Spread Characteristics of Non-Circular Supersonic Jets

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***Abstract*— The spread characteristics of supersonic jets play a vital role in defining the propulsion efficiency. In this study, the physics of non-circular supersonic jets is considered using CFD techniques. In this case, differences in supersonic core lengths and shock cell structure are considered. It was found that supersonic core lengths of these jets vary depending on their exit forms, keeping their area ratios constant. To avoid any losses in this section after the throat, it is decided to maintain the shape of the throat section similar to that of exit section. Finally, it is found from various studies that supersonic core lengths are reduced and mixing is increased because of geometrical asymmetry in these non-circular jets; also, an axis-switching effect is found in these non-circular nozzles. Nozzles with higher ratios are found to promote faster spreading of these jets. All these key findings are useful in designing advanced propulsion systems in aerospace applications, where potential benefits of using non-circular jets in terms of passive flow control and combustion efficiency are considered. The current results are obtained using two different methods: Numerical Simulation and Center Line Mach Variation Data, and are found to be in reasonable agreement with the experimentally obtained relation.**

Keywords*— *Non-Circular Jet, Supersonic Core Length, Shock Cell Structure, Axis Switching

I. INTRODUCTION

Circular cross-sectioned nozzles are the most common type of nozzle used, this type of nozzle tends to produce a very stable and symmetric jet of air that takes a long time to mix with the outside air. As a solution to this problem, engineers are looking towards the use of non-circular cross-sectioned nozzles. The advantage of this type of nozzle is that it is a passive solution to the problem and does not require the use of heavy machinery to control the flow of air. The reason this type of nozzle works better is that the irregular shape of the nozzle disrupts the symmetry of the shock waves present in the air. This controlled messiness helps to spread out the jet of air quickly and grab some of the outside air, resulting in the shortening of the high-speed core of the jet. With the help of the hydraulic diameter, we can understand the performance of all types of non-circular cross-sectioned nozzles used for supersonic jet mixing.

The supersonic core length can be calculated by using the equation:

Equation 1 Supersonic Core Length

$$L_c = \sqrt{\frac{P_{oi}}{P_a}} * \left[D_h - \frac{d}{2}\right] * (2l) * \left[\frac{C_{nc}}{C_{lip}}\right] * \frac{1}{\zeta}$$

where,

$L_c = supersonic\ core\ length$

$\frac{P_{0i}}{P_a} = Nozzle\ Pressure\ Ratio$

$D_h = Hydraulic\ Diameter = \frac{4 * Area}{Perimeter}$

$d = characteristic\ diagonal$

$l = diagonal\ equivalent\ value$

$C_{nc} = Non\ Circular\ Exit\ Perimeter$

$C_{lip} = Nozzle\ lip\ Perimeter$

$\zeta = Shape\ factor$

$= \frac{Circular\ Exit\ Perimeter}{Non\ Circular\ Exit\ Perimeter}$

II. LITERATURE REVIEW

In general, a supersonic jet can be classified as overexpanded, perfectly expanded, or underexpanded based on the pressure ratio between the exit of the nozzle and the ambient pressure. For overexpanded jets, the formation of oblique shocks takes place immediately at the exit, whereas underexpanded jets consist of a series of mach waves until pressure equilibrium is achieved. Although the conventional study of supersonic jets emanating from circular nozzles has been thoroughly discussed, the behavior of non-circular nozzles is less understood. Previous research focused primarily on the fundamental characteristics of the spreading of the jets.

For example, a specific study carried out by Behrouzi and McGuirk [1] on high aspect ratio rectangular jets found that the impact of the nozzle geometry on the development of the jets could be uncertain.

However, a study carried out by Tide and Srinivasan [2] found that the number of chevrons on the nozzle affects the location of the Mach disc significantly. Other comparative research conducted by Kim and Park [3] on circular, square, and triangular nozzles revealed the presence of notable differences in the half-width of the jets and the vorticity.

Research conducted by Gutmark and Grinstein [4] revealed the presence of a broad range of characteristics on various Mach numbers, including the fact that non-circular nozzles produce better mixing, axis-switching, and air entrainment compared to circular nozzles.

Although Tsutsumi [5] conducted research on the shock-cell structure of rectangular nozzles, quantitative information is limited, and the conventional formulas developed by Prandtl [6] and Pack to determine the shock-cell length are applicable only to circular nozzles.

Other research conducted by Ibrahim et al. [7] and Suzuki et al. [8] focused on the Mach-disc characteristics.

III. METHODOLOGY

A. Geometric Modelling

Numerical simulations were carried out on six different geometries using a Density-Based Solver with a design exit Mach Number of 1.8. The Mach Number at the exit of the nozzle is attained by using the Area-Mach relation. The k-ω turbulence model was employed, and grid independence was ensured prior to analysis ensuring the accuracy of the grid structure.

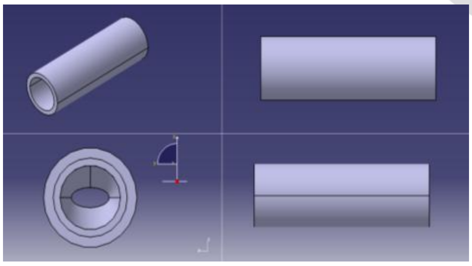


Figure 1 Elliptical Shaped Exit Nozzle

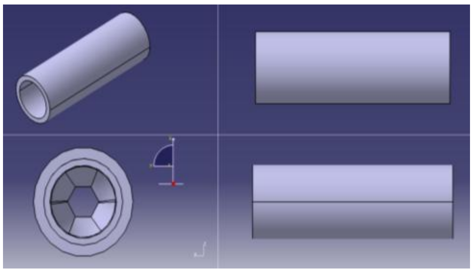


Figure 2 Hexagonal Shaped Exit Nozzle

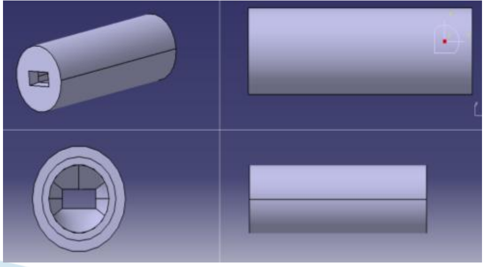


Figure 3 Rectangular Shaped Exit Nozzle

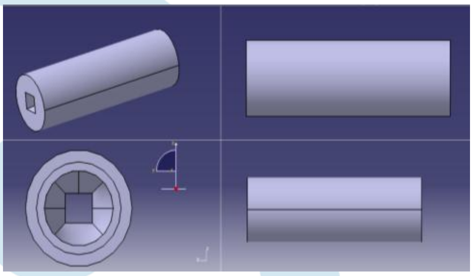


Figure 4 Square Shaped Exit Nozzle

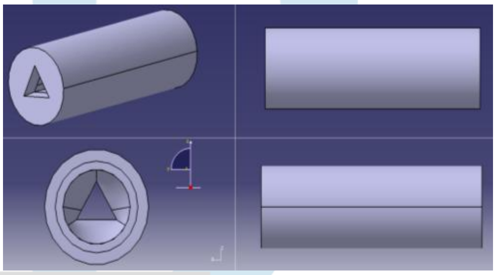


Figure 5 Triangular Shaped Exit Nozzle

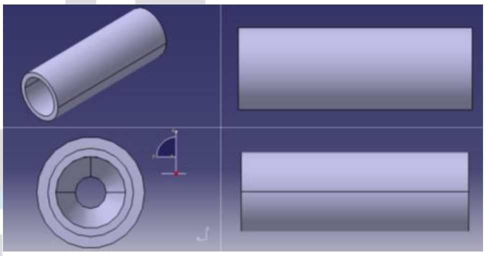


Figure 6 Circular Shaped Exit Nozzle

TABLE 1 NOZZLE DESIGN SPECIFICATIONS (COMMON TO ALL)

Area of the Inlet	380.13 mm^2
Shape of the Inlet	Circular
Length of the Convergent Section	70 mm
Area of the Throat	75 mm^2
Length of the Divergent Section	6.5 mm
Area of the Outlet	108 mm^2
Area Ratio (Exit to Throat)	1.44
Mach Number at the Outlet	1.8

B. Mesh Generation

Edge sizings have been given to each of the mesh with the required geometry sizings, a tetrahedrons method has been chosen to capture the flow and the computational domain was extended sufficiently downstream to capture the complete jet expansion and shock-cell structure. To ensure full capturing of the shock-cell system, the downstream domain has been extended to 6.5 times the length of the nozzle.

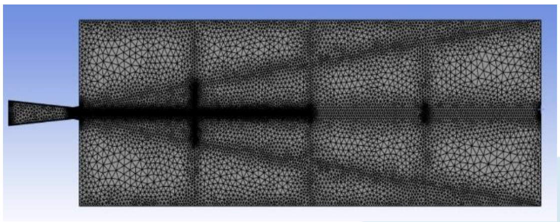


Figure 7 Cross Sectional View of the Mesh of the Nozzle with Domain

TABLE 2 MESH DATA

Preference of Physics	CFD
Preference of Solver	Fluent
Order of the Elements	Quadratic
Capture Curvature	Yes
Smoothing	High
Topology Checking	Yes

C. Solver Setup

Ansys Fluent was used for the simulation of the nozzles. Density based solver has been used for the flow field, and air was used as the working fluid. The SST k-ω model has been used as the turbulence model due to its ability to accurately predict shock-boundary layer interactions. The Inlet boundary has been defined by using a pressure inlet corresponding to the required nozzle pressure ratio, while the Outlet has been defined as pressure outlet with ambient pressure conditions. No-slip adiabatic wall conditions were applied to the nozzle walls. Implicit formulations and Second order methods for momentum, energy and turbulence equations have been used.

IV. RESULTS

The study investigated the nozzle exit geometry effect on the structure of the shock-cell, supersonic core behavior, Mach Variation, and jet spreading through CFD simulations. The grid independence was verified by comparing the centreline Mach number distributions for progressively refined meshes, and negligible variation was observed beyond the selected mesh. Numerical results demonstrated strong agreement with experimental results for all nozzle shapes. It has been observed that the Mach Number at the nozzle exit showed similarity with the experimental data. Circular jets had symmetrical shock cells of regular spacing with the longest core length. Non-circular geometries shed asymmetrical shocks that have a higher turning angle, which resulted in a faster decay of the supersonic core. Square and hexagonal jets had moderately enhanced mixing promoted by corner-induced vortical structures. Elliptical and rectangular jets showed aspect-ratio-dependent spreading with more rapid decay along the minor axis. The hydraulic diameter and the shape factor have been calculated for each of the nozzles, and have been tabulated in Table 3.

TABLE 3 COMPUTED VALUES OF HYDRAULIC DIAMETER AND SHAPE FACTOR

Exit Shape and Dimensions (in mm)	Hydraulic Diameter (D_h) (in mm)	Shape Factor (ζ)
Circular; a = 11.73	11.73	1
Rectangular; a = 14.70, b = 7.35	9.8	0.84
Elliptical; a = 8.28, b = 4.14	10.48	0.9176
Triangular; a = 15.79	9.116	0.77
Hexagonal; a = 6.45	11.1714	0.95
Square; a = 10.39	10.39	0.88

The numerical results and the Mach Variation plots have been calculated as follows.

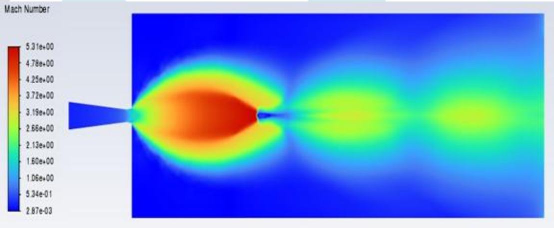


Figure 8 Circular Jet Spread

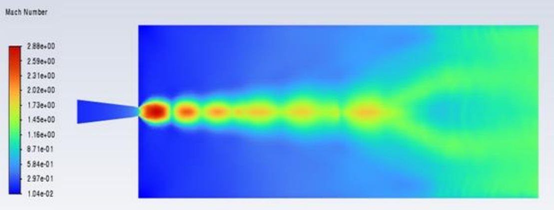


Figure 9 Rectangular Jet Spread

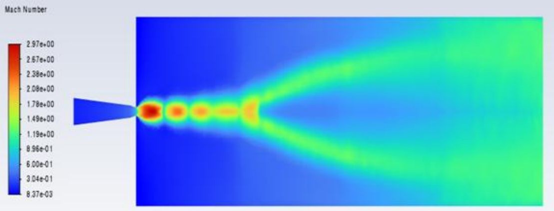


Figure 10 Elliptical Jet Spread

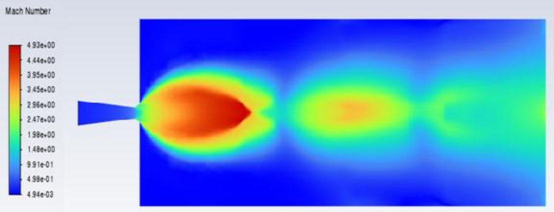


Figure 11 Triangular Jet Spread

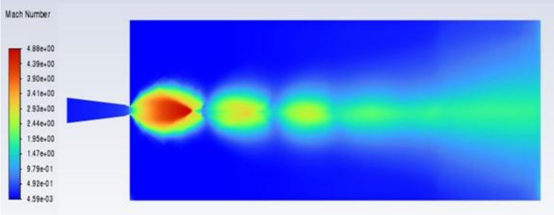


Figure 12 Hexagonal Jet Spread

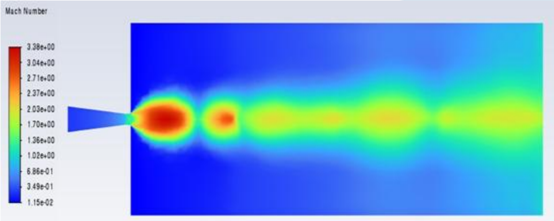
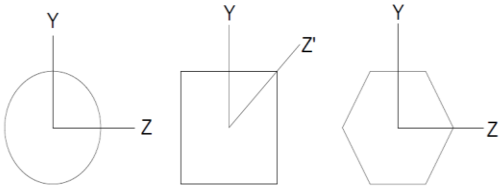
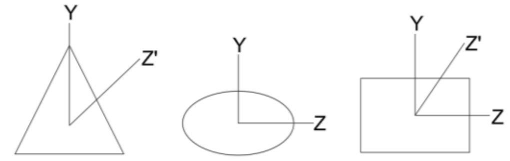


Figure 13 Square Jet Spread



(a) Circle (b) Square (c) Hexagon

Figure 14 Direction of Jet Expansion – Circle, Square, Hexagon



(a) Triangle (b) Elliptical (c) Rectangular

Figure 15 Direction of Jet Expansion - Triangle, Elliptical, Rectangular

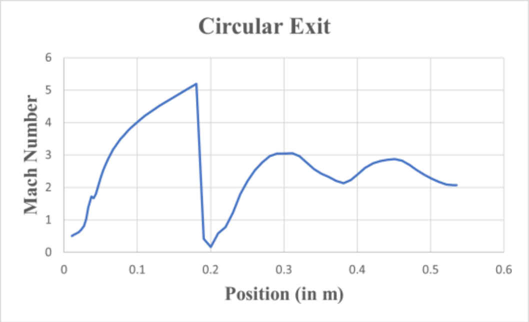


Figure 16 Circular Jet Centreline Mach Variation

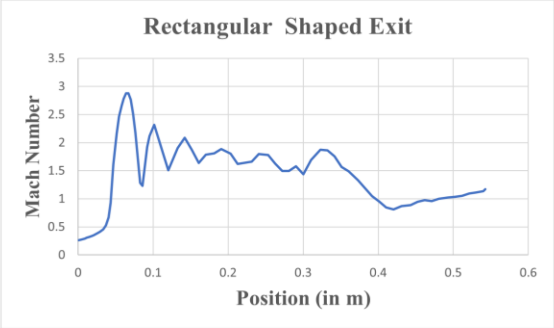


Figure 17 Rectangular Jet Centreline Mach Variation

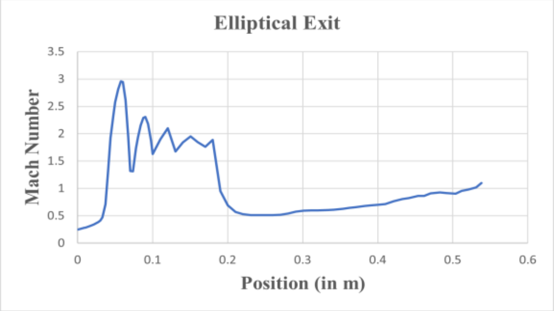


Figure 18 Elliptical Jet Centreline Mach Variation

Figure 19 Triangular Jet Centreline Mach Variation

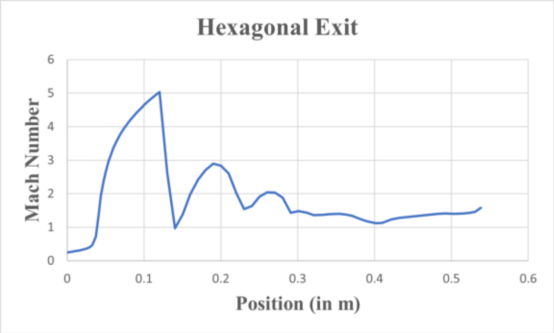


Figure 20 Hexagonal Jet Centreline Mach Variation

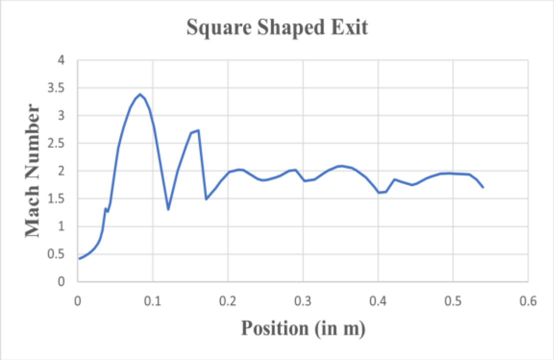


Figure 21 Square Jet Centreline Mach Variation

The centerline Mach Variation curves confirmed that the non-circular jets entrained more ambient air and lost momentum at a faster rate compared to circular ones. Axis switching, which occurs in non-circular jets due to unequal shear layer growth along the major and minor axes, resulting in periodic interchange of the jet cross-sectional orientation as the flow develops downstream, was also observed for all non-circular geometries, particularly for the elliptical and the rectangular exits which further accelerated mixing and caused more rapid collapse of the shock-cell system.

The results as a whole show that the exit geometry strongly controls shock strength, core-length behavior and jet spreading. The shock cell formations seen in the contours occur due to the mismatch between the pressure at the exit of the nozzle and the ambient pressure, leading to the formation of compression and expansion waves. Non-circular nozzles have consistently produced shorter, more distributed shock structures with improved mixing characteristics compared to circular configurations. Shock cell pattern was different for different geometries. For circular jets, the cells were symmetric and equally spaced. For non-circular nozzles, the pattern was asymmetric.

The supersonic core lengths of each nozzle have been calculated by the use of the Equation 1, and have been tabulated and compared with the Numerical Solution in Table 4. From the calculations and the numerical results, it has been observed that the values of the Supersonic Core Lengths have only a little deviation upon comparison, and the numerical results confirm the experimental calculations.

TABLE 4 SUPERSONIC CORE LENGTH

Exit Shape	**L_c (Analytical Value) (in mm)**	**L_c (CFD Result) (in mm)**
Circular	186.3	180.7
Rectangular	63.8	64.1
Elliptical	61.2	57.6
Triangular	162.1	170.5
Hexagonal	119.4	120.8
Square	92.9	89.3

It has been found that the length of the supersonic core, L_c, decreases when the aspect ratio or irregularity in the shape increases, and can be observed in the rectangular and elliptical exits, where the aspect ratio is the highest. The rate of jet spreading in elliptical and rectangular jets was the greatest.

V. CONCLUSION

The geometry at exit significantly influences the structure and spread of a supersonic jet. Non-circular geometries have shorter supersonic cores, faster decay, and higher mixing than their circular counterparts. Of all the shapes tested, elliptical and rectangular nozzles produced the highest spreading rates, due to higher aspect ratios, enhancing shear layer growth and promoting rapid jet spreading, while the circular, triangular and hexagonal nozzles maintained the longest cores respectively. This correlation presents a useful tool for nozzle designers.

VI. REFERENCES

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