Study of Axisymmetric Jets

Md. Abdul Azim
Dept. of Mechanical Engineering
BUET, Dhaka-1000, Bangladesh
Md. Tajul Islam
Dept. of Mechanical Engineering
BIT, Chittagong, Bangladesh
S. M. Nazrul Islam
Dept. of Mechanical Engineering,
BUET, Dhaka-1000, Bangladesh.

Abstract: Jets are produced by issuing air through two different nozzles. The boundary layer velocity profiles at the exit are with two different boundary layer thickness. The Reynolds number based on average velocity and exit diameter is 1.3 x10^4 for each case. The jets with different boundary layer at the exit are found to behave differently for achieving self-preservation. The spread of the jets are presented upto an axial distance of x/D=15 .

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INTRODUCTION

A free jet flows without contacting solid surfaces. When such a free jet formed by discharging fluid through a circular nozzle or an orifice is known as axisymmetric jet. Boundary layer forms within the nozzle and its separation at the exit initiates a shear layer in the free jet flow. This kind of jet flow is shown in Fig. 1 with three distinguishable layers: (1) Shear layer, (2) Ambient air, and (3) Potential core. For convenience of analysis, the turbulent jet flow is divided into three principal regions: (1) Initial region, (2) Transition region, and (3) Developed region. The initial region of a jet has a potential core of almost constant velocity initiating from the exit [10]. The transition region starts after the initial region by a sharp change in the centerline velocity. Further downstream, the developed region exists where the flow variables i.e.velocity, turbulence intensity etc. become approximately self-preserving. The combined initial and transition region is called the developed region of the jet.

The first theoretical treatment of a circular jet is given by Tollmien [2], who based his study on Prandtl's mixing length. Reichardt [4] has investigated on circular jets and compared the results of measurements with the theory due to Tollmien [2]. The results of measurements are in close agreement with the theory. Howarth [3] has also been investigated on circular jets, both on the basis of L. Prandtl's and of G.I. Taylor's assumption concerning turbulent mixing. The mechanism which governs the mixing of a jet issuing from a circular nozzle with the fluid in a large pipe is studied experimentally by Viktorin [5].

This paper presents the investigation of behavior of the flow of axisymmetric jet with two different initial conditions. The study of jet is relevant to many problems of diffusion, discharge of pumps, aircraft design, combustion in a chamber, fluid amplifiers and dryers.

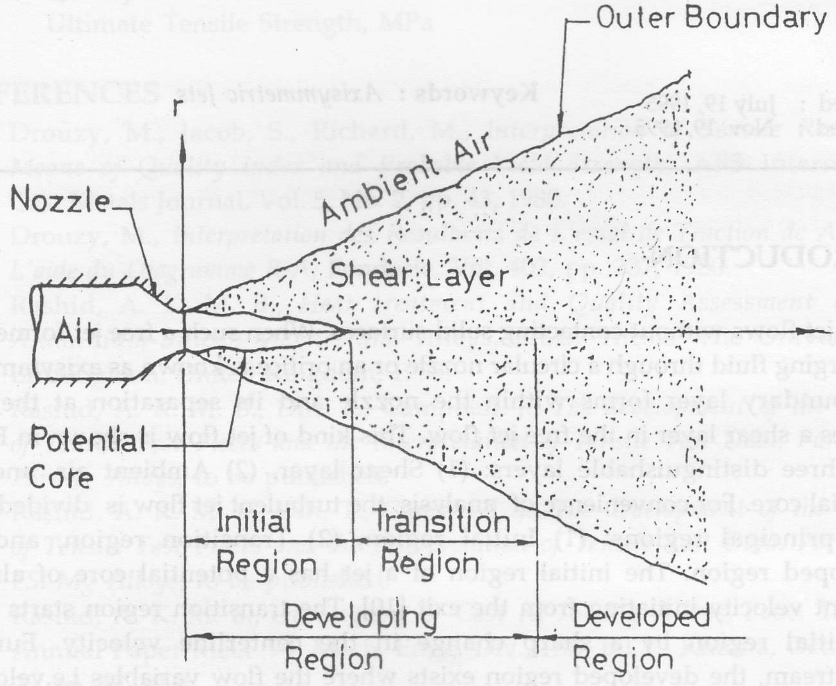


Fig.1 Jet geometry and nomenclature.

EQUATIONS

To study the behavior of the flow under consideration, the following flow parameters were determined. These parameters are:

i. Mean axial velocity, u

The value of this velocity can be obtained by knowing the difference between the stagnant and static head for a particular location of pitot-static tube in the flow stream. The velocity, u is given by [6], $u = k\sqrt{2gh_a}$.

From manometric equation, $h_a \gamma_a = h_o \gamma_o$. Hence for incompressible flow with velocity co-efficient k = 1, $u = \sqrt{2g(\gamma_o / \gamma_a)h_o}$

ii. Reynolds number, Re

It helps to determine the type of flow and $Re = uD/\nu$

iii. Displacement thickness, δ^*

It is the distance by which a boundary surface of a flow field needs to be displaced so that the amount of total fluid flow of a frictionless flow is reduced and becomes equal to the real flow. This displacement thickness is estimated by

$$\delta^* = \int_o^\infty (1 - u/u_m)dy.$$

iv. Momentum thickness, θ

Similar to the displacement thickness, momentum thickness is the distance by which a boundary surface of a flow field needs to be displaced so that the total momentum of a frictionless flow reduces and becomes equal to the real flow. It is obtained by

$$\theta = \int_o^\infty \left(u/u_m \right)(1 - u/u_m)dy$$

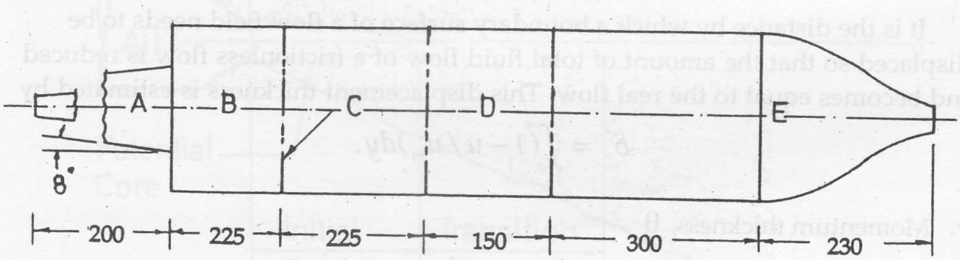
Both δ^* and θ for a particular axial distance are evaluated graphically.

v. Shape factor, H

It is obtained by the relation, $H = \delta^*/\theta$ which is interpreted physically as the ratio of pressure force to viscous force.

EXPERIMENTAL SET-UP

The schematic diagram of the set-up for producing axisymmetric jet is shown in Fig.2. The apparatus used to contain the flow is a circular cone connected to a square duct (150mm x 150mm) having a running length of 900mm. This duct terminated into a nozzle at the downstream side. The whole set-up was of G.I. sheet. Wire mesh of different mesh numbers were soldered inside the duct with the finer one in the downstream side. Packing tubes are placed inside the duct forming a honey-comb. Wire mesh and honey-comb before the nozzle are used for keeping the flow straight and stable. Other essential components of the set-up were: steel pipes, controlling valves, air chamber and compressor. The set-up is made horizontal with a levelling instrument and fixed rigidly to the base. The joints are made leak proof.



A: Circular Cone
B: Square Duct (150mmx150mm)
C: Wire Mesh
D: Honey-comb Chamber
E: Nozzle

Fig. 2 Experimental set-up for producing jets

The main element of the set-up is the nozzle. The nozzle has been given the shape of a cubic curve which corresponds to a stream line of the flow. The streamlined surface is given to the nozzle surface to avoid flow separation [9]. The cubic curve $Y^3 = 0.563X$ is obtained from cubic parabola, $Y^3 = a + bX$ with the conditions X = 0, Y = 0 and X = 150, Y = 37.5 as shown in Fig. 3. The entrance of the nozzle is a rectangle with aspect ratio 1:1. A short circular pipe of same internal diameter as that of the nozzle exit is mounted over the nozzle end. This is to make the nozzle end circular and to lead the nozzle profile to dY/dX = 0.

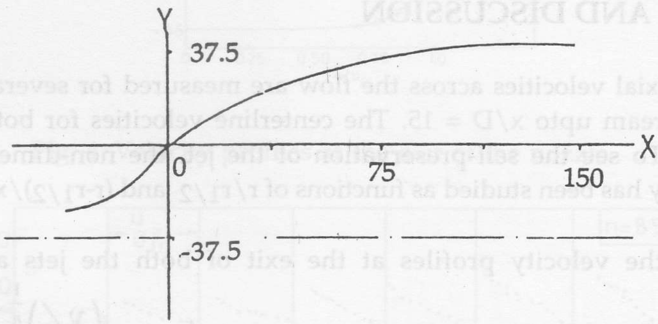


Fig. 3 Profile of the nozzle surface.

The experiment is performed by maintaining a flow from a plenum which was connected to the inlet of the setup. A constant pressure of about 377 kPa is kept by pressurizing air in the air chamber with the help of a compressor and controlling with the regulating by-pass valve, allowing air to pass out through auxiliary piping arrangement. The compressor could not be operated continuously as it needs intermittent cooling.

The flow velocity is measured by a pitot-static tube of 1.56mm bore. The manometer used was inclined tube making an angle of 30° with horizontal. The graduation on the tube is upto 0.25mm. The manometric fluid was oil having a specific gravity of 0.836. Graph papers has been placed on the table outside the nozzle on the downstream side. This has helped in locating the axial stations for placing the height gauge in turn the pitot-static tube.

The readings are taken at the exit of the nozzle i.e. at x/D=0 and at several stations upto a maximum of x/D = 15. The pitot-static tube is traversed vertically for each station. The readings are taken in steps of 2.5mm vertically for each station. But at x/D = 0, the steps were 0.25mm within 2.5mm from both upper and lower side of the inner surface of the nozzle.

RESULTS AND DISCUSSION

The mean axial velocities across the flow are measured for several positions in the downstream upto x/D = 15. The centerline velocities for both the jets are presented. To see the self-preservation of the jet, the non-dimensional mean axial velocity has been studied as functions of $r/r_{1/2}$ and $(r-r_{1/2})/x$.

In Fig. 4, the velocity profiles at the exit of both the jets are turbulent. Comparing these profiles with the suggested $u/u_m = \left(y/\delta \right)^{\frac{1}{n}}$, the obtained average values of n are 6.6 and 8.5. These values are close to the value proposed by Prandtl [1]. These values of n for two jets are attributed to the difference in initial conditions.

In Fig. 5, the mean axial velocities across the flow for different positions in the downstream upto x/D = 15 for both the jets are shown. This figure presents the spread pattern of the jets.

In Fig. 6, non-dimensional centerline velocity u_c/u_{ce} is shown as a function of x/D. It is observed that the jet with lower value of n decays a bit faster than the one with higher value of n. The centerline velocity is found to decay from the initiation of the jet. As a result of this, the potential core is not found to exist at all.

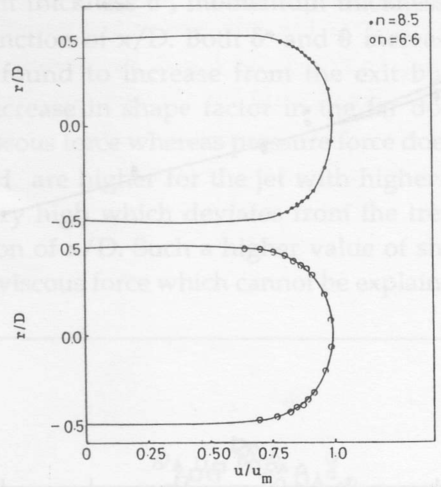


Fig. 4 Velocity profiles at the exit of the nozzle.

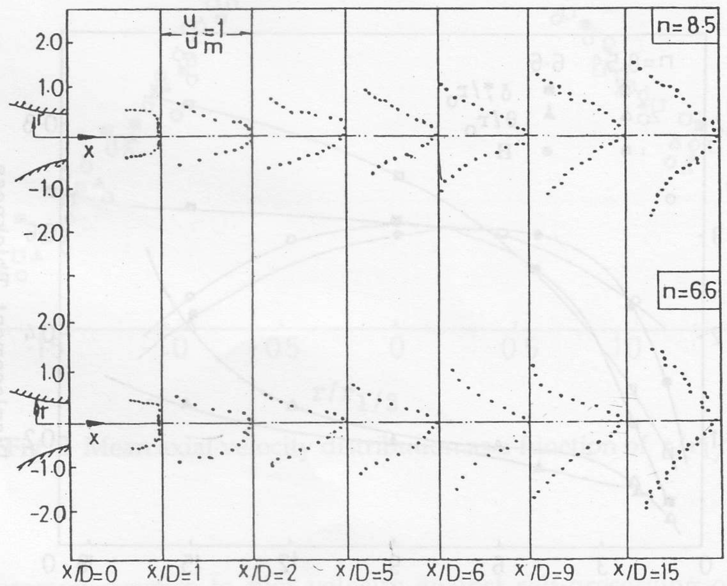


Fig. 5 Mean axial velocity profiles at different axial positions.

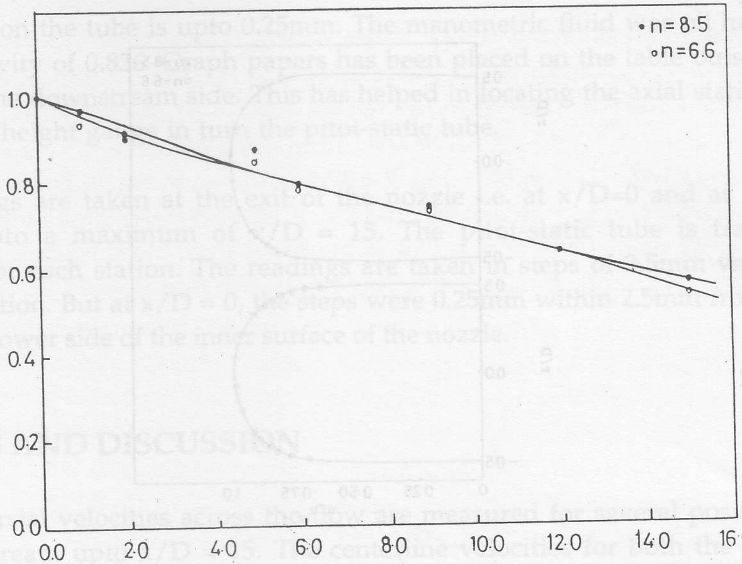


Fig. 6 Mean axial center line velocity.

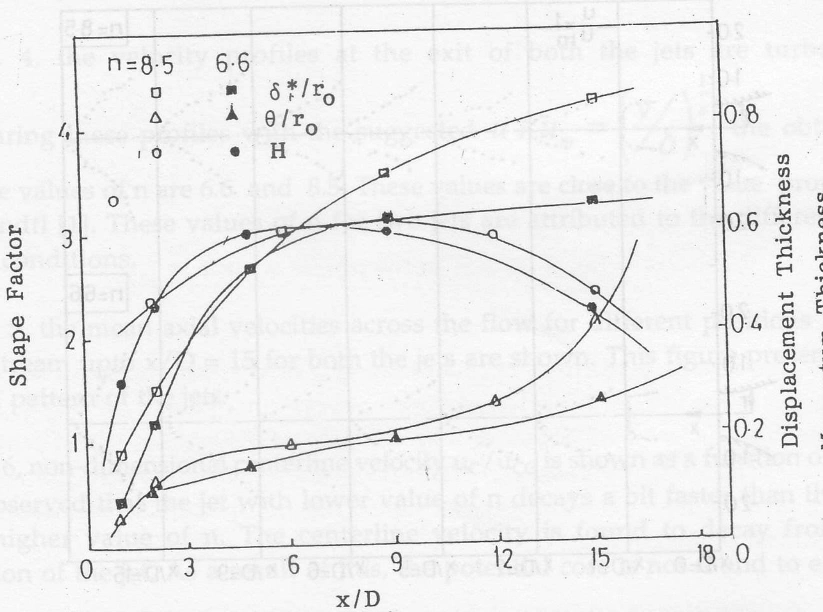


Fig. 7 Graph for δ^*/r_o, θ/r_o and H as a function of x/D.

In Fig. 7, displacement thickness δ*, momentum thickness θ and shape factor H are presented as a function of x/D. Both δ* and θ increase in the downstream. Shape factor is also found to increase from the exit but decreases in the far downstream. This decrease in shape factor in the far downstream may be the result of increasing viscous force whereas pressure force does not increase. It can be seen that δ*, θ and H are higher for the jet with higher value of n. The shape factor at x/D=1 is very high which deviates from the trend of the shape factor expressed as a function of x/D. Such a higher value of shape factor at x/D=1 is due to lower value of viscous force which cannot be explained.

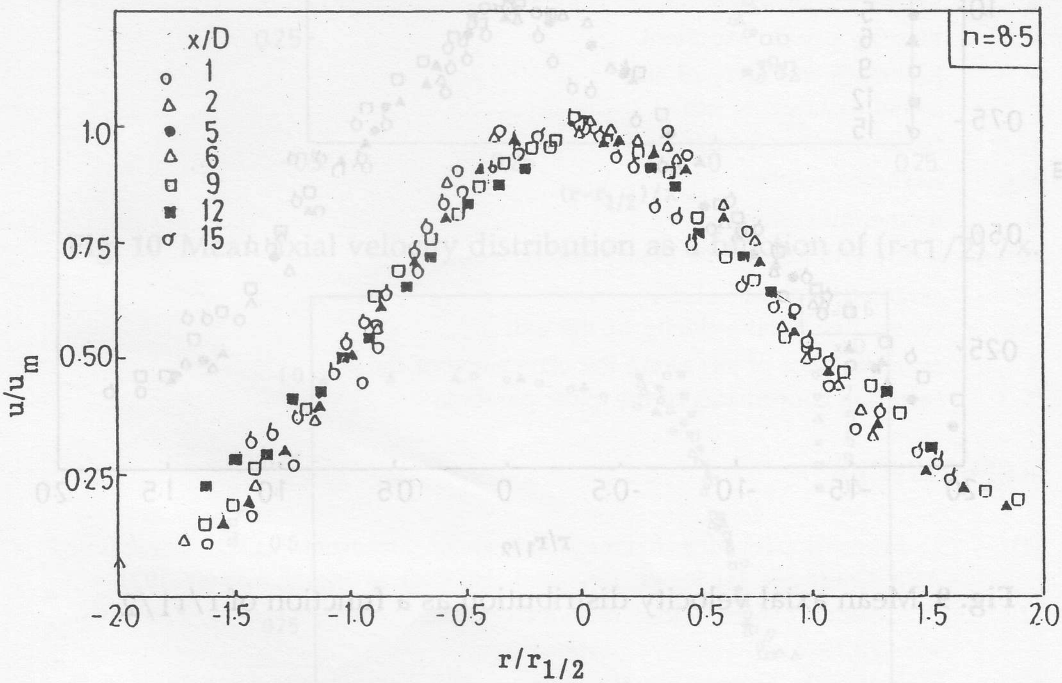


Fig. 8 Mean axial velocity distribution as a function of $r/r_{1/2}$.

It is a common practice to plot velocity against self-preserving or similarity variable to study the self-preservation of the flow. This self-preserving variable is defined in many ways by different authors to express the flow to be self-preserving. Reichardt [4] has used $r/r_{1/2}$ as the self-preserving variable for expressing the flow to be self-preserving. Schlichting [6], Von Frank [8] and others have used $(r-r_{1/2})/x$ as the self-preserving variable for expressing the flow to be self-preserving. In Fig. 8 and Fig. 9, the non-dimensional velocity are plotted against $r/r_{1/2}$. In Fig. 10 and Fig. 11, the non-dimensional velocity are plotted against $(r-r_{1/2})/x$. These figures indicate that the flow is more self-preserving with respect to $(r-r_{1/2})/x$ than $r/r_{1/2}$.

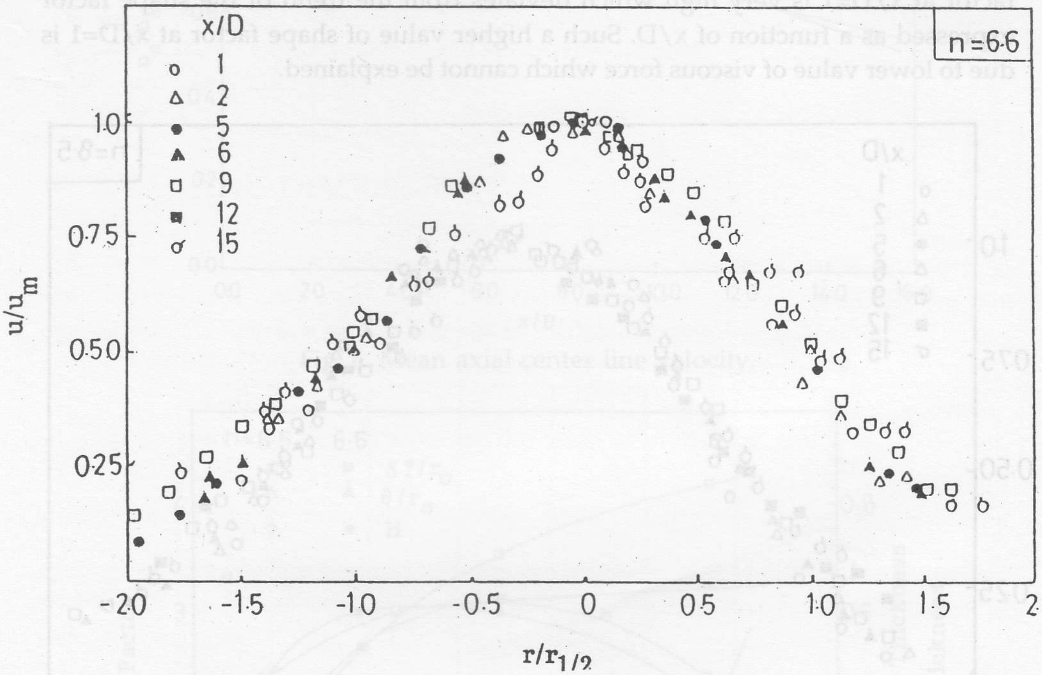


Fig. 9 Mean axial velocity distribution as a function of $r/r_{1/2}$

CONCLUSION

The level of precision in the mean axial velocity measurement is not enough to reveal some of the features of the jet flow. Potential core of the jet is one of them, existence of which can not be detected in the measurement. It was found that the displacement thickness at the exit has influence on self-preservation of the flow.

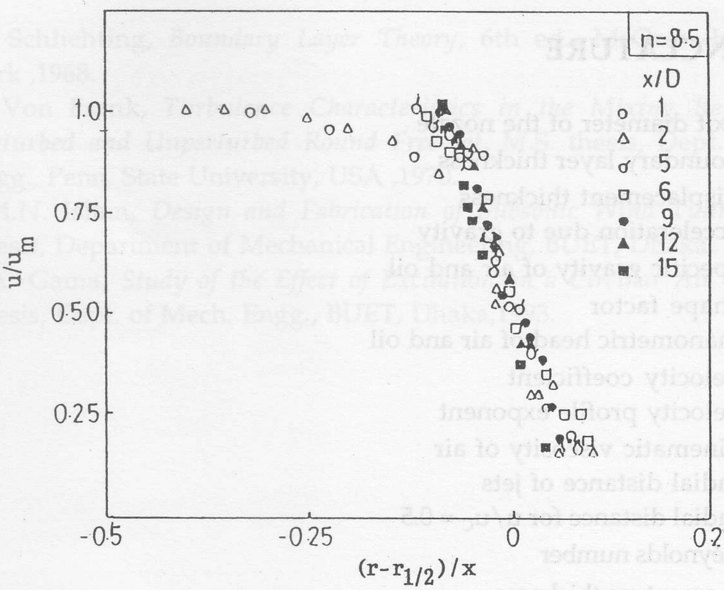


Fig. 10 Mean axial velocity distribution as a function of (r-r1/2) /x.

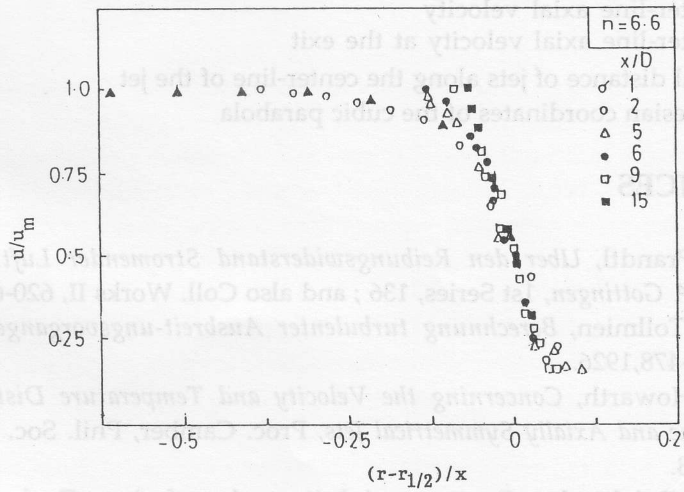


Fig.11 Mean axial velocity distribution as a function of $(r-r_{1/2})/x$.

Fig. 11 Mean axial velocity distribution as a function of (r-r1/2)/x.

NOMENCLATURE

D	exit diameter of the nozzle
δ	boundary layer thickness
δ^*	displacement thickness
g	acceleration due to gravity
γ_a, γ_o	specific gravity of air and oil
H	shape factor
h_a, h_o	manometric head of air and oil
k	velocity coefficient
n	velocity profile exponent
v	kinematic viscosity of air
r	radial distance of jets
$r1/2$	radial distance for $u/u_c = 0.5$
R_e	Reynolds number
θ	momentum thickness
u, u_m	mean and maximum axial velocity
u_c	center-line axial velocity
u_{ce}	center-line axial velocity at the exit
x	axial distance of jets along the center-line of the jet
X,Y	cartesian coordinates of the cubic parabola

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