# UPSTREAM INFLUENCE ON THE NEAR FIELD OF AN AXISYMMETRIC TURBULENT JET*


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Abstract

**The effects of the mean and turbulence characteristics of the upstream (initial) conditions on the evolution of the flow in the near field of an axisymmetric turbulent jet have been experimentally investigated. A total of seven upstream initial conditions were produced by different arrangements of screens, a baffle plate, and nozzle shapes. Centerline and radial distributions of the axial mean velocity and fluctuating axial and radial velocities, are obtained. The results showed that the mean and turbulence quantities in the near field are strong functions of the initial upstream flow conditions. For the cases studied, the decay rates of the centerline mean axial velocity is higher when no baffles or screens were installed in the settling chamber (corresponding to higher turbulence intensities), and the spreading rate is higher. This implies that it is the initially developed small scale dissipative turbulence, rather than the lateral diffusion of streamwise momentum which is primarily responsible for the higher decay rates observed.**


## INTRODUCTION

The upstream conditions have an important effect on any turbulent flow structure. This fact have been recognized long time ago by Prandtl in 1932 [1]. Therefore, many studies were conducted to investigate the effect of upstream or initial conditions on various types of turbulent flow. For example, Weir et al. [2] studied the effect of inlet disturbance on turbulent pipe flow, while Westphal and Johnston [3] studied the effect of initial conditions on turbulent reattachment downstream of a backward-facing step. The effect of wind-tunnel screens on the turbulent flow structure were also studied by several investigators [4-7]. The effect of upstream conditions on jet evolution were also investigated for both circular [8-9], and plane [10-11] jets.

Due to this effect of the upstream conditions on the flow structure, the study of changing the inside construction of the elements usually placed upstream the flow field may give answers to many questions concerning the flow structure. One of these elements is the settling chamber. On the other hand, screens are considered the most important component of the settling chamber. Therefore, since Prandtl [1] first suggestion about the use of screens to improve flow quality in wind tunnels, many studies were performed.

Screens are normally installed in the settling chamber to improve the mean flow uniformity and to reduce the intensity of the incoming turbulence. Further, the problem of turbulence supression by screens contains many interesting basic features of how turbulent eddies of disparate scales interact. On the upstream side there is a pressure redistribution, and a stream contraction into the center plane of the screen, whereas on the downstream side thin shear layers are present and vortices are shed [7]. East [5] showed that the sensitivity of the boundary layer in the working section is due to the condition of the downstream screen ( last screen). Further, the dependence of the flow upon the screens in the settling chamber is as great in large wind tunnels as it is in small tunnels. In addition, the spacing between screens and between the last screen and the contraction ( or nozzle) entry is important.

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Therefore, there are two important properties to be considered [12];

1. For the pressure drops through the screens to be completely independent, the spacing should be such that the static pressure has fully recovered from the perturbations before reaching the next screen.
2. For full benefits, from turbulence-reduction point of view, the minimum spacing should be of the order of the large energy containing eddies.

Another element that is sometimes installed in the settling chamber is a baffle plate. The plate is placed at the inlet of the settling chamber and concentric with it. The baffle plate serves to decelerate the flow entering the chamber and to disperse the fluid to the outer radius [13-14].

The contraction of the nozzle is an important component of a wind tunnel. For a good performance, the nozzle contour should give low adverse pressure gradients at the ends of contraction so that no separation of flow takes place. The boundary layer thickness at the exit should be small, and the nonuniformity in the velocity distribution at the exit must be small. A good contour should achieve these conditions with a small length to upstream diameter ratio. Several methods have been proposed to obtain the shape of contraction. Morel [15] give a bibliographic details of these methods.

The objectives of the present investigation were to relate the upstream conditions to the evolution of the flow in the near field of a circular jet. The pausity and need for such a study were repeatedly emphasized, where the existing confusion concerning the effect of initial conditions was emphasized. The study was carried out for two axisymmetric nozzles, with variable upstream conditions generated by placing screens and a baffle plate in the settling chamber.

The influence of all these variables on the mean and turbulent quantities and parameters are studied using laser Doppler velocimeter (LDV).

## THE EXPERIMENTAL SET-UP

A schematic diagram of the experimental set-up used in the present work is shown in Figure (1). Air from the laboratory supply was passed through filters, a pressure regulator, and a seeding generator before entering the settling chamber.

Air in the settling chamber passes through any of the combinations of a baffle plate and two identical screens (of open area ratio .533), before entering the nozzle. In the present work two nozzles were tested, a simple conical nozzle and a contoured one. Both nozzles have the same exit diameter (D = 1 cm.), length (L = 5 cm.) and contraction ratio of 1:25. The contour of the profiled nozzle is that proposed by Morel [15], and obtained by two power-law curves matched at a point and having their apexes at either ends of the contraction. The probing mechanism allowed the jet to be traversed in the radial directions using a vernier with a micrometer gauge capable of measuring within 0.01 mm. The whole set-up was mounted on a lathe bed. The probing mechanism also allowed measurements to be taken at any location in the longitudinal direction of the jet with a precission of 1 mm.

## THE LASER VELOCIMETER (LDV) AND ANCILLARY EQUIPMENT

A line diagram of the arrangement used for the present jet measurements is also shown in Figure (1). A 5 Watt Argon-Ion laser is used with a beam splitter/colour separator to generate two pairs of blue, 488 nm, and green, 514.5 nm, beams. These beams are caused to intersect by the optical transmitter system generating a region of orthogonal blue and green fringes. One set of fringes is arranged normal to and the other set parallel to the jet axis. An optical receiver system is focoused onto this small ellipsoidal region, of normal dimensions approximately 1.1 by 0.09 mm., which constitute the measuring volume. The flow passing through the measuring volume is seeded using a seeding generator. It is essential that the fluid in which the measurements are to be made is seeded with particles of size sufficient to allow the intensity of scattered light to be detected, while still representing the instantaneous velocity of the fluid. The average droplet size in the present work is 2.5 micron, with a particles density of $5 \times 10^5$ particles/cm$^3$. The green and blue lights of the alternating intensity, scattered by the particles are detected by the receiving optics, filtered to separate green and blue light, and converted to electronic signals by photo-multiplier tubes PMT. The high frequency bursts are then processed to provide simultaneous velocity measurements in two orthogonal directions. Processing of the data is almost exclusively carried out on a digital computer interfaced with the equipment. Configuration of the interface for the signal processor is described in the software manual for the 'LDA2D' program [16]. Standard methods for

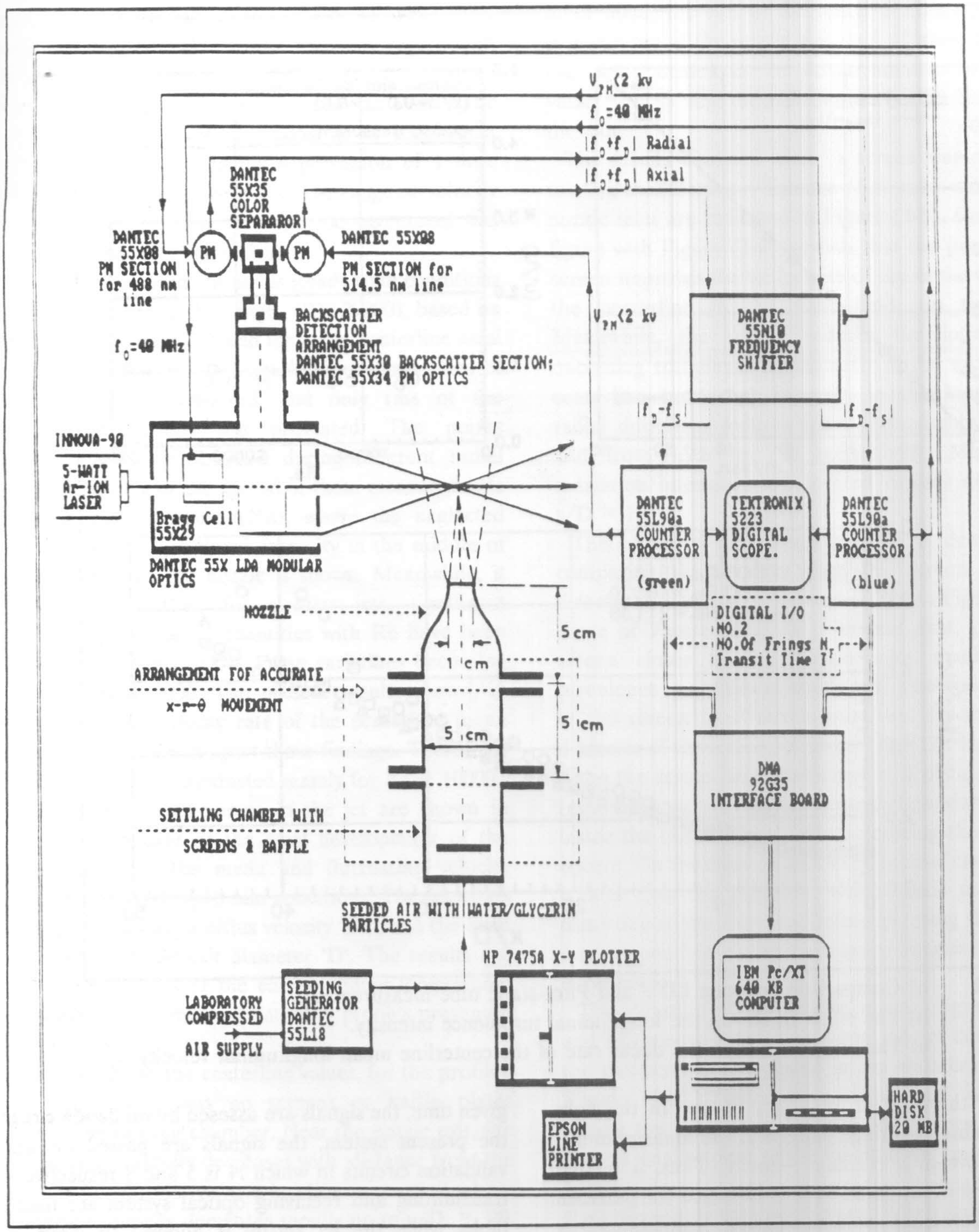


**Figure 1.** A schematic of the air jet facility and measurement scheme.

formation of the desired statistical results up to the fourth order are used.

In the present set-up, a Bragg cell is incorporated in the transmitting optical system. It is basically an acousto-optical modulator. When light from one of the two transmitted beams of a given colour passes through it, the light frequancy is shifted. The amount of shift is determined by the excitation frequency of the Bragg cell.

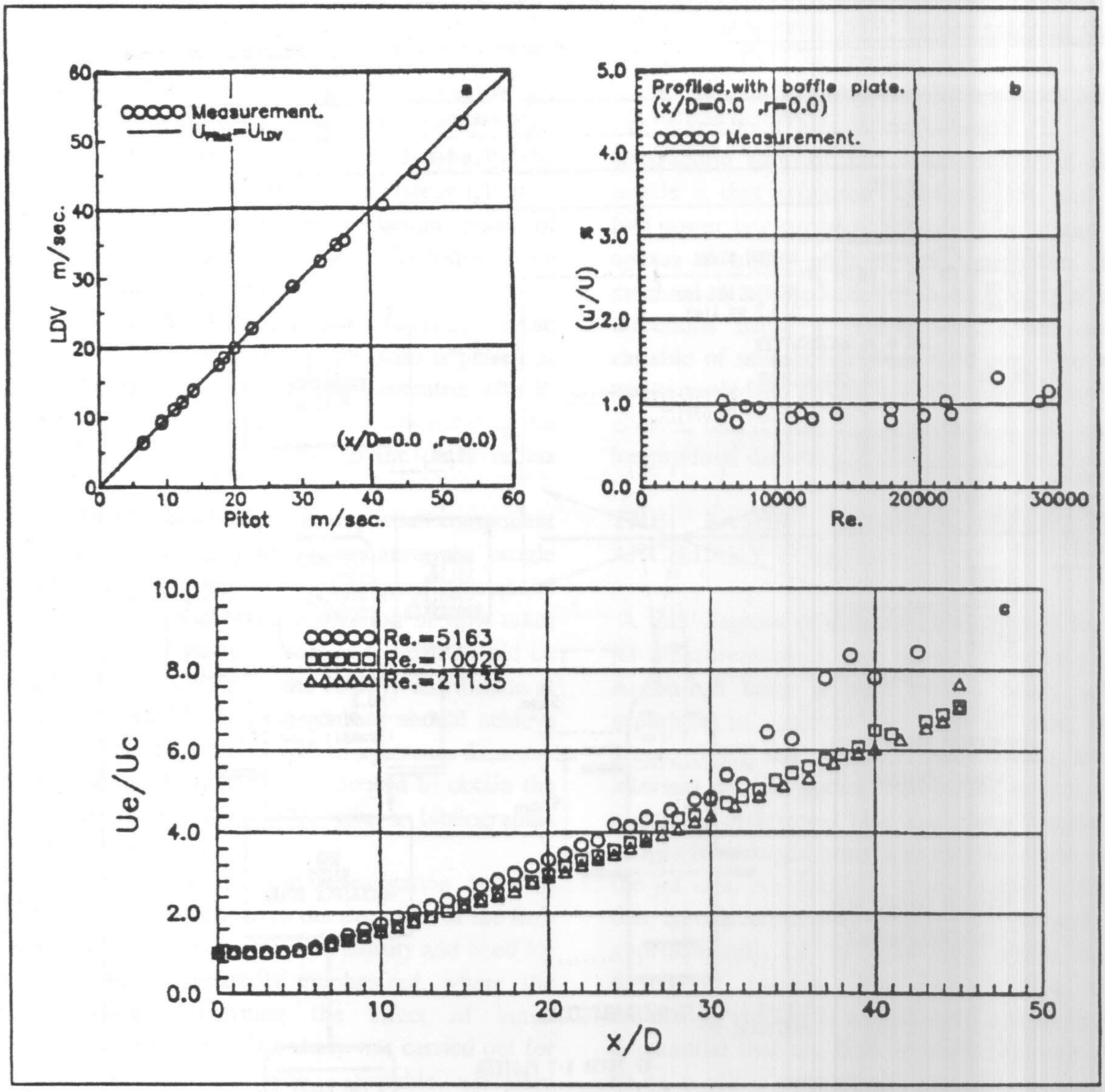


Figure 2. a) Comparison between LDV and Pitot-static tube measurements.
b) The effect of Re on the longitudinal turbulence intensity.
c) The effect of Re on the decay rate of the centerline mean longitudinal velocity.

The effect of this shift in frequency of one of the light beams is to cause the fringe pattern in the measurement volume to move at a constant velocity. Thus, a unique frequancy burst of scattered light is obtained for particles in the measurement volume having instantaneously positive, zero, or negative velocity.

The flow velocity is determined from the time taken for the particle to intersect eight fringes or eight cycles of the high frequency bursts (N). In order to confirm that the signals are valied results from the passing of a single seeding particle through the measurement volume at a given time, the signals are assesed by validation circuits. In the present system, the signals are passed through two validation circuits in which N is 5 and 8 respectively. The transmitting and receiving optical system are fixed on a table, while the jet set-up is allowed to move in two orthognal directions.

## RESULTS AND DISCUSSION

The first series of the experiments were designated to test the reliability of measurements, and to gain confidence in the corresponding settings of the equipment. Therefore, the mean axial velocity, in a uniform velocity region with a very low turbulence intensity, was measured obtaining simultaneous readings with the LDV and the Pitot-static tube. The Pitot tube was connected to a Lambrecht inclined tube manometer having a precission of 1 mm. The velocity was varied in steps over the range of velocity encountered in the jet flow. A very good agreement was obtained, as shown in Figure (2-a).

Tests were then carried out under steady state conditions for Reynolds number in the range (4000-29200), based on the nozzle exit diameter 'D', and the mean centerline axial velocity at the nozzle exit. The turbulence intensities at the exit were first measured, and only rms of the longitudinal fluctuations are presented. The points represent the results obtained during different radial traverses. Some idea of the spread of these measurements can be observed in Figure (2-b), where the neglected effect of Re on the turbulence intensity in the middle of the outlet section of the nozzle is shown. Meanwhile, it was reported [17] that, for circular jets, significant variations of all measured quantities with Re have been observed at Re below 10000. These variations becoming large at Re below 5000. The present results shown, in Figure (2-c), for the decay rate of the centerline mean velocity at different Re support these findings. Therefore, the present work was conducted mainly for Re ≈ 10000.

The results of measurements in the jet are shown in Figure (3), which present the axial development of the centerline values of the mean and fluctuating velocity components, for seven upstream conditions. The velocities are normalized by the jet efflux velocity 'Ue', and the axial distance by the nozzle exit diameter 'D'. The results are discussed with the aid of the corresponding longitudinal mean velocity, and turbulance intensity profiles presented in Figures (7, 9).

Figure (3-a) shows the centerline values, for the profiled nozzle, when there was no screens or baffle plates installed in the settling chamber. Near the nozzle exit, the centerline mean velocity decreases with distance from the nozzle. Further downstream, a location is reached where the centerline velocity decreases rapidly up to x/D ≈ 20. The root mean square rms value of the longitudinal fluctuating velocity u' decreases slightly from a value ≈ 9% at nozzle exit. Within a distance of 4D to 7D from the nozzle exit one can obsereve a rapid increase in the turbulence intensities due to the extension of the mixing subregion over the whole cross section of the jet. On the other hand, the rms of the radial fluctuating velocity ,v', is maximum at the nozzle exit, and of magnitude 15%. In the region near x/D ≈ 4, the intensity levels off at a value ≈ 11% and then decreases further downstream of the exit.

The results obtained when a screen was placed, in the settling chamber, at a distance of 50 mm. upstream of the nozzle inlet are indicated in Figure (3-b). Comparing this figure with Figure (3-a), reveals that the presence of the screen improves the uniformity of the mean velocity along the centerline in the near field, up to x/D ≈ 4. Meanwhile, the screen reduces the intensity of the oncoming turbulence significantly at the nozzle exit. The centerline turbulence intensity in the longitudinal and radial directions reduces from approximately 9% to 1% and from 15% to 7% respectively. Meanwhile, the maximum intensities are located further downstream at x/D ≈ 10.

The effect of the screen position is demonstrated by comparing the results, when the screen was placed directly at the nozzle inlet and shown in Figure (3-c), with those of Figure (3-b). It is evident that, placing of the screen closer to the nozzle inlet results in higher turbulence intensities at nozzle exit. The optimum distance of the screen from nozzle inlet was reported to be 0.2 diameter of the settling chamber, Ds [12]. In the first case, when the screen was positioned at a distance of 50 mm. (equivalent to one Ds), unnecessary boundary layer growth inside the chamber and before entering the nozzle would occure. On the other hand, in the second case the distance is less than the optimum which leads to a significant distortion of the flow just before entering the nozzle, and a corresponding higher turbulence intensity at nozzle exit is observed.

The variation of the relative mean longitudinal velocity and turbulence intensities along the jet centerline, when the two screens are placed in the chamber, is shown in Figure (3-d). The relative turbulence intensities have almost the same shape as with one screen, except that a second smaller peak of the longitudinal rms was observed. Meanwhile, the longitudinal rms in the near field is higher than the results with one screen. When only one screen is used, the distance required for the intensity to fall below the incoming level was found to be 15 mesh widths for all supercritical screens. This distance become larger if the incoming turbulence level and macroscale are reduced, which is the case of screen combinations [7]. Further, the distance between the two screens (≈Ds) in the present

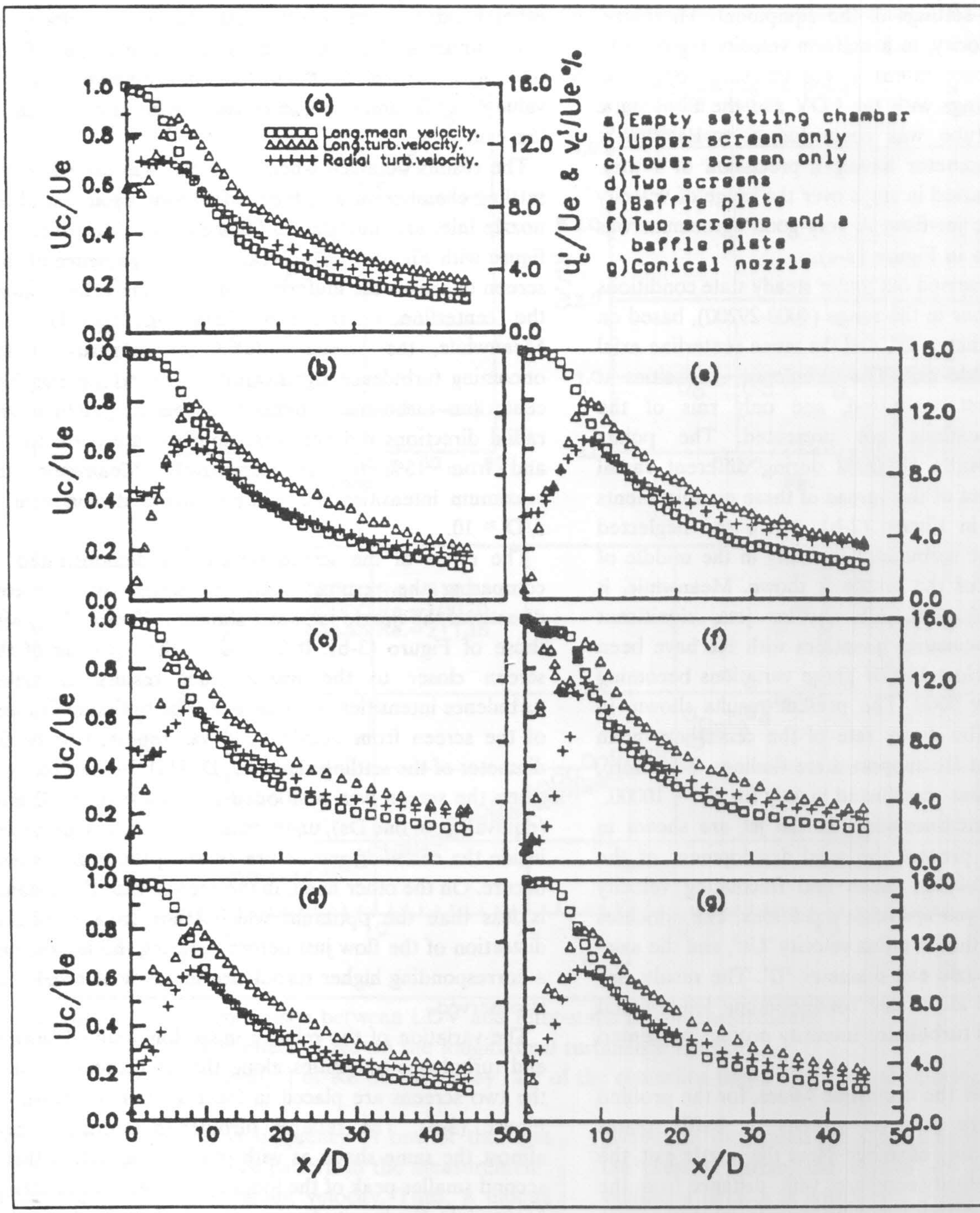


Figure 3. The effect of upstream conditions on the centerline mean and fluctuating velocities.

study is five times the distance performs successfuly ( ≈ 0.2 Ds) [12].

The results obtained when a baffle plate was installed in the chamber, shown in Figure (3-e), are rather interesting. The effect of the baffle plate on the mean velocity and turbulence quantities are very much the same as those obtained when the lower screen only was used. Meanwhile, the radial rms is further improved. This result indicates that, the baffle plate could be a good substitute to screens. However, the effect of geometry and position of the plate would need further investigation.

With two screens and a baffle plate, installed in the

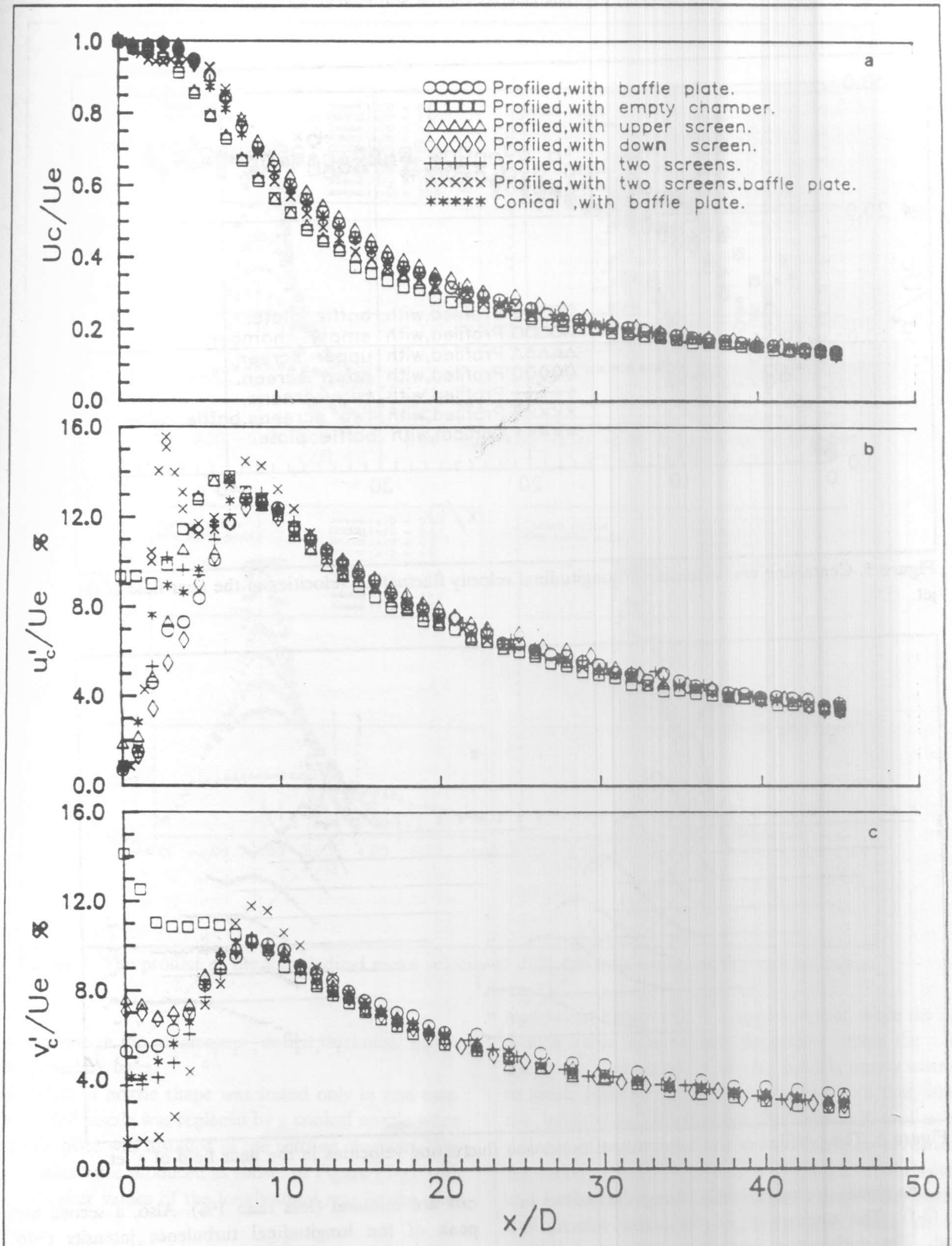


Figure 4.The evolution of the centerline mean velocity and turbulent velocities, for all upstream conditions.

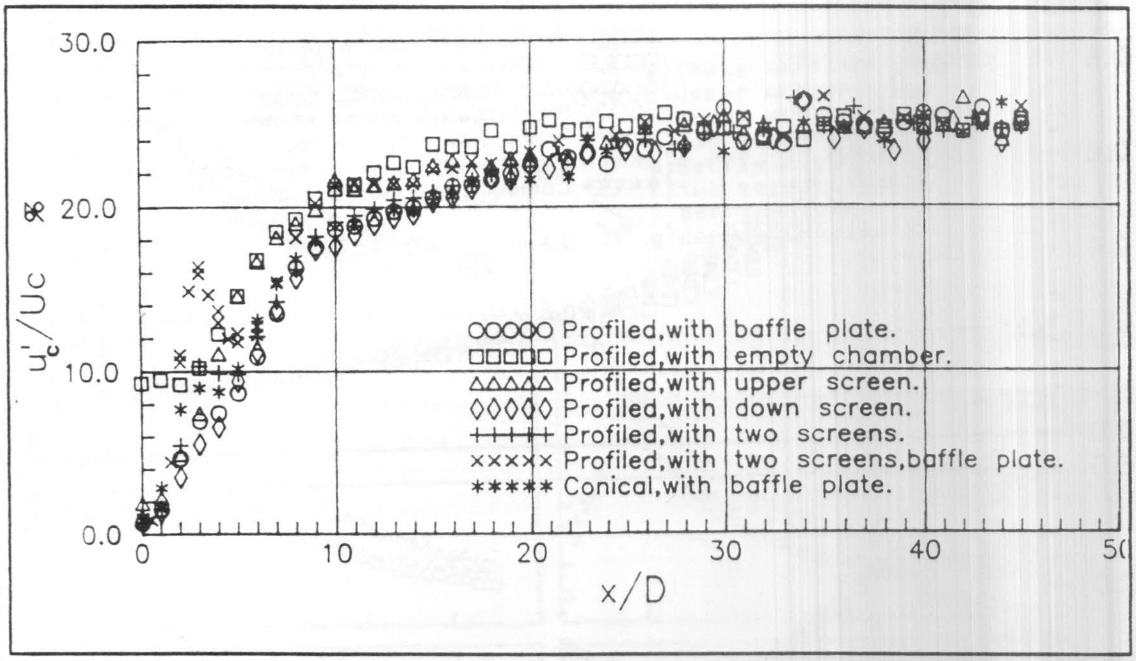


**Figure 5.** Centerline rms intensity of longitudinal velocity fluctuating velocities in the near field of the jet.

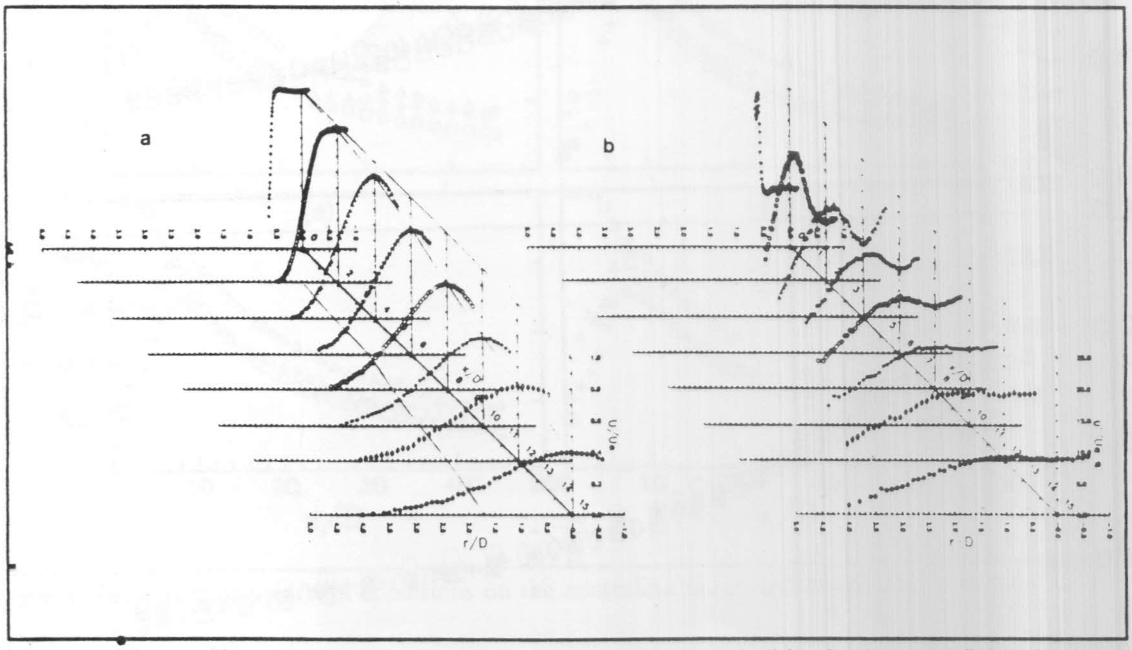


**Figure 6.** The profiles of the longitudinal mean and fluctuating velocities in the near field of a jet.

chamber, the results are significantly changed as shown in Figure (3-f). The uniformity of the axial velocity is distorted. The turbulence intensities are remarkably increased in the near field, while the values at the nozzle exit are minimal (less than 1%). Also, a second higher peak of the longitudinal turbulence intensity (≈16%) wasobserved at an axial distance of x/D ≈ 3. The same trend was observed, by Bradshaw [8], which was attributed

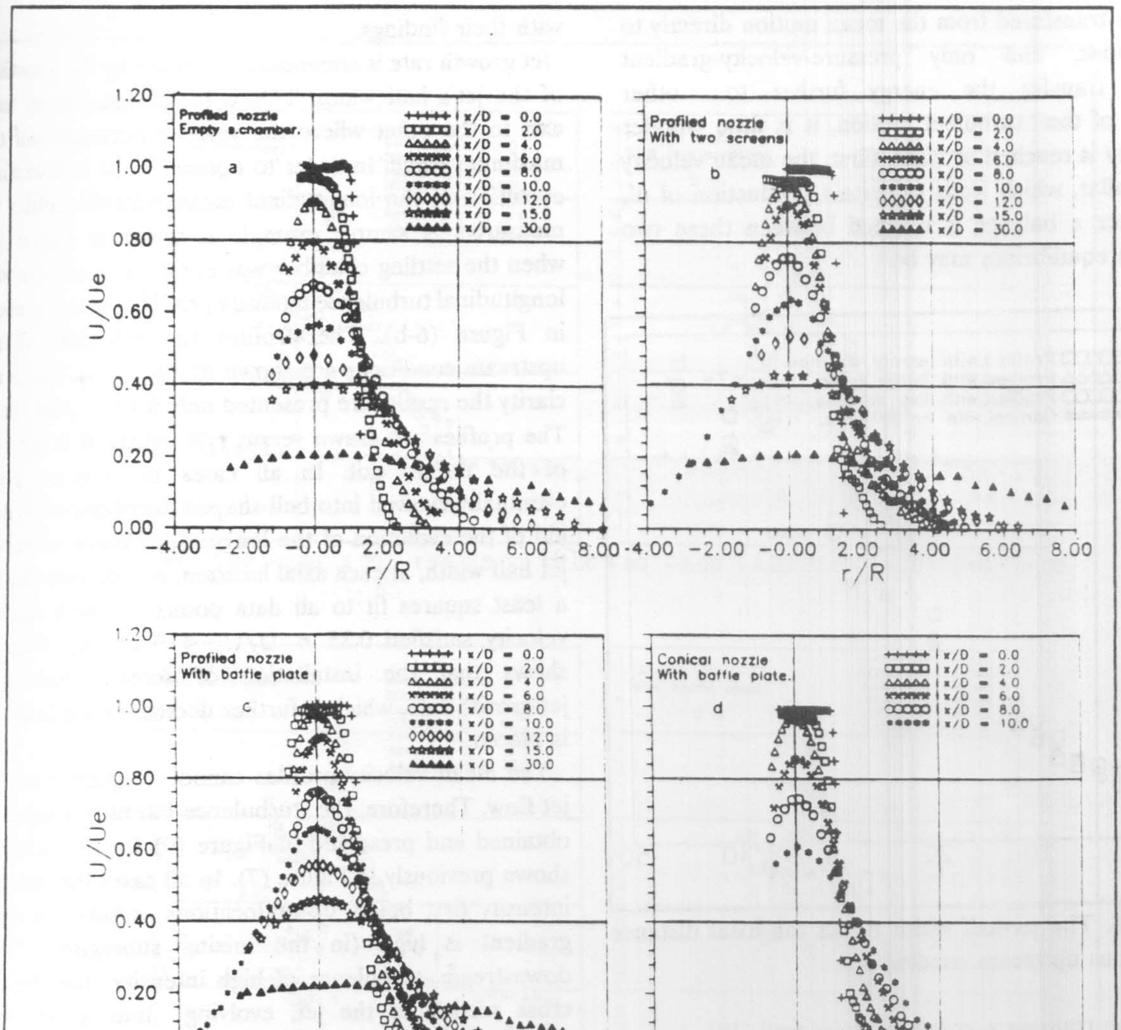


Figure 7. The profiles of the longitudinal mean velocity at different axial locations, for various cases.

to an increase in the momentum- deficit thickness of the initial boundary layer.

The effect of nozzle shape was tested only in one case. The profiled nozzle was replaced by a conical nozzle when the baffle plate was installed in the settling chamber. The same results were produced as shown in Figure (3-g), with slightly higher values of the longitudinal rms in the near field.

The results of the above conditions are all plotted together in Figure (4). It is apparant that, while the initial growth rates of rms are dependent upon the initial conditions, behaviour in the far field is nearly insensitive to same. However, it is interesting to note that, whereas the longitudinal fluctuations become self similar some distance at around 45 diameter downstream of the nozzle, the radial turbulence intensity appears to attain similarity at a further distance downstream. A given body of fluid is said to be in a self preserving state when all of its turbulent components are in equilibrium. However, since the energy is transfered from the mean motion directly to u' fluctuations, and only pressure-velocity-gradient correlations transfer the energy further to other components of the turbulent motion, it is little wonder that similarity is reached in steps. First, the mean velocity becomes similar, which leads to certain production of u', and only after a balance is reached between these two quantities an equilibrium may be

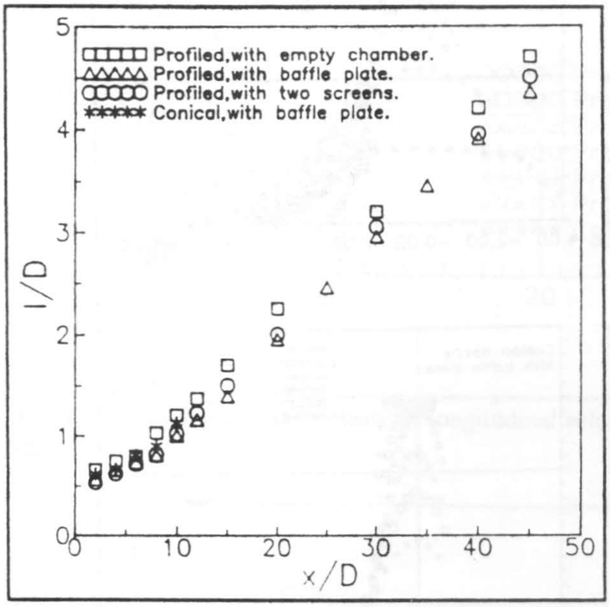


**Figure 8.** The jet-half width versus the axial distance for various upstream conditions.

attained in the transverse components as well [18].

On the other hand, to examine the achivement of self preservation, $u_c'/U_c$ data along the jet centerline are plotted against x/D as shown in Figure (5). For all cases an asymptotic value of about 25% at x/D ≈ 45 is reached, which means that $u_c'/U_c$ distribution in the far field is not sensitive to the upstream conditions. The asymptotic value of $u_c'/U_c$ for circular jets show quite a wide variations from 0.19 to 0.32 [19]. There have been tentative suggestions by various investigators that the initial conditions may be important. This is certainly true in the near field of jets, which is clearely demonstrated in the present study, while it is difficult to explain a continued influence in the far field unless there is large deformation of organized structure. Hussein and Husein [19] have reported that the centerline turbulence intensity in the self preserving region of jets is in the range 0.245 ± 0.005. The present results, shown in Figure (5), agree with their findings.

Jet growth rate is commonly measured by the growth rate of the jet's half width. This is the distance from the jet axis to the point where the velocity becomes half of its maximum value. In order to obtain the jet half-width, the evolution of the longitudinal mean velocity profiles were measured. A sample example is shown in Figure (6-a), when the settling chamber was empty. The corresponding longitudinal turbulence intensity profiles are also presented in Figure (6-b). The profiles for only four different upstream conditions are shown in Figure (7). Further, for clarity the results are presented only for few axial stations. The profiles are drawn versus r/R, where R is the radius of the nozzle exit. In all cases the top-hat profiles eventually evolved into bell shaped distributions. With the aid of the evolution of the longitudinal mean velocity, the jet half width, at each axial location, was obtained by using a least squares fit to all data points at which the mean velocity satisfied $0.35 < U/U_c < 0.65$ [20]. Figure (8) shows that the installation of screens reduces the jet-growth rate, which is further decreased if a baffle plate is placed.

The mean velocity profiles cannot uniquely identify the jet flow. Therefore, the turbulence intensity profiles were obtained and presented in Figure (9) for the same cases shown previously in Figure (7). In all cases the turbulence intensity first builds up at locations where the velocity gradient is high (in the mixing subregion). Further downstream, turbulence of high intensity fills the whole cross section of the jet, evolving into a bell shaped distribution. All the longitudinal velocity fluctuations had a peak profile initially. The location of the peak turbulence level shifted away from the jet axis with increasing streamwise distance. However, peak value of the velocity fluctuation occurs at the nozzle exit, when the settling chamber was empty. In case of other upstream conditions the peak value occured at an axial distance of approximately $r/R \simeq 2$.

## CONCLUSION

The following conclusion may be drawn from the experimental results obtained for axisymmetric turbulent jet working under different upstream conditions;

1. Connecting the screen directly to the nozzle inlet results in higher turbulent intensities at the nozzle exit.
2. The baffle plate could be a good substitute to screens.

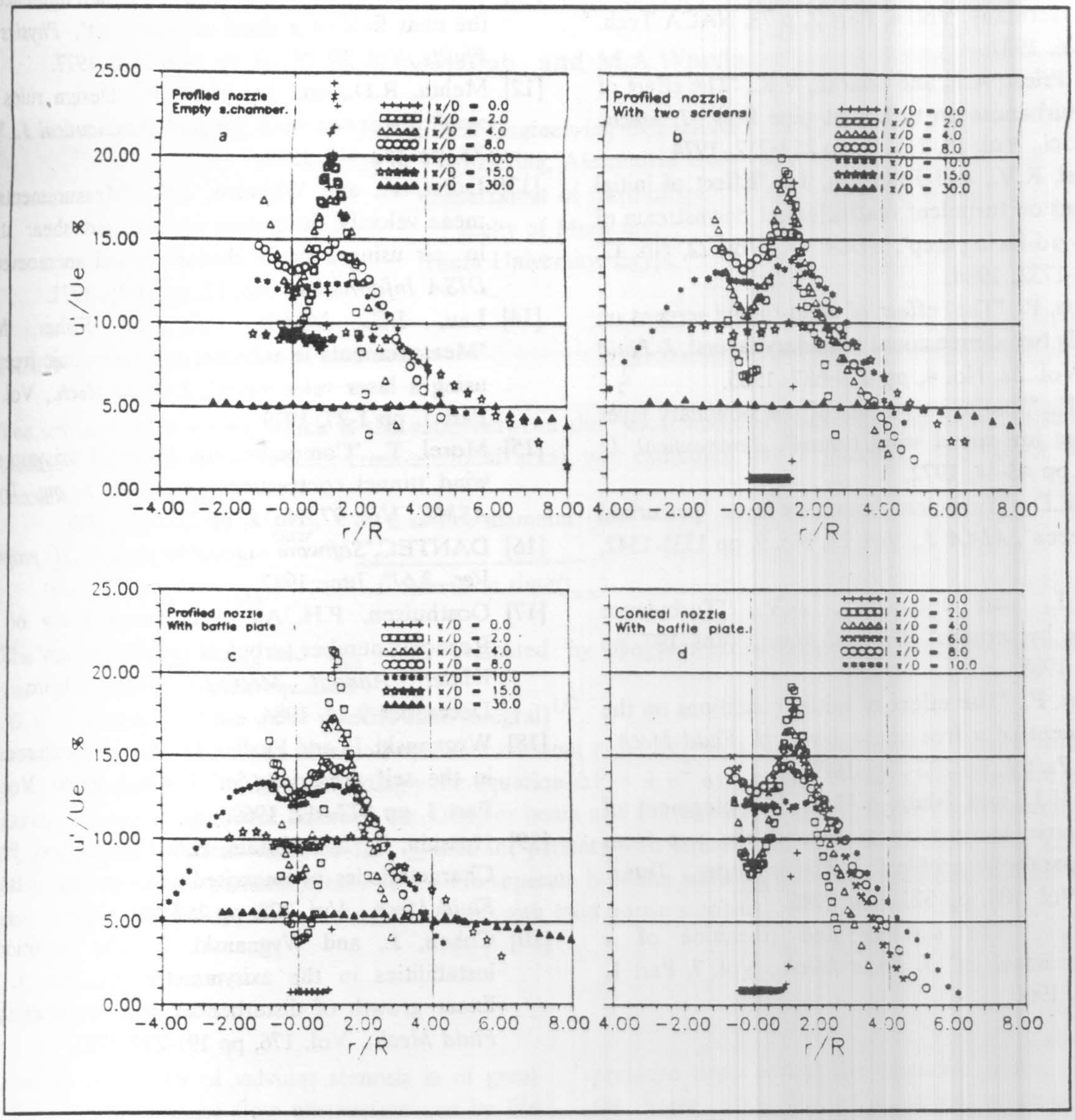


Figure 9. The profiels of the longitudinal turbulent velocity at different axial locations, for various cases.

However, the effect of geometry and position of the plate would need further investigation.

3. The nozzle shape has a small effect on the jet flow structure.
4. The initial growth rates of the root mean square of the turbulent velocities are dependent upon the initial conditions, while the behaviour in the far field is nearly insensitive to same.
5. Similarity is reached in steps, starting by the mean axial velocity and ending by transverse turbulent component.
6. An asymptotic value of $u_c'/U_c \approx 25$ % was obtained in agreement with Hussain and Husain results.
7. The installation of screens reduces the jet growth rate, which is further decreased if only a baffle plate is placed in the settling chamber.

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