. EXPERIMENTAL SETUP

The supersonic jet experimental setup used in this investigation consists of the total pressure sensor and a Schlieren imaging facility.

The equipment details of supersonic jet facility are provided in Table 1.

Table 1: Equipment Details

Equipment	Specifications
Compressors	• Motor H.P. = 30 • Working pressure = 12kgf/cm^2 • RPM = 810
Reservoir 1 & 2	• Capacity = 7.5 m^3 (each) • Working pressure = 20 kgf/cm^2
Reservoir 3,4 &5	• Capacity = 2.500 m^3 (each) • Working pressure = 20 kgf/cm^2
Moisture separator	• Model = HPVS-4 • Design pressure = 1600 kPa • Test pressure = 24 kPa

Figure 1 shows the experimental setup and partial parts of Schlieren flow visualization setup.

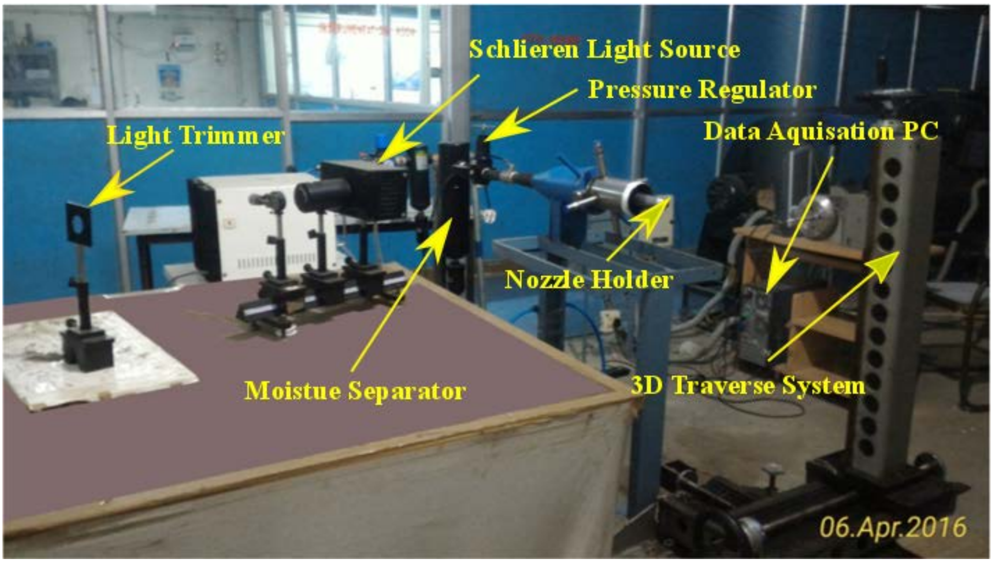


Fig. 1 Experimental Setup (supersonic Jet Facility at Madras Institute of Technology)

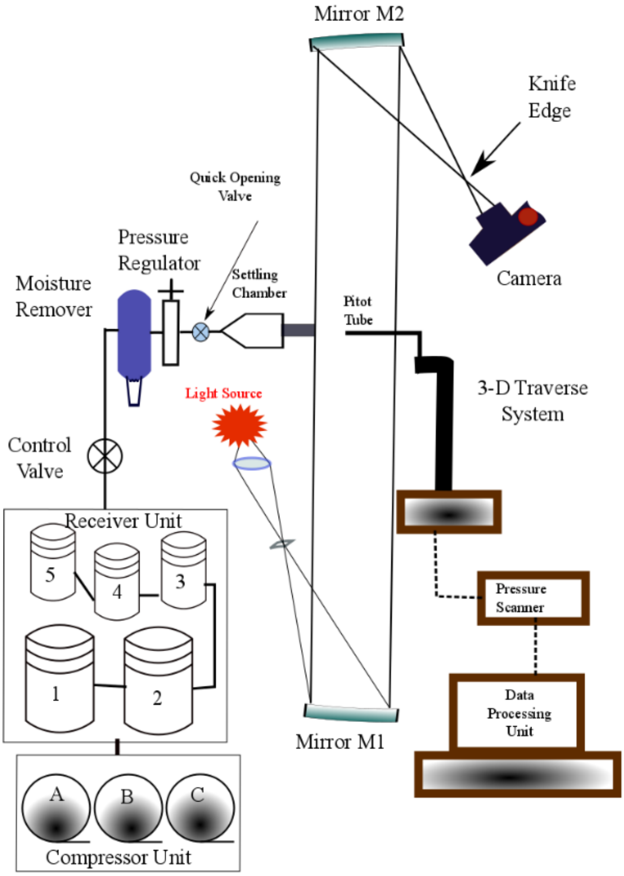


Fig. 2 Schematic Diagram of Experimental Setup

Experimental layout plan setup is shown in the above Figure 2. The nozzle design parameters are depicted in Figure 3.

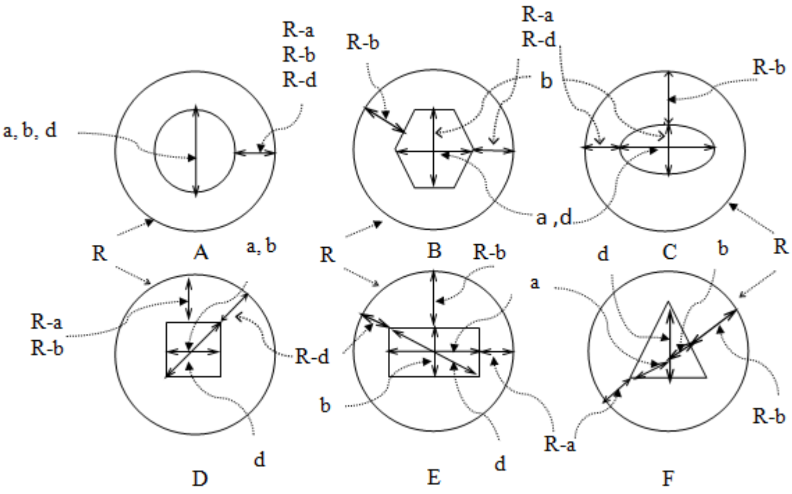


Fig. 3 Nozzle Exit Geometry Shape

3. COMPUTATIONAL DETAILS

The results obtained from three different sources (total pressure, Schlieren image and CFX results) were analyzed for each exit geometry. Figure 4 shows Numerical Simulation Fluid Domain with Boundary Conditions.

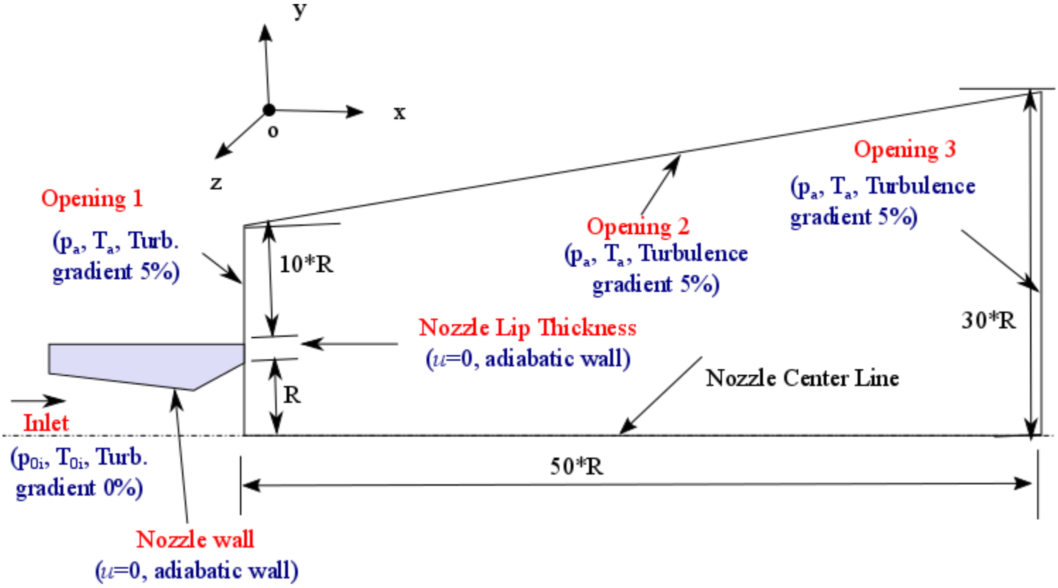


Fig. 4 Numerical Simulation Fluid Domain with Boundary Conditions

Carefully the mesh was generated to study the specific characteristics of supersonic jet behavior.

The unstructured mesh was created inside and subsequently a structured prism was created on the outside of the domain. The unstructured mesh was created inside and a structured prism was created of the domain.

The density mesh was created from the nozzle throat to 150 mm of the nozzle exit.

The meshing of computational domain was carried for various cases with an average of 1 million nodes and 5 million elements.

The minimum grid size of 5μ was created in the supersonic core region and jet boundary. The k-ε is one of the most proven turbulence model used for numerical solutions.

For convergence of the numerical solutions the criterion used was RMS residual values of mass, momentum, and energy where equations should be reduced below 10^{-4}. The obtained results by various methods were matching within agreeable limits.

The emphasis was given to build the empirical relations with responsible parameters contributing for shock cell structure, decay and spread characteristics.

For each nozzle the exit geometry hydraulic diameter

$$D_h = \frac{4*Area}{Wetted\ Perimeter}$$ and shape factor

$\zeta = \frac{C_e}{C_{nc}}$ were computed, and found to be unique for each nozzle.

The shape factor is defined in Figure 5.

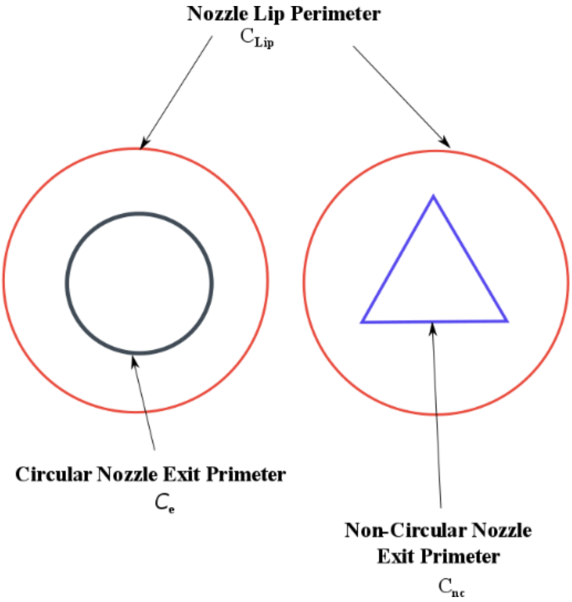


Fig. 5 Shape factor $\zeta = \frac{C_e}{C_{nc}}$

Table 2: Exit geometry anatomy and hydraulic diameter

Exit Shape	***a*** **(mm)**	***b*** **(mm)**	***d*** **(mm)**	**D_h (mm)**
Circular	11.73	11.73	11.73	11.73
Hexagonal	12.9	11.16	12.9	11.17
Square	10.4	10.4	14.7	10.4
Triangular	9.12	4.67	13.8	9.12
Elliptical	16.6	8.3	16.6	10.45
Rectangular	14.7	7.35	16.4	9.8

With the above influencing parameters, the supersonic core length was approximated as $L_c = \sqrt{\frac{P_{oi}}{P_a}} * (D_h - d/2) * 2l * \frac{C_{nc}}{C_{Lip}} * \frac{1}{\zeta}$.
The results obtained from this relation were in agreement with experimental and CFX results. The experimentally obtained results are presented in Table 3.

Table 3: Experimentally Obtained Supersonic Core Length

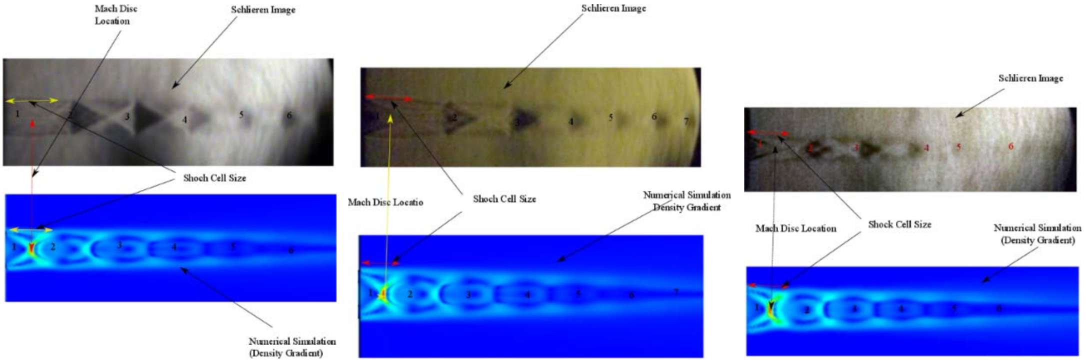
Inlet Total Pressure (kPa)	Circular (mm)	Hexagonal (mm)	Square (mm)	Triangular (mm)	Elliptical (mm)	Rectangular (mm)
400	93	90	73	68	54	48
500	95	98	82	81	63	54

Inlet Total Pressure (kPa)	Circular (mm)	Hexagonal (mm)	Square (mm)	Triangular (mm)	Elliptical (mm)	Rectangular (mm)
600	111	111	95	84	67	61
700	120	120	105	88	78	66
800	133	129	109	92	80	70

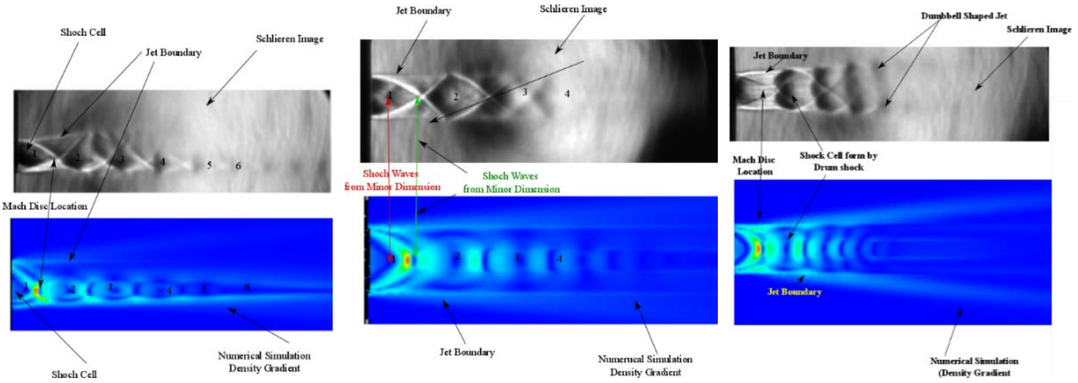
4. RESULTS AND DISCUSSIONS

In the current investigation the shock cell structure (shock cell length and shape, location of Mach disc, supersonic core length are purview of shock cell structure), jet spread characteristics and influencing factors for jet half-width and axis-switching phenomenon were studied. For verification and validation, the current results were compared with the results obtained by earlier researchers.

The comparison of Schlieren image and density gradient with (p_{0i} 600 kPa) is illustrated in Figure 6.



(a) Circular (b) Hexagonal (c) Square



(d) Triangular (e) Elliptical (f) Rectangular

Fig. 6 Comparison of Schlieren Image and Density Gradient (p_{0i} 600 kPa)

5. JET STRUCTURE

The shock cell is defined as *“the axial distance of instigated wave (shock wave or expansion fans) and its reflected wave till encounter with opposite reflection”*. The shock cell structures of under expansion and over expansion jets are shown in Fig. 7 and Fig. 8.

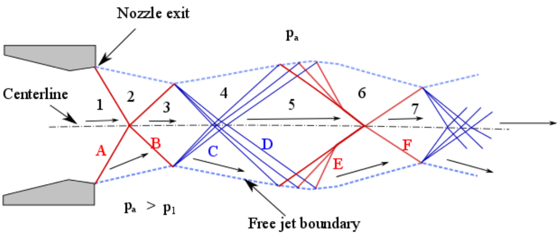


Fig. 7 Over Expanded Supersonic Jet Structure

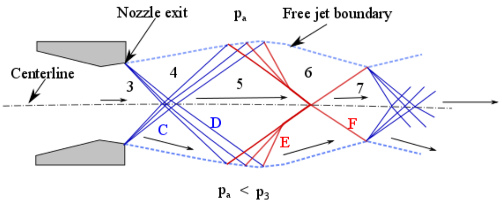


Fig 8. Under Expanded Supersonic Jet Structure

The supersonic core length, structure and anatomy were different for different exit shape geometry of noncircular jet. The instigated shock and expansion waves of noncircular jet were treated differently by various factors like ambient pressure, wave-turning angles, interaction of shock waves and jet boundary.

Shock Cell Length Grow With Nozzle Inlet Pressure *(p_{oi})*.

It was observed that the shock cell lengths were smaller in size during over expanded operation than under expanded operation. This was due to the shock waves formed at nozzle exit in over expansion operation but expansion fans were formed at nozzle exit during under expanded operation, which expanded the jet further and makes the shock cell length bigger.
Shock cell structures were different for different nozzle exit shapes because the strength of the shock wave and expansion fan vary from point to point on nozzle exit perimeter.

Empirical relation for supersonic core length

$$L_c = \sqrt{\frac{p_{0i}}{p_a}} * (D_h - d/2) * 2l * \frac{C_{nc}}{C_{Lip}} * \frac{1}{\zeta}$$

Irrespective of exit geometry shape supersonic core length increased for under expansion case and decreased for over expansion case with respect to optimum expansion. This investigation showed that circular shaped nozzle produced longest supersonic core and shortest in case of rectangular shaped nozzle. This decay pattern was found to be true for over-expanded, under-expanded and correctly expanded cases.

The results obtained from the total pressure, Schlieren image, numerical simulation and results obtained from empirical equations were in good agreement in the current investigation, [8]. Shock cell length, Mach disc location, shock pattern, supersonic core length were under the purview of shock cell structure.

Longitudinal Decay Characteristics

i. Dumbbell shape supersonic core was observed in midfield of supersonic jet issuing from rectangular shaped nozzle causing longitudinal decay faster due to the rapid momentum flux change.

ii. For the optimum expansion condition, 90% of total inlet pressure loss in supersonic jet from a circular nozzle occurred at 200 mm and for the rectangular case it was 108 mm from the nozzle exit.

iii. For the circular and hexagonal jets, 50% of the total inlet pressure was lost within the mid field and for the rest of the noncircular jets, 50% of total inlet pressure loss occurred in near field.

6. CONCLUSIONS

The salient findings and conclusions of this study are stated below**.**

i. The current results obtained from four different methods (total pressure data, Schlieren image, numerical simulation and experimentally obtained relations) had shown the reasonable agreement.

ii. A shape factor ζ and geometric configuration factor (ξ), describe and characterize the noncircular shapes of the nozzle exit planes.

iii. Each shock cell strength depends on p_{max} and p_{min} pressure ratio.

iv. The decay of supersonic core length is the function of hydraulic diameter D_h, shape factor ζ and geometric configuration factor (ξ).

v. In the current investigation, the rectangular jet had a rapid supersonic core decay.

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