Investigating One-Dimensional Turbulence Intensity of Circular and Non-Circular Jets

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Abstract — **Fluid dynamics and heat transfer sectors have undergonerevolutionary improvements with the study of turbulent flow in recent decades and still different ongoing researches are making breakthroughs in those sectors. In this research, the fluctuation of pressure in the flow field was measured using differential pressure transducer to investigate the turbulence region of conventional circular jet as well as non-circular (rectangular, square and triangular) jets in the flow axis only. The method was approached to introduce a cost-efficient technique as the alternative of high- cost particle image velocimetry, acoustic Dopplervelocimetry. The objective was to investigate the change in turbulence characteristics of different jets and compare performance which can be applied to aerodynamics, propulsion, heat transfer or environmental studies. Simultaneous measurements of pressure in the flow field were taken using pitot-tube which was converted into velocity applying dynamic pressure theory. The jet flow was created using a blower in an airflow facility and the area of inlet and outlet of all the nozzle was equal to maintain the initial jet flow characteristics. The turbulent intensity, mean shear layer and potential core length of the jets have been derived from the measured data. The study revealed that square nozzle didn't have a significant impact in the flow field whereas the rectangular jet had an increased average shear layer and the triangular jet had a decreased potential core length compared to the conventional jet.**

Keywords **—Jet, Turbulence, Differential pressure, Circular Jet, Shear region, Aerodynamics.**

I. INTRODUCTION

A shear region is produced between the moving and ambient fluids when the fluid at motion enters a quiescent body of the same fluid, causing turbulence. Turbulence dominates all other flow parameters and enhances flow mixing, energy dissipation, drag and heat transfer. Most of the flows encountered in nature, e.g.: flow over an aircraft wing, atmospheric boundary layer over the earth's surface and oceanic currents are all turbulent in nature [1,2]. During the 1960s, research on turbulence has been conducted to discover some deterministic features that revealed the bursting process in the near-wall region produced most of the turbulent energy [3]. The research on coherent structures and mixing in cross flow was observed using particle image velocimetry and laser-induced fluorescence. Experimentation on circular, elliptical and square-shaped nozzles revealed that the global mixing performance is enhanced for nozzles which have a high aspect ratio and blunt shape [4].The investigation on background turbulence of a turbulent jet with Doppler Velocimetry (ADV) measurements was found to be inaccurate when measuring turbulence statistics and necessary improvements were done in the measurement technique. It was also discovered from that research that Jet's width increases and mass flow rate decreases in the presence of background turbulence at higher Reynolds numbers [5]. In 2012, some researchers have performed Reynolds-Averaged Navier-Stokes simulations to investigate the effect of nozzle geometry on the turbulence characteristics of incompressible fluid flow through nozzles at Reynolds number of approximately 50,000. They showed that mesh topology plays a major role in determining the accuracy of the results when compared to experimental data. They analyzed the flow through a baseline nozzle and three modified versions (extended, grooved and ringed) by comparing the mean flow and the turbulence intensities. Their simulations indicated that certain changes in nozzle geometry would result in major changes to the operating conditions of the nozzle, and this would have a significant impact on the energy consumption in such devices [6].

Turbulence intensity is defined by the ratio of the standard deviation of fluctuating flow velocity to the average flow speed at certain point of the flow field [7].

$$I = \frac{\sigma_v}{\bar{V}} \quad \text{……} \quad (1)$$

Where, I denotes turbulence intensity at a point;

σ_v denotes standard deviation in velocity in the point;

$\bar{V}$ denotes average velocity of that point of the flow field. [8]

According to dynamic pressure theory,

$$P_v = \frac{1}{2} \times \rho \times \bar{V}^2 \quad \text{……} \quad (2)$$

Where,

P_v denotes dynamic pressure at a point in the flow region;

ρ denotes density of air;

$\bar{V}$ denotes average velocity of that point of the flow field. [2]

A new and cost-efficient method to study turbulence intensity of free jets with a Differential Pressure Transducer (DPT) was devised where pressure was converted into an electrical voltage. The pressure was measured with a pitot static tube which was fed into the DPT. Calibrations were needed to acquire accurate pressure data and convert it to the velocity using eqn. 2[8]. Circular, square, rectangular and triangular jets were taken into consideration. To study velocity fluctuation at a certain point, continuous data was taken by Arduino Micro-controller with 10 milliseconds interval from which intensity were measured at some specific points along flow axis using eqn. 1. The jets were produced by a blower circulated in an air flow chamber with the nozzle inlet velocity of 20 ms^{-1}.

II. Experimental Setup

The airflow facility to produce jet flow consists of a centrifugal blower, settling chamber, flow straightener with honeycomb structure, reducer and nozzle shown in fig. 1 (except nozzle). The pitot-tube was mounted on a traverse mechanism which can move in three axis of the measuring table which was detached from the air flow facility (fig. 2). The blower was powered by a DC power supply of 220W which produced airflow of 12 m/s initially. The flow was circulated through settling chamber and flow straightener with honeycomb structure to ensure a laminar flow. The flow straightener was 15 cm long and 37 smaller pipes of diameter 1.5 cm were used to construct the honeycomb structure. The reducer was designed by the method of bell mouth entry to have the smooth flow through the reducer with minimum loss. The nozzle inlet diameter was 5.41cm. The area was same in the nozzle outlet section. The three Cartesian axis are shown in fig. 2 with the traverse mechanismof the measuring table.

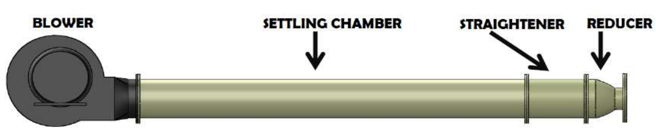


Fig. 1. Different parts of the air flow facility

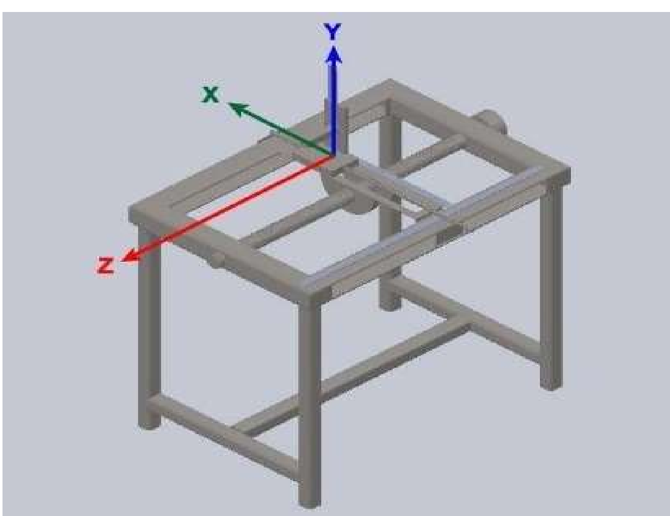
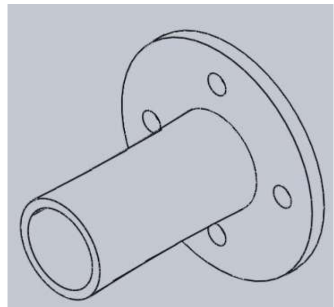


Fig. 2. Traverse mechanism of the measuring table with axis direction

The figure 3-6 show the four nozzles ofthe experimentation band the dimensions of the given nozzles are shown in table 1. The centre of mass of the outlet of the nozzle geometry was considered as the origin.



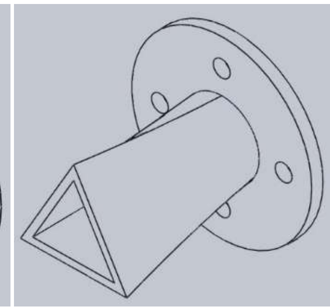
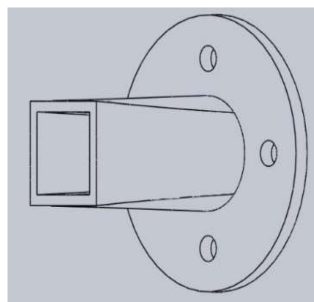


Fig. 3. Circular nozzle Fig. 4. Circular nozzle



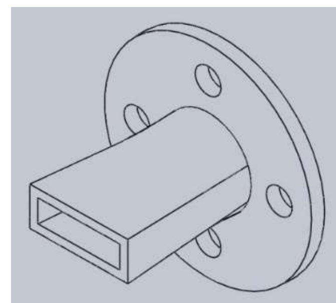


Fig. 5. Square nozzle Fig. 6. Circular nozzle

TABLE I Dimensions of the Jet Nozzle Outlet

Type	Dimensions (cm)
Circular	5.41 Diameter
Rectangular	7.58×3.03
Square	4.79
Triangular (equilateral)	7.286

A. Data Acquisition System

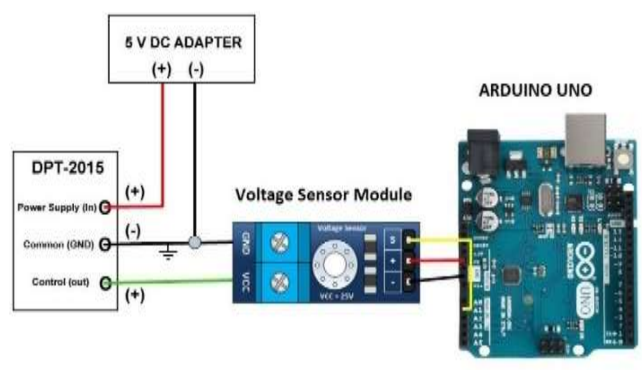


Fig. 7. Circuit diagram of data acquisition system

Fig. 7 shows the circuit diagram of the data acquisition system where a differential pressure transducer of Johnson Control

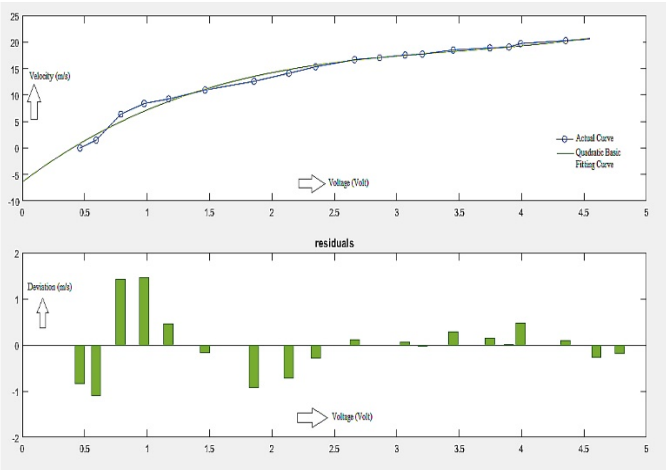


Fig. 8. Calibration Graph (up) with deviation from the actual curve (down)

DPT-2015, 5V power supply, voltage sensor module and arduino microcontroller are used. As the Arduino software was not incorporated with the storage of the measurement data, Parallax Data Acquisition Tool Software (PLX-DAQ) was usedwhich acquires up to 26 channels of data from any microcontrollers and drops the numbers into the columns of Microsoft Excel sheet.

B. Callibration of DPT-2015

Calibration of DPT-2015 were done on Wind Tunnel of Aerodynamics Lab of Aeronautical Engineering Department, Military Institute of Science and Technology, Dhaka. The voltage produced by the DPT-2015 was captured via PLX_DAQ for the different velocity at the wind tunnel test section. The velocity vs. voltage data were plotted at MATLAB® to obtain a suitable equation with the basic curve fitting operation (fig. 8, up). From the basic fitting curve, a cubic equation was taken into consideration for the optimum error. The equation was:

Velocity = (0.4455 x Voltage^3) – (4.621 x Voltage^2) + (17.78 x Voltage) +6.42

The residuals shown in figure 8 (down) was the significant deviation from the actual curve which showed significant error in the low velocity.

III. Results and Discussion

In the jet flow, the flow direction was considered as Z-axis, the vertical direction perpendicular to horizontal plane was Y-axis and X-axis was perpendicular to Y-Z plane as shown in fig. 2.The origin was the center of mass of the nozzle exit. The DPT was properly calibrated by taking readings in the wind tunnel. The calibration error was within 20% when the flow velocity was under 10 ms^{-1}. It became significantly low as velocity was increased. The error in low velocity couldn't be compensated as the voltage change with respect to the velocity was very small. The solution for this matter is to increase the voltage output with an amplifier or higher voltage range of pressure transducer.

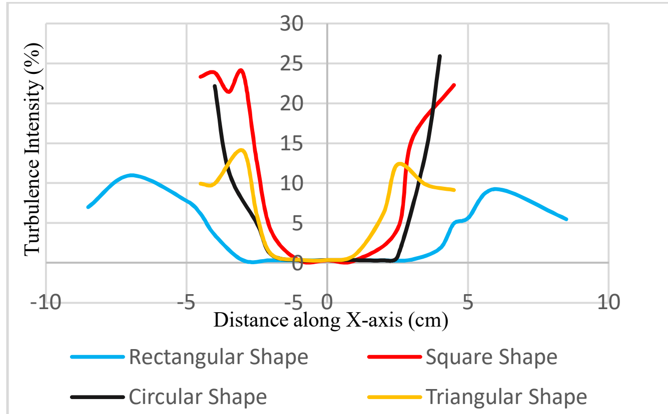


Fig. 9. Turbulent intensity profile comparison between different cross-sectional shape nozzle at z = 8cm

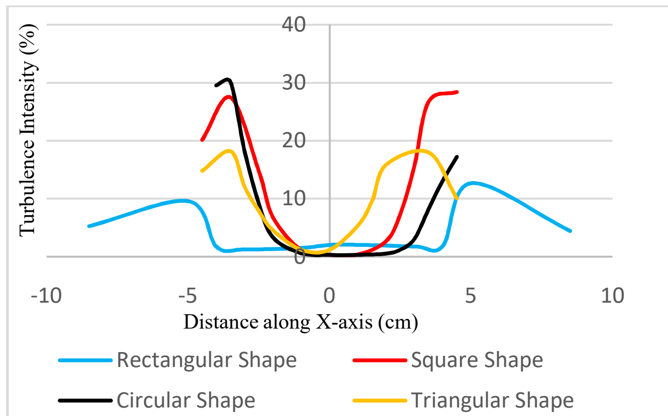


Fig. 10. Turbulent intensity profile comparison between different cross-sectional shape nozzle at z = 16cm

The readings were taken along X axis at Y = 0 cm and Z= 8 cm, 16 cm and 32 cm for the four different nozzles. The data is shown in Fig. 9, 10 and 11. The data in fig. 9 indicates that the flow retains its nozzle exit shape as the intensity was close to zero in that region. The circular and square jet's intensity reached around 25% at maximum in the shear region. The shear region can be explained between the region where intensity begins to rise and fall down again. Average shear layer was calculated from that. The rectangular jet attained around 10% maximum intensity whereas intensity was less than 20% in case of triangular region. Along Z axis, intensity was almost zero which indicated jet characteristics was not impaired. In fig. 10 and 11intensity grew higher than the preceding data followed by the previous order which proves shear region is increasing as flow is moving forward. The intensity of 10% at the core of rectangular jet (fig. 10) indicates fully developed turbulent region.

Considering the data of three positions, it can be inferred that Square and circular jets has turbulence region ofsame nature and it has reached maximum intensity which indicate high drag. But steepest curve of triangular jets indicates the shear region is smaller whereas the rectangular jet has largest shear region. The fig. 12 is the comparison of mean shear layer width which was measured by average of the width of the hill section of the curves. The maximum width was discovered in rectangular jets which is ideal for mixing (fig 12). The triangular jet attained lowest intensity (fig 9-11) and lowest shear area (fig 12) which could be used in drag reduction.

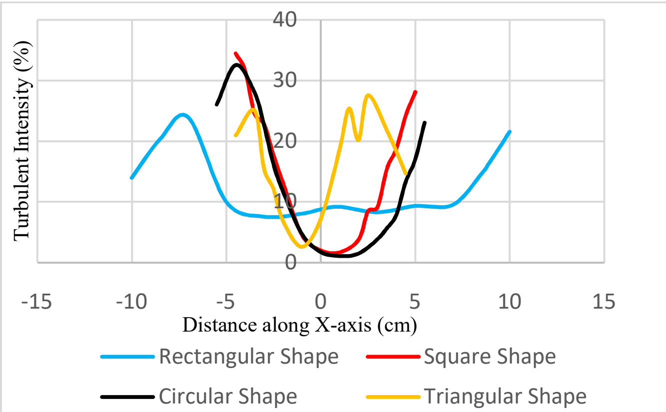


Fig. 11. Turbulent intensity profile comparison between different cross-sectional shape nozzle at z = 32cm

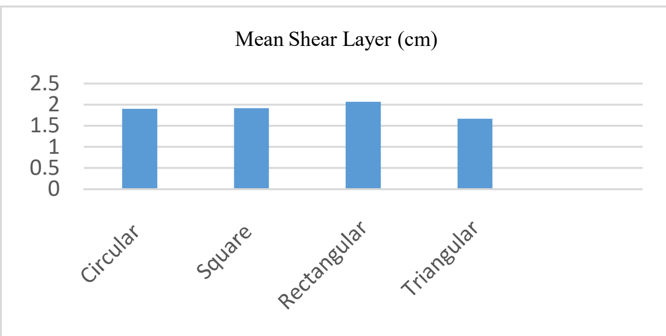


Fig. 12. Mean shear layer width of different jets

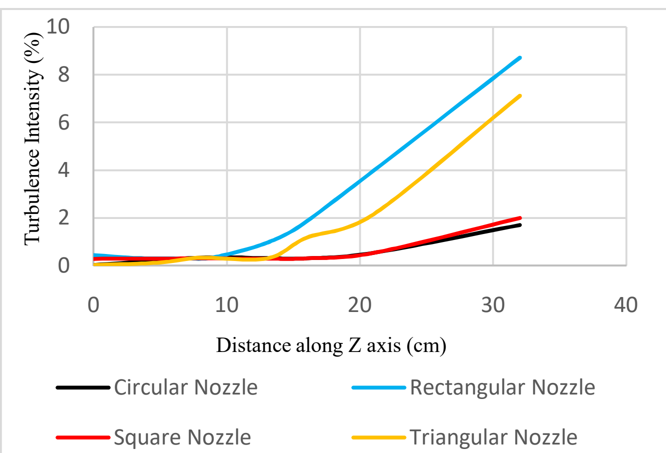


Fig. 13: Turbulence intensity of different jets along Z-axis

The potential core length can be determined from fig. 13which display intensity of different jets along Z-axis. The potential core length is considered the length where intensity reached 2% and shown in table 2. Circular jets has the maximum length, greater than 32 cm which can be utilized to circulate fluid/energy efficiently.

TABLE II Potential Core Length of Different Jets

Type of Jets	Core Length (cm)
Rectangular	17
Triangular	21
Square	32
Circular	>32

The comparison in this study is not fully accurate yet as the data were taken in only one axis only. As turbulence is a three-dimensional parameter, acquired data have not representeda clear picture. For further study, orifice of the of the pitot-tube need to oriented in X-axis and Y-axis to get three dimensional value of turbulence. Also data along Y-axis can be taken to observe the three-dimensional flow field.

IV. Conclusion

A cost-efficient method was conducted to study turbulence infour types of free jets which could be implied in any fluid dynamics study. Their boundary layersin horizontal axis were observed using differential pressure transducer. Calibration of DPT was done with optimum accuracy within limited resources and could be further improved. The data showed that rectangular jet flow was most dispersed and triangular jet would have smallestshear region whereas maximum potential core was obtained in circular jet. These different outputs of different jets make them efficient for different purposes. However, turbulence is a three dimensional phenomena and it was measured in only one-dimension due to limited resources which leaves us a scope for further research and improvements.

References

[1] Oh, H.W., 2010, *Advance Fluid Dynamics*, IntechOpen, London, 272 p.
[2] Cushman-Roisin, B., 2014, *Environmental Fluid Mechanics*, John Wiley & Sons, Inc., NY, 480 p.
[3] Gustavsson, H., 2006, *MTM 162: Introduction to Turbulence*, [pdf] Retrieved from www.ltu.se
[4] Salewski, M., Stankovic,D. and Fuchs, L., Mar 2008,*Mixing in Circular and Non-circular Jets in Crossflow,* Flow, Turbulence and Combustion, Volume 80, Issue 2, 255–283p.
[5] Khorsandi, B., 2011, *Effect of Background Turbulence on an Axisymmetric Turbulent Jet*, McGill University Libraries.
[6] Yu, Y.,Shademan,M., Barron, R., M., andBalachandar.R.,2012, *CFD Study of Effects of Geometry Variations on Flow in a Nozzle*, Engineering Applications of Computational Fluid Mechanics, Vol. 6, No.3, 412-425p.
[7] Pipinato, A., 2015, *Innovative Bridge Design Handbook,* Elsevier Inc., Philadelphia, 878 p.
[8] Product Bulletin DPT-2015, 2015, *Differential Pressure Transmitter for VAV Box Applications: Johnson Control[pdf]*,Johnson Control, Wisconsin, retrieved from johnsoncontrols.com