Preliminary Studies on Compressible Jet Flow from a Pipe with Square Cross-section

Tinesh K¹, Avinash S² and Kannan B T³
Department of Aerospace Engineering, SRM Institute of Science and Technology, Kattankulathur, Kanchipuram District, 603 203, India.

E-mail: ktinesh001@gmail.com

Abstract. Jet flow through pipes/nozzles has been successfully applied in various fields and has a further wide scope in fields of Flow Control and Acoustic Suppression. In the past few decades, jet flow through pipes and nozzles have been widely exploited, researchers found that non-Circular Pipes possess some unique properties, with which the need for research in this field increased. This work presents the properties of jet flow from a Square Pipe (L/D=5) over the Circular ones. Experiments are done in Compressible flow conditions using 3-D fabricated Pipes of Circular and Square cross sections. The cross sectional area of the pipe exit is maintained same for both the Pipes to facilitate comparison of results. This study highlights the advantages of Square Pipes over the conventional ones via pressure measurements.

1. Introduction
Jet flow analysis is a field with wide scope for experimentation and research. After years of study this field still has a lot of way for improvement. Jets are common in modern days having applications ranging from simple home appliances such as hair drier to the most complex space propulsion systems. Due to its extremely wide range of applications and scope in aeronautical industries various components of jet flow phenomena has always been a choice of study for research community. The scope of this project is to study the mixing characteristics of square pipes as opposing to circular ones. Based on this study various nozzles of different exit cross sectional geometry will be created and further a study relating to Acoustic suppression will be conducted in later days of this year.

1.1. Jets
Jet flow may be defined as a flow of fluid with excess momentum produced by a limited cross section into a vast space of low momentum fluid of same or different medium. Jets are often produced by nozzles or orifices. In other words anything that produces jets is called nozzles. Jets are of various kinds such as free jet, wall jet, co-flow jets, impinging jets, opposing jets. This study deals with jet flow issuing from a pipe type nozzle (of free jet). A typical schematic of free jet flow and its regions are displayed in Fig 1. The figure is a schematic of jet flow produced by this test setup. The pressurised air flow from the settling chamber traces a polynomial curved path inside the settling chamber owing to the stagnation at edges and exits through the duct and this transforms pressure energy into velocity maintaining conservation of momentum, due to this reason the stagnation pressure reading measured by pitot tube at the very nozzle exit is the pressure inside settling chamber. Once flow exits the duct at the very exit the jet displays a constant velocity/top hat profile. And momentum...
transfer begins at the jet boundary, the shear layer picks up air mass from outside atmosphere and imparts momentum to it due to entrainment and vortex formation, due to this phenomena mass flow of jet increases between two jet cross sections located at two different axial distances. This momentum transfer continues till 150D where the jet is supposed to die completely, because of this the velocity of jet decreases and the velocity drop from boundary spreads radially into the core.

The zone where the jet velocity is constant and is equal to the nozzle exit velocity \( V_{ce} \) is called as jet potential core, this region extends from the nozzle exit 0D up to 6D and the region around this is the primary mixing region. Following this region come the developing region where the jet velocity drops considerably, this region extends to 12D; these two regions are the ones that are often under studied. Next comes the fully developed region in this region the velocity varies very slowly until velocity is matched with surrounding atmosphere, this region extends up to 150D though theoretically the region extends up to infinity.

\[\text{Figure 1. Jet Flow out from Free Jet Setup.}\]

1.2. Pipe Jets
Pipe jets are most commonly used ones in aircraft engines for mixing, and in other applications such as thrust augmentation by boundary layer alteration. It is also used as flow control devices in active/passive flow control units.

This experimental research of pipes relating to aerospace applications lie in the developing flow (of pipe flow) region where the developing boundary contributes to the area restriction producing jet flow. This flow region makes acceleration possible (Nozzle), the phenomenon of boundary layer growth
makes it act as a nozzle in the developing region (of pipe flow). The pipe jet features various complex physical phenomena which makes it very difficult to study by cfd analysis hence researchers often go with experimental methods.

2. Experimental Setup and Design
There are various components that are important in performing experiments on Jets. The components can be subdivided into Open Jet Facility, Data Acquisition Facility, Design and Fabrication of Pipe & its Holder.

\[\text{Figure 2. Schematic of Open Jet Facility.}\]

2.1. Open Jet Facility
The open jet tunnel is one of the efficient mechanism to generate almost all kind of jets. The open jet facility used for experiments is shown in Fig 2. This setup consists of pressurized air tank, pressure valves, open jet tunnel and pressure gauges. The pressurized air tank is the operating source of this facility; the tank is of capacity 5 cubic meter and is capable of holding pressure up to 20 Bar, this tank is pressurized using 2 reciprocating compressors. The pressure is delivered to the open jet tunnel through pipelines made of mild steel (to withstand the pressure) via a gate valve and a pressure regulating valve. The end of the pressure regulating valve is connected to the diffuser; the diffuser expands the pressurized air into the settling chamber. This air that is settled in settling chamber is used to produce jets.

2.2. Data Acquisition Facility
Data acquisition is the important part of all experiments. In this experiment pressure data is recorded. The system consists of a pitot tube, pressure transducer, pressure data recording software, and an automated traverse mechanism. The pitot is pivoted to the traverse mechanism; this mechanism has 2 degree of freedom (horizontal and vertical) and is operated by means of software controlled electrical motor. The pressure picked up by pitot is transduced into electrical signals and this signals were processed using arduino UNO and the absolute pressure values in Bar is recorded in the laboratory computer.

2.3. Design and Fabrication
The major part involves design and fabrication of pipes and its holder.
2.3.1. Pipe/Nozzle. The nozzle design criteria involves understanding of available facility and the scope of the project. Fig 3 shows the pipe nozzle with square cross section. In order to study square cross sections, it should be compared with well-studied cross sections the most common type of nozzle is of circular cross section. From literature the common circular/axisymmetric nozzle of diameter $D=15$mm is chosen.

![Pipe Schematic](image)

Figure 3. Pipe/Nozzle Design.

The cross sectional area of circle with D of 15mm is $176.7\text{mm}^2$. This area is considered to be equivalent and the dimension/side of square for this area is found to be 13.28mm. Further according to [4] the ratio $L/D$ of 5 is selected and the model was designed using CATIA for both circular and Square Nozzles. This design was converted into STL format and is used to manufacture the nozzle by 3d printing.

2.3.2. Holder. In order to attach the nozzle fixed with the end flange of the settling chamber a coupling and a holding mechanism was designed. Fig 4 shows the schematic of the mechanism. The above part was designed using CATIA and is checked for compatibility with nozzle and settling chamber end holder flange by using CATIA Assembly feature. Then the part was manufactured in mild steel using a mild steel rod and lathe operation. The lathe operation includes drilling, boring, threading, chamfering, and knurling.

3. Experimental Methodology

The following steps are performed in series to avoid any unnecessary disturbance or errors in experimentation.

3.1. Initializing

The nozzle is assembled with holder by means of thread in coupling as shown in Fig 4; this setup is then assembled with settling chamber by means of the end support flange setup as shown in Fig 2.once the assembly is complete the setup will resemble Fig 5. Now the gate valve is checked and is closed to isolate the pressure tank from the network. The compressor is switched on and the tank is pressurised to a pressure of up to 18Bars. Restart the Laboratory computer; the traverse is aligned with the jet axis, the pitot tube is connected with the sensor/transducer, sensor is connected with the DAQ and finally to the data monitoring system which is the laboratory computer. Once these are done the facility is ready for experimentation.
3.2. Test Initial Checkups and Precautions
The following were done to avoid error in readings

- Tank pressure was checked to avoid unnecessary termination of experiment.
- The lines were checked for leakage and intactness.
- The nuts and bolts holding the setup together is checked and fastened to improve safety.
- The functionality of pressure gauge was checked.
- The axis of nozzle and the axis of movement of traverse mechanism are checked.
The pressure sensing and monitoring unit was checked by measuring atmospheric and the median value was noted to be 1.012Bar.

The day time conditions was found to be 31°C and by correlating with the international standard atmosphere database with temperature and altitude (6.7m above mean sea level), atmospheric pressure of 1.01245Bar and velocity of sound of 349.61m/s is found.

The experiments were conducted at same time of the day to avoid temperature change from causing error.

Potential blockage to the free jet up to a distance of 150D is removed to remove interference from that object.

3.3. Assumptions

Certain assumptions were made to facilitate experimentation

- Temperature and atmospheric condition change is minimal along the experimental duration.
- Pitot tube associated blockage is negligible.
- Blockage due to traverse mechanism is nominal.
- The roughness offered by inner surface of nozzles is nominal.
- Pitot tube efficiency is nominal.
- Transducer, amplifier and transmission efficiency is maximum.

3.4. Procedure

Circular nozzle is fixed at the end of settling chamber. Data acquisition system is switched on, automated traverse mechanism is operated and the pitot lip is placed exactly at the centre of the pipe exit. The pressure regulating valve is opened slightly to let minimum mass flow. The gate valve is opened and pressure builds up in settling chamber and starts producing jet. Now the pressure regulating valve is adjusted to give a constant gauge pressure of 1Bar (absolute pressure = 2Bar) above atmosphere. The data monitoring system is checked and pressure obtained $P_{ce}$ is found to have 2Bar pressure at nozzle exit. The gate valve is closed. Thus the entire system is calibrated. The data acquired is refreshed and experiment is started. The gate valve is opened, the pressure readings are taken by adjusting the automated traverse, and stagnation pressure at an interval of every 2mm is taken while constantly monitoring the settling chamber pressure, in case pressure in settling chamber decreases the pressure regulating valve is adjusted. Centre line pressure ($P_c$) readings are taken upto a distance of 180mm (12×15mm) along the jet axis corresponding to 12D where the developing region is supposed to end in a free jet flow conditions. The DAQ recorded data is saved and refreshed. The gate valve is closed; air pressure in Tank is checked for content of necessary pressure for performing next experiment with Square nozzle. The holder is removed square nozzle is placed in the holder and is fixed to the settling chamber. Traverse mechanism is moved to the centre of nozzle exit of square nozzle, gate valve is opened, pressure is regulated and the entire experiment is repeated with square nozzle. The data is saved and is used to understand the physics.

4. Results

The Pitot tube data for both circle and square nozzles were obtained and plotted in the form of graph and the results were evaluated. The graphs were plotted after making the parameters non-dimensional by using reference pressure as stagnation pressure and the reference length scale from the nozzle diameter. The readings are taken from the Pitot tube for every 0.5 mm and only selected readings are plotted to make the graph look better. The figures 6 and 7 show the decay of pressure along the axis of the jet. The initial region of constant value is called the potential region and the drop in pressure after the potential core is the decay region. The decay region is fitted with a linear curve fit to provide the slope resulting in the decay rate. The results suggest that the square jet resulting from the short pipe nozzle has faster decay and shorter potential core.
Figure 6. Pressure Decay of Circle and Square Pipes.

A comparison between decay characteristics of nozzles with circular and square nozzle is shown in graph Fig 6. The detailed explanation of decay characteristics of circular and square nozzle is shown in graph Fig 7 (a) and (b) respectively.

Table 1. Nozzle Characteristics.

| Nozzle Geometry | Potential Core (in D) | Characteristic Decay |
|-----------------|-----------------------|----------------------|
| Circle          | 4                     | 0.0478               |
| Square          | 3.2                   | 0.0475               |

Table 1 shows the experimental outcomes of this research. Jet Mach number of 1 is computed from \( P_e \) and \( P' \) using Rayleigh-Pitot equation (by iteration) exactly at the nozzle exit.

The reasons for the faster decay and shorter potential core of square jet areas follows

- Flat sides generate larger vortices
- Corners generate smaller vortices
- Square jet mixes faster due to more vortices than circular jets
- Complex vortices in the near field results in faster mixing and faster decay
- Energy loss in potential core of square jet is more than the circular jet
Figure 7. Potential Core and Characteristic Decay. (a) Circular Nozzle, (b) Square Nozzle.

5. Conclusion
This research concludes with the finding that square nozzles possess better mixing properties in comparison with circular ones. From Fig 6 we can find that the potential core of square nozzles is
smaller than circular nozzles. Also we can see that the developing region pressure drop curve is more decaying in nature at the beginning and gradually reduces ending up with almost same decay rate as the circular one towards the end. Though from the trend line characteristic decay Fig 7 the characteristic decay may be negligible, the comparison with graph Fig 6 shows that the decay rate is relatively more at the beginning. This may be because of the presence of sharp corners in square nozzles, the sharp edges diffuse rapidly at jet boundary near nozzle exit producing strong shear layer and ingesting more air mass from surrounding in the beginning and as instabilities move further the sharp edges disappear and pulls together becoming a jet flow with circular cross section on nearing 12D, this morphing of cross section geometry as shown in [1] may be the reason for decline in decay rates when the flow enters fully developed region. Thus the research concludes that the mixing is rapid in case of square jets at the beginning and ends up almost with same decay rate as circular jets at an X/D of 12.

Nomenclature

- X: Jet axial distance from nozzle exit in mm
- D: Equivalent diameter = 15mm
- $P_{ce}$: Stagnation pressure at the nozzle exit in jet flow
- $P_c$: Stagnation pressure at any distance X along jet axis
- $V_{ce}$: Velocity at the nozzle exit in jet flow
- $P_o$: Maximum stagnation pressure obtained in jet flow
- $P'$: Static pressure of atmosphere
- DAQ: Data acquisition system

Acknowledgment

We are thankful to the following people who offered support for the completion of this project: HOD, Department of Aerospace Engineering, SRMIST for the Project Approval. HOD, Department of Aeronautical Engineering, Rajalakshmi Engineering College, Thandalam for Access to Jet Facility. Mr.Surendra Bogadi, Department of Aeronautical Engineering, Rajalakshmi Engineering College, Thandalam for Guidance and Support. Mr.Anish, Staff, Fab Lab, SRMIST, for Assisting with 3D Printing of Pipe/Nozzles. Mr.Mohan, Lathe Operator, Engineering Works, Guindy for Assistance in Lathe Fabrication of Coupler and Holder.

6. References

[1] Gutmark E J and Grinstein F F January 1999 Flow Control with Non-Circular Jets Annual. Rev. Fluid Mech. 31 239–72
[2] Xu G and Antonia R A 17 August 2002 Effect of different initial conditions on a turbulent round free jet Experiments in Fluids 33 677-683
[3] Munt R M June 1977 The interaction of sound with a subsonic jet issuing from a semi-infinite cylindrical pipe J. Fluid Mech. 83 609-640
[4] Jothi T J S and Srinivasan K 26 June 2009 Role of initial conditions on Noise from Under-Expanded Pipe Jets Physics of Fluids 21 066103
[5] Ethirajan Rathakrishnan 2019 Applied Gas Dynamics 2nd edn (Chennai, JohnWiley & Sons Ltd) Chapter 12 451-546