Preliminary Studies of Compressible Jet Flow from a Pipe with Hexagonal Cross-section

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Abstract. The present study is an experimental investigation of compressible jet flow from a pipe with a hexagonal cross-section. The pipe is fixed to a settling chamber which is supplied with compressed air by a storage tank via a pressure regulator. The experimental methodology includes the measurement of centreline variation of stagnation pressure and the visualization of shock structures. The results from the present pipe shape considered for the present study will be compared with the results of jet flow experiments from a circular pipe. The diameter of the circular pipe is taken as 15mm and the same is fixed for the hexagonal pipe. The L/D ratio of the pipe is chosen as 5. The nozzle pressure ratio will be varied according to the source available and the measurements will be taken via a Pitot tube connected to a Pressure Scanner. The positioning is controlled by a traverse mechanism which can move in axial and transverse directions. The results obtained will be discussed in detail with the help of relevant literature.

1. Introduction
Compressible flow is the one that deals with the flows having significant changes in volume/density if the compression in flow medium is more than 5% it is termed as compressible flow. Jet flow can be defined as any fluid flow exiting out of a nozzle or an orifice that has an excess momentum compared to the energy possessed by the surrounding fluids. Jet flow has influenced the modern world in many ways from basic house applications to spacecraft manoeuvring. Literature has proved its importance and various methodologies people adapted to understand and alter jets according to their required different needs. In our study, the pipes can also be considered as a nozzle because of boundary layer growth that develops from the surface of contact through which the flow occurs, due to this area is restricted as flow propagates inside the pipe and this causes an acceleration in the flow. Prasanta Kumar Mohanta [1] performed experiments on supersonic jets to understand the effect of hydraulic diameter on supersonic core length and to understand the supersonic flow decay. In their study, three different conical CD nozzles with three different exit geometries were considered. Shocks and expansion waves were visualized in this experiment. Their results depicted that shorter the hydraulic diameter the faster the jet mixing is. The non-circular exit geometries were found to have mixing rates faster in comparison with circular exits. Experiments were performed on non-circular incompressible free jets by Manivannan P [2]. In his study hot wire anemometric measurements were carried out on three different jets obtained on three nozzles of three different geometries i.e. circular, hexagonal and cruciform cross-sections. Their results depicted that, the circular jet has a wider potential core region and lower velocity decay rate and jet half-width when compared to the non-circular jets. Quinn W R
[3] compared the results of a turbulent air jet issuing from a sharp-edged elliptical slot with the same issuing from around circular slot. Their results showed that there was a shorter potential core length and a higher far-field spread rate for the elliptic jet. The other recent literature regarding jets were about usage of validation [7], multiple nozzles [8], mixing enhancement [9, 10], aero-acoustics [11], noise characterization/reduction [12] etc. The present work concentrates on the study of hexagonal shaped pipe jet from short pipes with flow in the compressible regime.

2. Methodology
A circular pipe was taken of carefully considered cross-section was designed, fabricated and was taken as reference pipe nozzle and a hexagonal pipe with an equivalent cross-sectional area as that of the above said reference circular pipe was designed. The geometrical designs of both the pipes were made using CATIA V5. The L/D ratio of the pipes was chosen to be 5. The diameter of the circular pipe is taken as 15mm after considering literature by various authors and the same is fixed for the hexagonal pipe. The side of the hexagon was calculated as 8.66mm using equivalent area consideration, considering the area of the circle inscribed in the circular pipe of diameter 15 mm to be equivalent to provide ease of comparison. In the outlet and the inlet face (see fig 1) of the pipe, the external diameters were 20mm and 25mm respectively thereby adding enough thickness to satisfy the strength requirements to hold the jet without damage to the nozzle. The inlet area and the exit area of the pipes were maintained the same. The pipes were 3D printed using strong and fine plastic filament of higher strength in the process of fabrication.

2.1 Pipe Geometry Calculations
The design calculations of the circular and hexagonal pipes that were mentioned under the previous heading are as follows.

2.2 Base Circular Pipe Geometry
Reference circle diameter is 15mm, Reference circle radius (r) is 7.5mm then,

\[
\text{Area of circle} = \pi r^2 = \pi \times 7.5^2 = 176.7 \text{ mm}^2.
\]

2.3 Hexagonal Pipe Geometry
Area of the Hexagon is 176.7mm²

\[
\left( \frac{3 \times \sqrt{3}}{2} \right) a^2 = 176.7 \text{ mm}^2 \Rightarrow a^2 = \frac{2 \times 176.7}{3 \sqrt{3}} \Rightarrow a = \sqrt{\frac{2 \times 176.7}{3 \sqrt{3}}} = 8.66 \text{ mm}
\]

Where a is the length of the side of the hexagon

2.4 Pressure Measurements
The pressure measurements were carried out in the REC test facility using pitot pressure ports and pressure acquiring units. Positioning of the pitot tube is with the help of a 2D traverse mechanism which can move in two perpendicular directions i.e. axial as well as radial directions, the traverse is automated such that the positioning is controlled using a circuit that controls the two motors that are connected with the ends of horizontal and axial beams that position the pitot tube in the jet field. Pitot pressure data acquisition was done by using the data acquisition units and the data acquired is displayed in a laboratory minicomputer. The location of the shock cells could be approximated from the pressure variations along the jet centreline pressure readings. Pitot tube measured pressure variations were considered for observation. The data obtained were analysed and the results were compared accordingly. The centreline pressure \( P_c \) is made non-dimensional by exit pressure \( P_0 \).
2.5 Pipe Exit Geometry
Figure 1(a)-circular Figure 1(b)-hexagonal represents the design and the measurements of the nozzle front view (exit geometry) and lateral view for each of the above-mentioned nozzles shapes. For a circular pipe, the major axis, the minor axis and the diagonals taken along the entire length of the nozzle is equivalent to the nozzle exit diameter D (15mm). In hexagonal nozzle, unlike circular nozzle, the side ‘a’ that was calculated in the above section is taken for designing the nozzle, unlike circular nozzles the diagonals are not the same at all the location angles of the hexagonal pipe.

![Figure 1](image)

a) Circular Pipe
b) Hexagonal Pipe

All dimensions are in mm

Figure 1. Design geometry of a) Circular Pipe and b) Hexagonal Pipe.

2.6 Pipe Holder
The Jet tunnel exit has an internal thread for a length of about 20mm. A coupling was designed as per the required dimensions with an external thread to fit with the internal thread at the exit of the jet it was fabricated using a lathe and threaded externally at two ends for a depth of 20mm. A nozzle/pipe holder was designed to fit the pipes into it and to hold it fixed along with the coupling, nozzle holder was fabricated using brass with the help of lathe in such a way that one exit of the holder will be connected to the coupling and the other exit of the holder will hold the nozzle such that the nozzle is projecting out.

2.7 Experimental setup
A pictorial view of the experimental set up is shown in Figure 2. The open jet facility shown in the figure is used for the experimentation. The experimentation set up consists of an air storage tank (pressurized), diffuser, settling chamber, pressure gate valve, pressure regulator valve, pipelines,
Reciprocating air compressors (two of piston type), holder support plate. Automated traverse mechanism, a pitot probe. The traverse mechanism is used to position the Pitot tube at the nozzle exit center and in any relative position (in mm) from the center of the nozzle exit. Compressed air is supplied to the settling chamber from the pressurized air storage tank (using two reciprocating air compressors) via the pipelines and the diffuser. The settling chamber was connected to the air storage tank via diffuser by using pipelines. Pressure gauges were fixed above the settling chamber and air storage tank to continuously monitor the pressure to obtain constant NPR and to maintain a particular amount of pressure in the tank to avoid unwanted pressure drop respectively.

Figure 2. Pictorial view of the experimental test set up.

2.8 Experimental Procedure
The experiment was conducted at a nozzle pressure ratio (NPR) of value 2; to achieve this, the gauge pressure in the settling chamber is set to 1 bar i.e. excess to that of the surrounding ambient pressure. The alignment of the holder and pipe with the horizontal axis of the traverse mechanism is checked. Pitot tube axis and the traverse mechanism horizontal beam are aligned to coincide with each other, free-motion/ movement of the traverse mechanism is checked. The centreline pressure readings were taken along the axial directions at a regular interval of 2mm starting from 0D to 14D i.e. beyond the developing region of the jet flow. The Pitot tube data is transduced with the help of a pressure sensing device and is transformed into readable data using the data acquisition system and the final display of the result is done using a laboratory minicomputer.

3. Results and discussion
In this study, attempts have been made to understand the effect of the nozzle cross-section geometry on jet potential core length and the Decay characteristics of the jet in its developing region. From the values obtained in the above experiment, the following graphs have been plotted and the table showing the details that were observed in the graph as a result of experimentation is displayed below.

Table 1. Comparison of potential core length and decay constant.

| Cross-Section | Potential Core Length | Decay Constant |
|---------------|-----------------------|----------------|
| Circle        | 4D                    | 0.0478         |
| Hexagon       | 4.53D                 | 0.0518         |
3.1 Length of potential core

The potential core is the region where the flow characteristics match those of the nozzle exit. Due to different exit geometry, the jet mixing process of a primary jet to ambient jet was different resulting in different lengths of subsonic core length. The potential core lengths of Circle & Hexagon were 4D, 4.53D respectively. The Hexagonal jet was having greater potential core length when compared to circular jet due to the pipes having sharp corners and flat sides. When comparing Hexagonal jet with a circular jet the increase in the potential core length in the case of the Hexagon jet was 13.25%. From

**Figure 3.** Centreline pressure distribution for a) Circular Jet and b) Hexagonal Jet.
the graphs plotted, the decay constant of Circle, Hexagon, was 0.0478, 0.0518. The characteristic
decay was measured by taking the trend line from the graph after the potential core region for all the
jets. The decay of the subsonic core was due to overall mixing and spreading characteristics of the
main jet with the ambient air. The exit diameter and its relation with the major axis, minor axis and the
diagonal plays a major role in decaying the subsonic core length.

3.2 Jet spreading behaviour
The readings were taken from the nozzle exit up to a distance of X/D = 12 for both the pipes to
investigate the jet spreading behaviour. It was found out that the jet spreading was predominant in the
sharp angles than straight sides or smooth curves. Multiple locations along the centreline were
considered starting from the nozzle exit at X/D = 0 to X/D = 12. Jets from circular nozzle spreads
inwards or outwards in all X/D locations. Hexagonal jet spreading is almost similar to the circular jet
with slight exception near the corner flow with small curl in flow direction.

From the above seen results, the potential core of hexagonal jet is longer than the circular jet. This
might be due to the reason that the evolution of stream wise vortices from the flat edges and corners
introducing fine scale mixing. The decay constant is also higher for the hexagonal jets when compared
to the circular ones. The decay is essentially due to vortices and resulting shear interaction and finally
leading to higher mixing. The entrainment characteristics should also have influenced the faster decay
of hexagonal jet. The uncertainty of the experiments performed in the present study are found to be
less than 2 % and it is sufficient for research purposes.

4. Conclusion
The present study is about the experimental measurements of pressure decay from pipe with hexagonal
cross-section and finite aspect ratio. The experimental setup used for this work is a typical free jet
setup that can produce subsonic to supersonic jets. Nozzles printed by rapid prototyping are mounted
on the nozzle holder and experiments were carried out by using automated traverse and a digital
pressure transducer. The potential core distance of the Hexagonal Jet is found to be wider when
compared with the circular Jet. The decay constant for the hexagonal jet was slightly higher than the
circular jet indicating that the pressure decay for hexagonal jet fast when compared to the circular jet
in compressible regime.

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