MEAN VELOCITY AND STATIC PRESSURE IN A SHARP-EDGED CIRCULAR NOZZLE JET

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Abstract An axisymmetric jet issued from a sharp edged circular convergent nozzle has been studied experimentally in the near field at Reynolds number 5.3×10^4 to search the saddle shape behavior of mean velocity and the role of mean static pressure in the jet flow. Due to the vena contracta effect the centerline mean velocity of the jet increases about 4.2% of its exit value and corresponding decrease of mean static pressure is found in the potential core of the jet. Streamwise mean velocity shows saddle shape profile adjacent to the mixing layer near the exit (due to secondary current). Velocity peaks are associated with corresponding drop of mean static pressure. This saddle shape behavior is found to die down at the end of the potential core. The geometric virtual origin is at downstream of the nozzle tip and the entrainment rate is increased nonlinearly with the axial distance. A partial self-preservation of mean velocity is attained earlier than that of mean static pressure.

Key Words Axisymmetric Jet, Circular Convergent Nozzle, Saddle Shape Behavior, Jet Flow, Vena Contracta Effect

چکیده جتی که دارای محور تقارن بوده و از یک شیپوره همگرای دایروی و لبه تیز خارج می شود به طور تجربی در حوالی عدد رینولدز ۵/۳×۱۰۴ مطالعه شده است تا رفتار زین شکل سرعت میانگین و نقش فشار استاتیک میانگین در شارش جت بدست آید. به سبب تأثیر قسمت باریک شیپوره (گلویی شیپوره)، میانگین محوری شیپوره در حدود ۴/۲٪ از مقدار خروجی افزایش می یابد و در ارتباط با آن فشار ایستای (استاتیک) میانگین در هسته پتانسیل شیپوره کاهش می‌یابد. سرعت میانگین خط جریان نیمرخی به شکل زین در مجاورت لایه مخلوط شونده در نزدیکی خروجی (به سبب جریان ثانوی) نشان می دهد. اوجهای منحنی سرعت به کاهش افت فشار ایستای (استاتیک) مربوطه وابسته است. این رفتار زین شکل در انتهای هسته پتانسیل محو می شود. اصل واقعی شکل هندسی در پایین دست دنباله شیپوره بوده و آهنگ همراه کشیدن به طور غیر خطی نسبت به فاصله از محور افزایش می یابد. به خود نگهداری نسبی سرعت میانگین زودتر از فشار ایستای (استاتیک) میانگین می رسیم

INTRODUCTION

It is commonly assumed by most researchers including Schlichting [1], that the mean static pressure in the direction of the jet flow is negligibly small compared to other mean forces of the flow field. Sforza et al.[2] found that the static pressure within the jets is atmospheric. Miller and Comings [3] and Hussain and Clark [4] have shown that in plane jet negative static pressure exists everywhere in the mixing field except for the positive pressure (above atmospheric) in the potential core region immediately adjacent to the nozzle exit. Hussain and Clark [4] also explained the existence of negative mean static pressure by the boundary layer form of the spanwise transverse mean momentum equation. Negative static pressure in the mixing field have also been reported in rectangular jets [5], in square jets [6] and in round jets [7]. Islam and Ali [8] also found that this positive pressure is encountered everywhere in the potential core and negative pressure exists in the mixing field.

Quinn and Militzer [5] found in sharp edged square slot jet a strong acceleration of the flow in the central line close to the exit where curvature effect (the vena contracta effect triggered by the sharp-edged exit of the slot) is accompanied by a drop in the mean static pressure causing the velocity to increase to it's maximum value. Moore [9] found that the centerline mean velocity in axisymmetric jet (issued from a nozzle with exit parallel section followed by a conical contraction) is increasing over the first half-diameter downstream from the exit. This is due to the incomplete acceleration of the fluid inside the nozzle.

Saddle shape mean velocity profiles are existed in rectangular jet [5], in the square jet [6], in the tapered jet [10] and in the three-dimensional wake [11]. These saddle shape profiles are found apparently more pronounced in flows from sharp-edged rectangular slots [12]. Quinn et al.[5] and Islam and Ali [13] showed that the saddle shape profiles occur in the mixing region, appears to move in downstream direction and seem to disappear in the region where the shear layers merge on the jet centerline, they also shown that in the potential core region the static pressure drops significantly adjacent the mixing layer before it start to recover to the atmospheric value at the edge of the jet. In rectangular jet flows the saddle shape profiles of mean velocities are found to increase to 20% of its centerline values [12] and in square jet flows it is about 2% more that its centerline value [14]. Some attempts have been made to find the cause of these saddle shape phenomena. Van Der Hegge Zijnen [15] hypothesized that saddle shape may be caused by the superposition of the velocity induced by vortex rings surruonding the jet upon a uniform mean streamwise velocity. Such circumferential vortex rings exist in all jet flows and consequently saddle shape mean velocity profiles are observed in the initial region of all jet flow fields. Again vortex stretching hypotheses have been postulated to account for this behavior in partially bounded turbulent jet flows [16]. Near the exit "turbulence driven secondary flows" have been suggested as a possible cause of this type of profile [17]. The static pressure within the jet also might play a role in the formation of these mean stream wise saddle shape profile [5,6].

The objective of this present study is to measure the axial mean velocity and static pressure in the initial region of the jet to find out the initial boundary layer state and self-preserving zone, to search saddle shape profiles of mean velocity and the role of mean static pressure in the jet flow. Also some other properties are calculated from mean velocity distributions, to predict the flow characteristics of the jet.

EXPERIMENTAL RIG AND METHODOLOGY

The expeniment is carried out in an air jet facility as shown in Figure 1. The set-up consists of two settling chambers, fan unit, a flow controller, diffusers, an excitation chamber and a flow nozzle. The air supply in the system is provided by the fan unit which consists of two aerofoil axial flow fans one with fixed speed motor and the other with variable speed motor. The overall length of the set-up is $8.1m$.

Air enters the fan unit through the butterfly valve which controls the air flow. A silencer is fitted at the discharge of the fan through a vibration isolator to reduce both noise and vibration generated at the fan section. Flow from the silencer enters the settling chamber through a 6° diffuser. In this chamber the flow straightner and a wire screen net are used to straighten the flow as well as to breakdown large eddies generated at the fan discharge. The flow from the diffuser enters the second settling chamber through

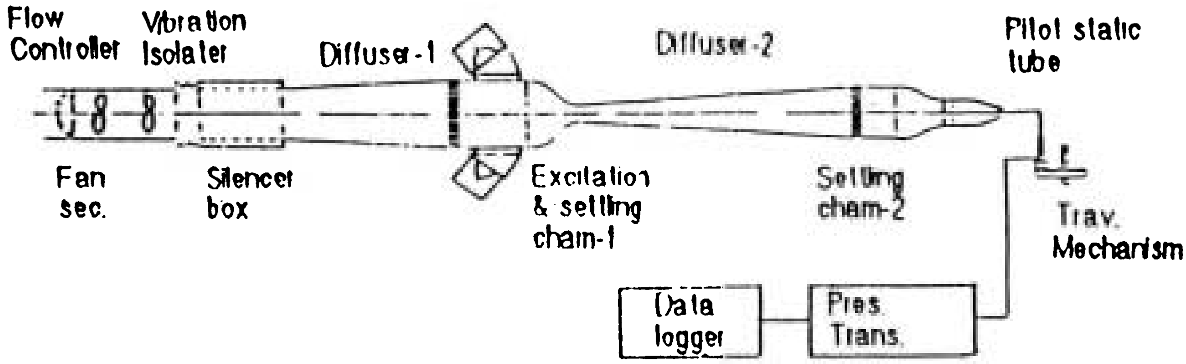

Figure 1. Schematic diagram of experiment set-up.

a nozzle and a second diffuser there also a straightner and a wire screen are used for ensuring axial flow free from large eddies which may be generated in the upstream side of the flow. Finally air discharges through a circular convergent nozzle (cubic profile, $y = 0.615x^2 - 0.0034x^3$; exit diameter, 80 *mm* and contraction ratio based on area, 9:1) with vertical exit flange (2.5 nozzle dia) as shown in the Figure 2.

The measurement of mean velocity and static pressure are taken by 1.6*mm* outer diameter pitot-static tube along with pressure transducer (range 10%) and digital microvoltmeter with data logging system. The pitot-static tube is traversed with resolution 0.01*mm* by traversing mechanism. The exit centerline of the nozzle in the direction of the flow is taken as the positive x-axis and the transverse distance pointing upward as positive y-axis as shown in Figure 3.

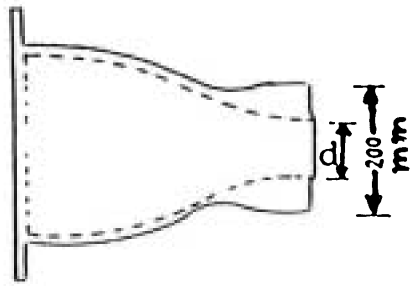

Figure 2. Schematic diagram of test nozzle.

RESULTS AND DISCUSSION

The exit boundary layer profile of mean velocity is shown in Figure 4. The profile having shape factor 1.3, differs from the Blasius profile. So the initial boundary layer profile may be considered as turbulent.

The centerline mean velocity and corresponding mean static pressure distributions are presented in Figure 5. It was found that the regular decay of velocity starts after $x/d = 4.5$. From this behavior it can be said that the potential core exists up to 4.5 diameter downstream from the exit. It is seen that near the exit the velocity sharply rises up to x/d=1. Its increase rate then decreases but continues to increase slowly up to the end of the potential core. Similar results were also found in the sharp edge circular nozzle [18], in the circular nozzle jet with long exit section of conical contraction [9], and in the sharp

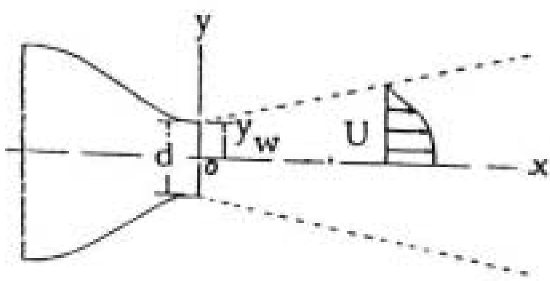

Figure 3. Coordinate system.

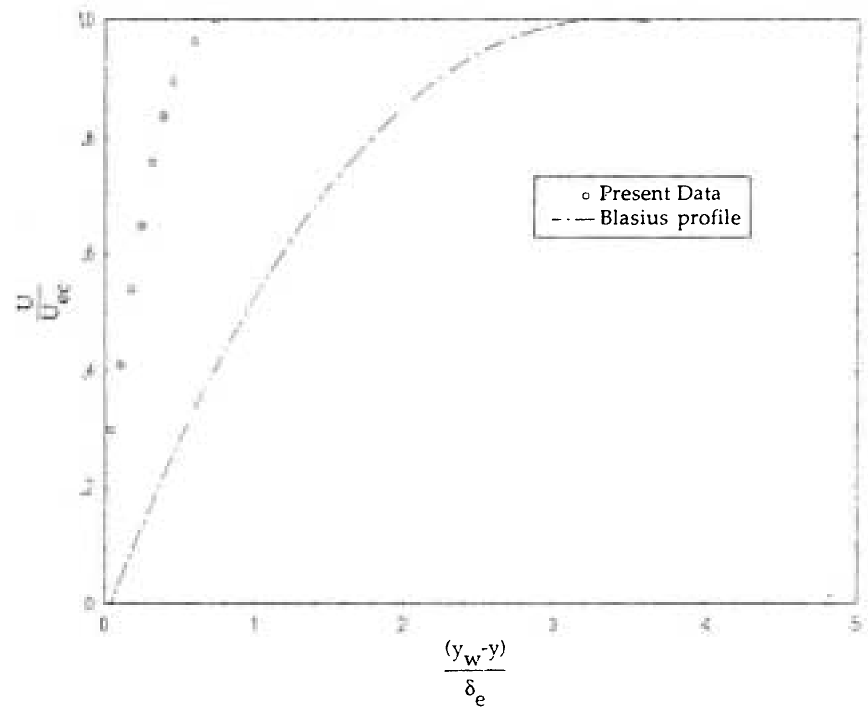

Figure 4. Initial boundary layer profile.

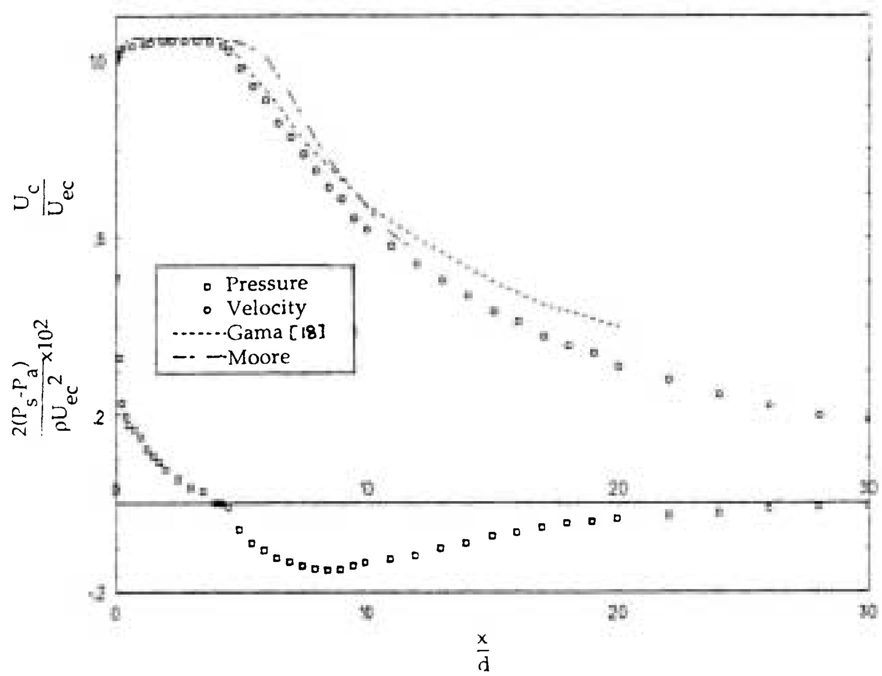

Figure 5. Centerline mean static pressure profiles.

edge square jet [6]. In the present case this may have happened due to vena-contracta effect (triggered by the orifice type jet due to exit vetical flange). This vena contracta effect was also supported by Quinn and Militzer [6]. From the static pressure distribution curve, it is seen that the exit pressure is positive and a sharp decay is observed near the exit. Further the pressure decreases slowly to atmospheric value at the end of the potential core where the velocity increases to maximum (about 4.2% of its exit value). Form this phenomenon it may be concluded that pressure also plays a major role on centerline mean velocity acceleration in the potential core as well as on its length.

The streamwise mean velocity profiles, as presented in Figure 6, are of saddle shape type. The maximum peak velocity of this profile is observed at the nozzle exit. The saddle shape appeare to move towards the jet centerline with downstream distance and seem to disappear at the end of the potential core. Similar conclusion was also drawn for the rectangular jet [5]. From the corresponding static pressure distribution curve, as shown in Figure 7, it is seen that the negative minimum pressure is found at $x/d = 0.5$ along axial direction, which varies with the location of maximum peak of saddle shape mean velocity (at $x/d = 0.0$). This phenomenon is confirmed by Quinn et al[5] as well.

The iso-velocity lines are shown in Figure 8. The spread of the shear layer is found approximately linear up to the extent of the potential core. After that (ie., beyond 4.5 diameter) transition starts and the constant mean velocity lines no longer linearly varies with axial distance, specially along the outer edge of the jet. It is also seen from Figure 8 that the line $y_{0.99}$ intersect the x-axis approximately at 4.5 diameter downstream from the exit, which again shows that the potential core exists upto 4.5 diameter downstream distance.

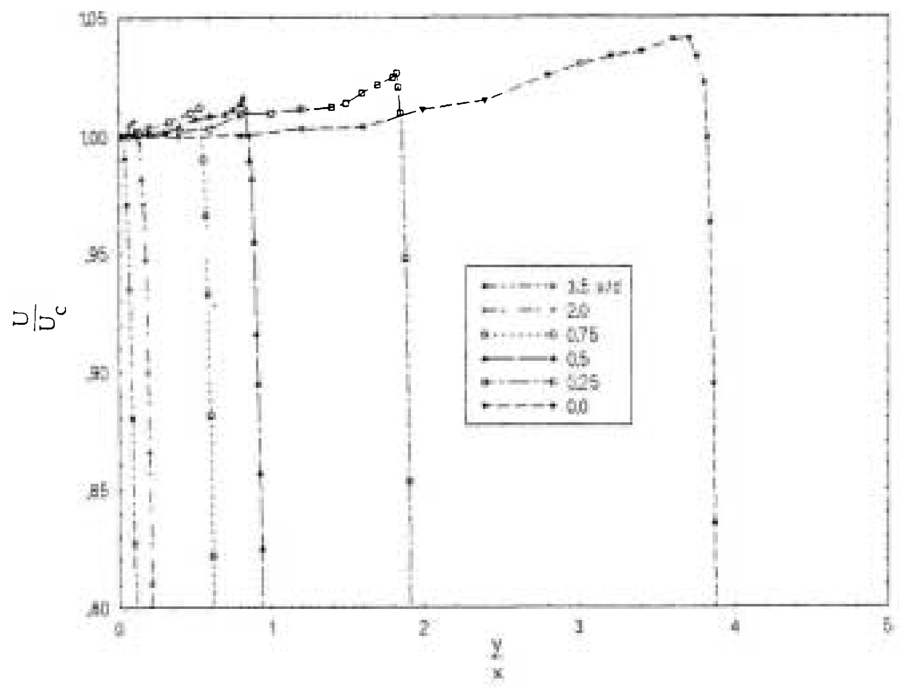

Figure 6. Stream wise mean velocity profiles.

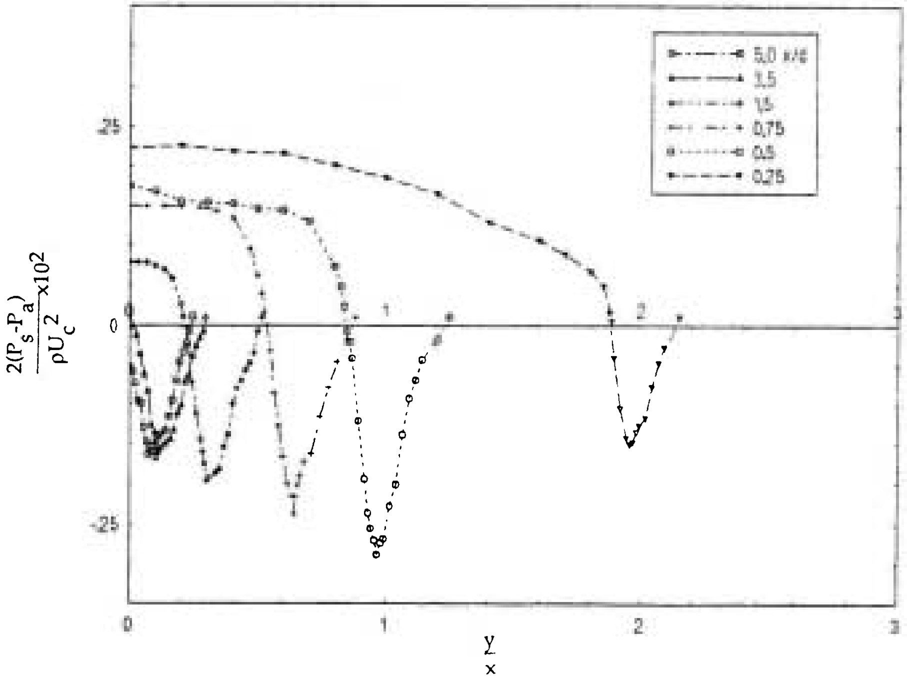

Figure 7. Stream wise mean static pressure profiles.

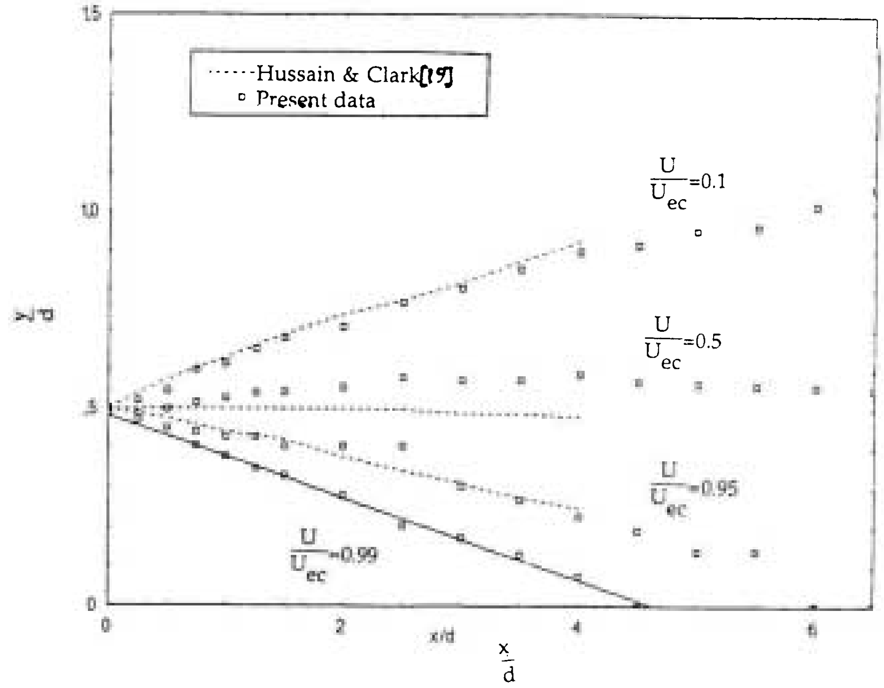

Figure 8. Iso velocity lines.

The streamwise variation of shear layer local momentum thickness is presented in Figure 9. By linear extrapolation it is found that geometric virtual origin is located at 0.5 diameter downstream from the nozzle exit. Similar results were also found for the turbulent jet [20].

The partial self-preservation profile of mean velocity in the initial region is shown in Figure 10. The jet is found to be self-preserving from $x/d = 0.5$ to 4.5. After that, the jet loses its self-preservation characteristic. This fact may be due to the transition or the absence of potential core. The present result is found to be in close agreement with that Azim [21]. The partial self-preservation profile of mean static pressure in the initial region is shown in Figure 11, and the jet is found to be self - preserving from $x/d = 1.5$ to 4.5, which indicates that the mean velocity becomes self-preserving earlier than the static pressure does.

The non-dimensional entrainment rate calculated from the mean velocity profile is presented in Figure 12. It was found that the entrainment rate varies non linearly with increasing axial distance. Similar result was also found by Hill [22] and Ho and Gutmark [23].

Uncertainties in the measurement of mean velocity, pressure and Reynolds number are estimated by determining the single sample measurement technique [25] (using the uncertainty interval of odds 20 to 1). It is estimated that the uncertainty of mean velocity is within ±0.41% and pressure within ±1.08%. The lateral turbulent intensities of the jet are estimated to be in the range of 2% to 14%. The corresponding errors in the measurement of static pressure are found to vary from 0.09% to 2.5%.

CONCLUSIONS

The present measurements in turbulent jet at Re_d=

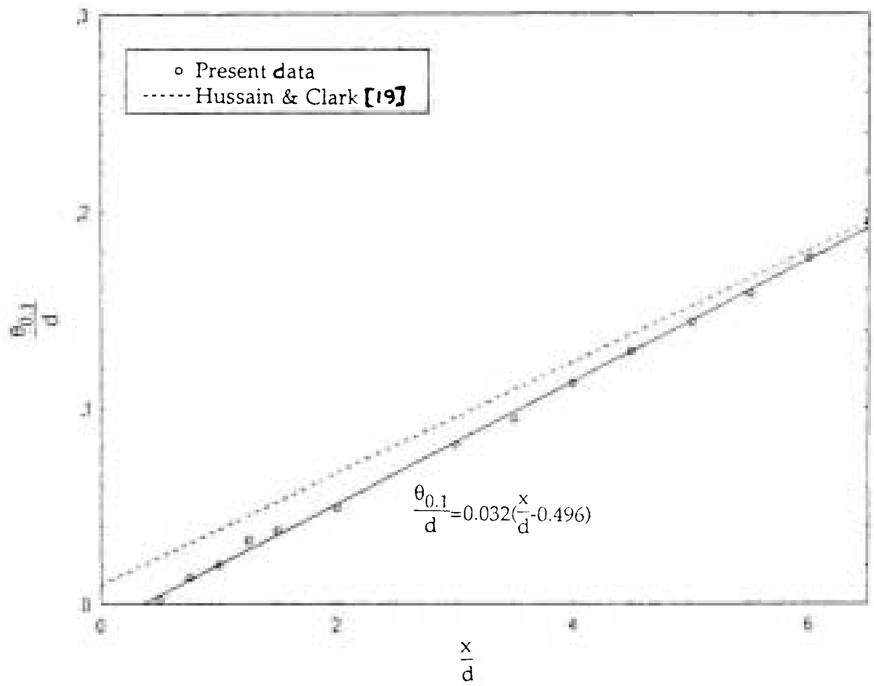

Figure 9. Shear layer local momentum thickness.

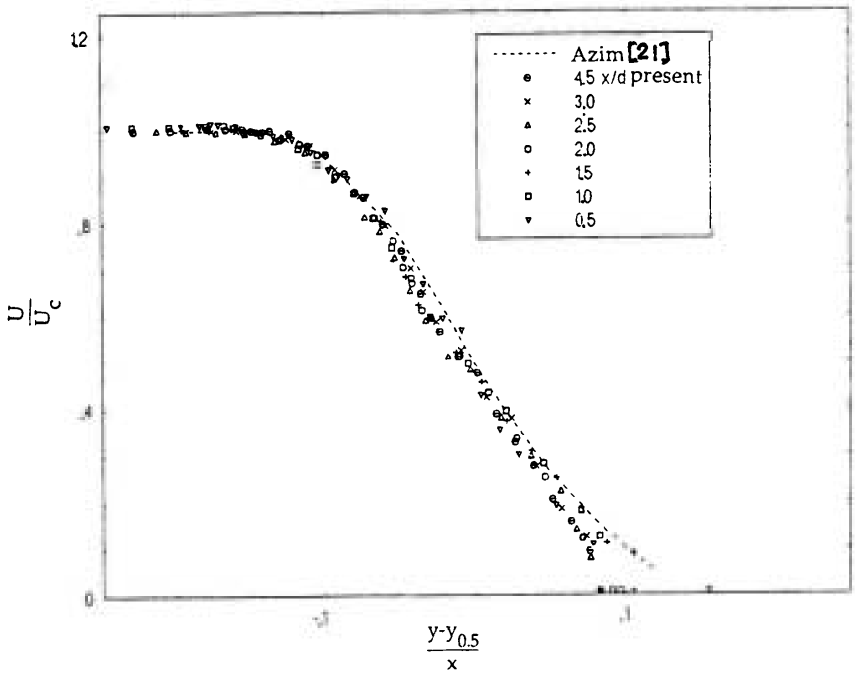

Figure 10. Partial self preservation of mean velocity profiles.

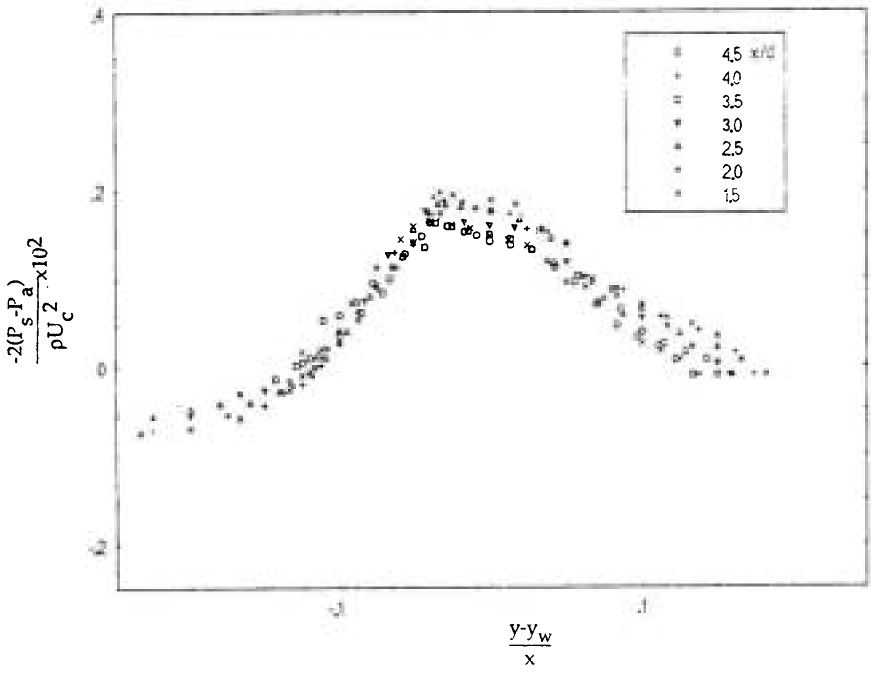

Figure 11. Partial self preservation of mean static pressure profiles.

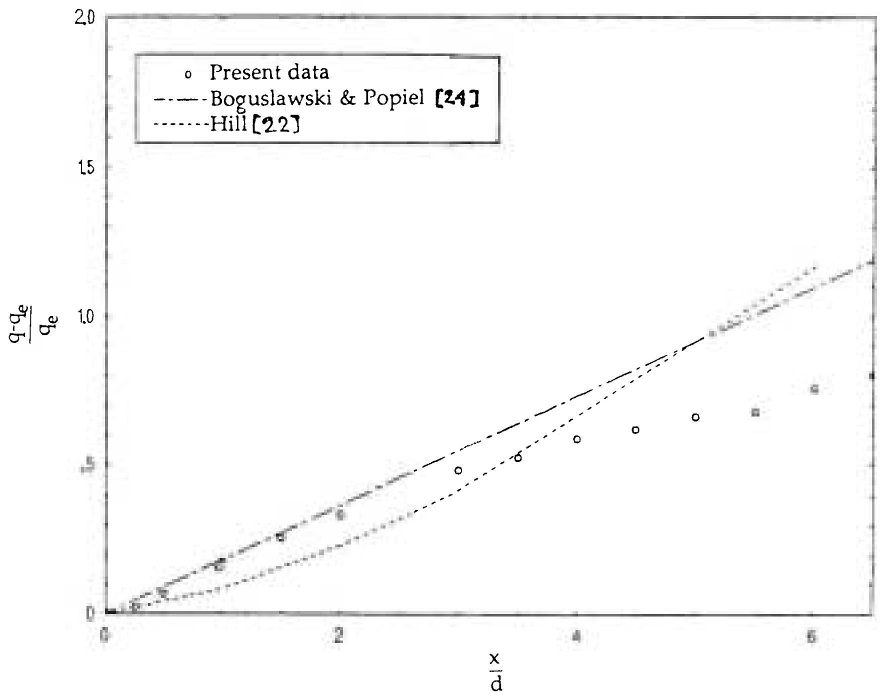

Figure 12. Entrainment rate along axial direction.

5.3×10^4 lead to the following conclusions.

1. A small increase of centerline mean velocity (about 4.2% of its exit value) and corresponding sharp drop of mean static pressure are found close to the exit within the potential core.

2. The saddle shape behavior of mean velocity profile is found in the mixing region and becomes maximum at the exit, but corresponding drop of mean static pressure is not significant with the saddle shape mean velocity profile. The saddle shape behavior dies down beyond the end of the potential core, where the static pressure is atmospheric.

3. Geometric virtual origin is found 0.5 nozzle diameter downstream from the nozzle tip.

4. Parital self-preservation of mean velocity profile in the initial region is found from $x/d = 0.5$ to 4.5 but for static pressure it is from $x/d = 1.5$ to 4.5.

5. The entrainment was found to vary non-linearly with downstream distance.

NOMENCLATURE

d	= exit diameter of the nozzle
o	= physical origin
Re_d	= Reynolds number (based on nozzle exit diameter)
U	= mean velocity in axial direction
U_{ec}&U_c	= exit and local centerline mean velocity
U_m	= maximum streamwise mean velocity
P_s&P_a	= mean static and atmospheric pressure
x&y	= coordinates in axial and transverse direction
$y_{0.95}$&$y_{0.99}$	= transverse distance, where U/U_{ec} 0.1&0.5
q_e/ρ	= exit mass flux
δ_e	= exit displacement thickness, $\int_0^{d/2}(1-\frac{U}{U_{ec}})\,dy$
θ_e	= exit shear layer moment thickness, $\int_0^{y_{0.1}}\frac{U}{U_{ec}}(1-\frac{U}{U_{ec}})\,dy$
$\theta_{0.1}$	= shear layer local momentum thickness, $\int_0^{y_{0.1}}\frac{U}{U_{ec}}(1-\frac{U}{U_{ec}})\,dy$

$$q/\rho = \text{mass flux}, \; 2\pi U_{ec}\int_0^{y_{max}} \frac{U}{U_{ec}} y\,dy$$

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