EXPERIMENTAL STUDY ON THE DEVELOPING REGION OF LOW REYNOLDS NUMBERS CIRCULAR AIR JETS

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ABSTRACT

This paper reports on LDA measurements in the developing region of turbulent circular air jet. The objective is to study the effect of Reynolds number on the flow behavior in the developing region of an air jet discharging freely into the surrounding environment. The relative influence of using a wall at the jet exit is a second objective of the present study. Therefore, all experiments were conducted once more after placing a circular wall at the nozzle exit. Measurements were made using a two-component Laser Doppler Anemometer, and included mean velocity, turbulence intensity, skewness factor, flatness factors and power spectrum. Measurements were taken up to 10 nozzle exit diameters in the downstream direction for different exit Reynolds numbers in the range of 1400 to 20000. The Reynolds number was found to have a strong effect on the jet flow behavior in the developing region; the centerline velocity decays faster (decay constant for free jet = 6.11 at Re = 19400, = 1.35 at Re = 1430) and the potential core gets shorter with decreasing Reynolds number. The wall was shown to slow down the decay of centerline velocity due to the restricted interaction with the surroundings. Profile measurements of the skewness and flatness factors indicate that the jet flow becomes more intermittent with decreasing Reynolds number. Power spectrum measurements of the streamwise fluctuating velocities reflect the high energy content of the high Reynolds number jet. They also reveal that there is greater energy at the higher frequencies with increasing Reynolds number. The turbulence energy of the jet out of a wall, as indicated by the power spectrum, is lower than that of the free jet case due to the reduced mixing with the ambient.

Keywords: Turbulent, Air jets, LDA, Skewness, Flatness factors.

Nomenclature

A, x_o	constants defining velocity decay rate, Equation (1)
d	nozzle exit diameter
Re	jet exit Reynolds number, = $U_o d/\nu$
U, $\bar{U}$, u	instantaneous, time average, and fluctuating streamwise velocities
u′	rms streamwise velocities
x, r	streamwise and radial directions
Δt	residence time of the seeding particles inside the measuring volume

Subscripts

i	refers to the ith particle
m	jet centerline
o	jet exit

INTRODUCTION

Turbulent round jets have been investigated extensively because of their prime importance to many industrial and environmental applications and problems. It is also realized that the round turbulent jet is considered as a benchmark for research into the understanding of turbulent flows. Further, it serves as a simple model for evaluating turbulence models that attempt to predict complex flows. The round turbulent jet has been studied theoretically and/or experimentally,

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where in most cases the exit Reynolds number has been relatively high (above 10000); Hinze and Van der Hegge Zijnen (1949), Corrsin and Kistler (1955), Rodi (1982), Obot, et. al (1984), Schneider (1985), George, et. al (1988), Panchapakesan and Lumley (1993), Hussein, et. al (1994) and others.

The documented publications on jet flows seem to agree that if the Reynolds number at the jet exit is greater than a few thousand, the radial spread of the mean velocity field and the decay of the mean centerline velocity in the downstream direction are independent of Reynolds number, Re. Further, if Re is less than 30, the jet is laminar, normally called "dissipated laminar jet", Pearce (1966) and Ungate, et. al (1975). According to the work of Pearce and Ungate , et. al, for Re greater than 500, the jet has a laminar length after which it becomes turbulent. This laminar length decreases with increasing Re. For Re greater than 2000, the jet becomes turbulent at station very close to the exit, with the spread of the jet becoming constant.

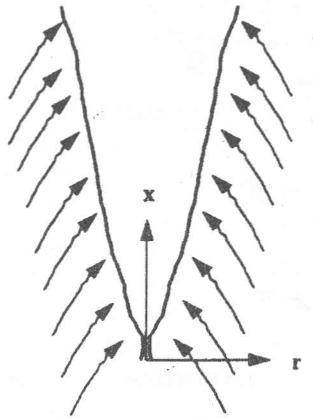
Obot , et. al (1984) have studied the mean flow in the near-field (up to 10d) of round jets at two moderate Reynolds numbers; 13000 and 22000. Their main objective was to investigate the effect of the nozzle geometry, rather than exit Reynolds number, on the jet behavior. However, they reported that entrainment for each nozzle studied was independent of the exit Reynolds number. This is in agreement with Ricou and Spalding (1961) who have shown that the entrainment coefficient decreases with Reynolds number up to a Reynolds number of 10,000 beyond which the entrainment coefficient takes a constant value. It is to be noted here that Subramanian and Mokhijani (1985) have made the same conclusion on the entrainment by the jet flow, but for the plane (slot) jet.

Fondse , et. al (1983) have experimentally investigated the dependence of the jet flow in the development region on the exit boundary layer state, and on the turbulence intensity at the exit. They have shown that the jet with a laminar boundary layer at the exit entrains more fluid, while that with a turbulent boundary layer reduces the entrainment rate by 15 %. The influence of exit Reynolds number on the jet behavior was reported by Oosthuizen (1983) . He has shown that for lower values of Reynolds number at the jet exit, more entrainment into the jet was obtained, which consequently leads to a faster decay of the centerline velocity with wider spread of the jet flow. Rajaratnam and Flint - Petersen (1989) investigated the variation of the spread rate of circular jets with Reynolds number. They found that the spread rate decreases continuously with Reynolds number, reaching an asymptotic value of 0.16 at Reynolds number of ≅ 10,000. Apparently, the asymptotic spread rate value of 0.16 obtained by the authors is higher than that for a high Reynolds number jet (≅ 0.09). The reason for this difference is not clear, as already pointed out by the authors.

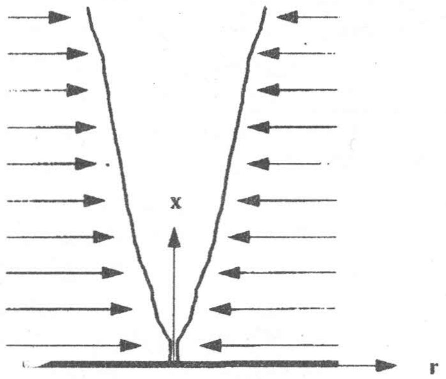
Outgan and Namer (1986) have carried out an experimental study on the low Reynolds number jet, but for the plane case. They have reported variations in all measured jet quantities, albeit not monotonic, with Reynolds number. The asymptotic behavior of the jet flow was reached at Reynolds number of ≅ 6000.

Also, the use of a flush wall with the jet exit plane is usually justified by avoiding the influence of the structure of the jet flow facility which will be different from one setup to another. Kotsovinos (1978) has pointed out to the important role of solid boundaries on the jet flows by stating that the entrainment into a jet flow will depend , among other factors, on whether the jet is issuing out of a wall or in a free space (see figure 1). Accordingly the jet behavior characteristics are expected to be different for both cases. Schneider (1985) has also shown, through his analysis on the round and plane jet flows, that the jet flow from a wall suffers from a momentum reduction in the streamwise direction due to the induced outer flow resulted from the wall. Further discussion on this phenomenon can be found in Hussein , et. al (1994).

Due to the very little studies reported on the low Reynolds number range, particularly for round jets, it is felt that more understanding and detailed knowledge of low Reynolds number circular jets are still needed. This could lead to a greater understanding of turbulent shear flows in general and expand the data base on low Reynolds number circular jets in particular. For this reason, the present experimental work is undertaken to study the characteristics of circular turbulent air jets in the near-field region (up to x/d=10), having discharge Reynolds number between 1400 and 19400. The relative influence of using a wall on the jet exit plane on the jet characteristics is another objective of the present study.



Entrainment into a round jet in free space



Entrainment into a round jet out of a wall

Figure 1. Entrainment into a round jet.

TEST FACILITY AND PROCEDURE

The air flow system is designed carefully to deliver a flow of uniform velocity and low turbulence intensity at the nozzle exit. The discharge air velocity through the nozzle ranges from 1 m/s to 40 m/s. These velocities correspond to a Reynolds number, based on the nozzle exit diameter, of 1300 to about 51000. A centrifugal fan with 3000 rev/min. is the prime mover of the air. The belt driven fan operates by a 0.75 kW dc. thryristor controlled motor and is provided by a forward curved impeller. The discharge air velocity at the nozzle exit is set using a manually adjusted potentiometer.

Air exiting the fan enters a 20 cm long duct with a nominal diameter of 10 cm. The duct is connected by a flange to the fan housing. After the 20 cm long duct, the air passes though a linen cloth filter and then through aluminum flow straighteners. After the flow straighteners, the air passes through three screen meshes that have three different open-area ratios of 0.6, 0.5 and 0.4 respectively.

Following the screens, the air enters the jet-flow nozzle. The nozzle is machined out of a cylindrical block of aluminum, and was designed to smoothly accelerate the flow (Elkorashy, 1995). The nozzle has a contraction ratio of 10:1, an exit diameter of 2 cm and a straight neck of 4 cm long. Measurements of the velocity at the nozzle exit is found to be uniform within 0.5 %. Turbulence intensity measured 2 mm downstream of the nozzle exit is less than 1.5 % for exit velocity of 10 m/s. A sketch showing the outline of the test facility is given in Figure (2).

A 300 mW Argon-Ion 2-component LDA (Dantec) system was used in backscatter mode and generated green (514.5 nm wavelength) and blue (488 nm wavelength) colors. Each color is used to measure one component of the velocity vector. A photo multiplier converted the scattered light received from the measuring volume into an electrical signal which was analyzed by a Dantec Flow Velocity Analyzer (FVA) enhanced signal processor model 58N40. A computer-controlled 3D traversing system, having a traverse accuracy of 0.1mm and maximum travels of 590 mm, 590 mm and 680 mm in the x, y and z directions, was used to move the fiber optic probe, and consequently, the measuring volume inside the jet flow field. The focal length of the probe lens is 400.7 mm and the measuring volume formed by the vertical and horizontal pairs of laser beams is an ellipsoid of minor axes of about 116 μm and major axis of about 2.44 mm. In the experiment arrangement, the minor axes were parallel to the streamwise (x) and radial (r) measurement directions and, consequently, the major axis was perpendicular to the measurement plane. FLOware, an application software for Dantec's Flow Velocity Analyzer-based LDA systems, was used to control the position of the measuring volume, acquire and process data and finally calculate most of the statistical results of the flow.

The source for the signal in the LDA is the scattering particle. Smoke generator using Shell Onida Oil is used to seed the room. To avoid bias in the LDA measurements due to the concentration of particles, the room was seeded and filled with smoke prior to the test and the blower was used to distribute the particles uniformly. The smoke generator was then turned off before collecting the data.

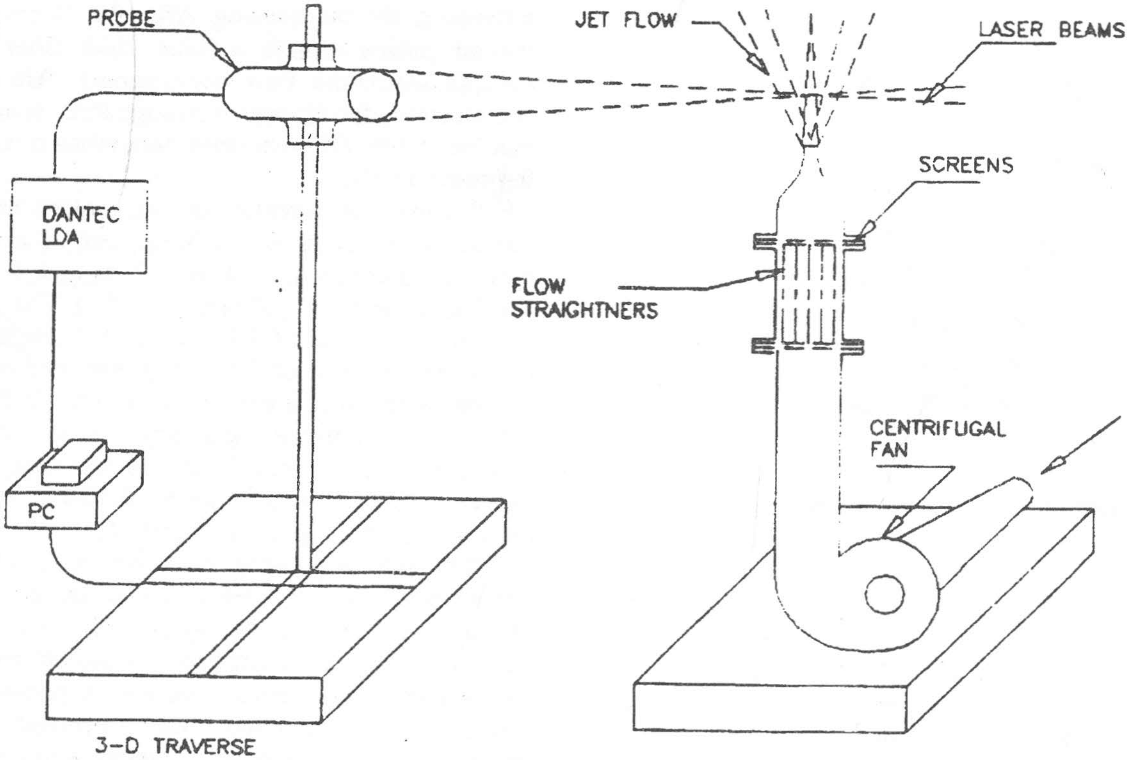


Figure 2. Test facility.

Most of the uncertainties in the measurements are bias or systematic errors. The bias error is mostly due to the evaluation of the angle between the laser beams, the laser wavelength, and the Doppler frequency. All errors were combined by the root-sum-square and calculated to be 0.8 %. The precision error is decreased by increasing the independent samples. The overall uncertainty of the measurement ranges from 1 % to 1.3 % depending on the flow conditions. Since most of the uncertainties in the experiment are bias or systematic errors, the data can be compared with each other with a degree of confidence. However, to avoid many sources of bias in processing techniques, the residence time weighting technique was used to compute the mean values (George, 1988). In brief, if Δt_i is the residence time of the ith particle and U_i is the velocity associated with it while it was in the measuring volume, the mean ($\bar{U}$) and rms (u') of the particle velocities are given by:

$$\bar{U} = \frac{\sum_{i=1}^{N} U_i \Delta t_i}{\sum_{i=1}^{N} \Delta t_i} \tag{1}$$

and

$$u' = \frac{\sum_{i=1}^{N} (U_i - \bar{U})^2 \Delta t_i}{\sum_{i=1}^{N} \Delta t_i} \tag{2}$$

First, extensive preliminary measurements of the mean velocities were made with a pitot tube connected to an electronic micromanometer. This is done to check the gross behavior of the jet flow and to verify the jet symmetry about its vertical centerline (Elkorashy 1995). Second, the main experiments were performed with the LDA probe mounted on a traversing system and the traversing system aligned with the jet central axis.

In the present study, three groups of measurements have been made. In the first group, axial measurements of the mean streamwise velocity, turbulence intensity, skewness factor and flatness factor were made up to 10 nozzle-exit diameters (10d) in the downstream direction, x. The measurements were repeated for four exit Reynolds numbers of 1430, 2790, 5190 and 19400. In the second group, radial-profile measurements of the same quantities were made at two downstream stations of x/d = 6 and 8, and for two exit Reynolds numbers of 3000 and 4800. The third group included spectral measurements of the streamwise fluctuating velocity at the jet centerline for x/d = 2, 4 and 6. These measurements were performed for four different exit Reynolds numbers of 3000, 5305, 8000 and 26700. It is to be noted that the whole experimental program was repeated twice; once for the free jet situation, and once more after placing a circular plywood wall of 80 cm diameter flush at the nozzle exit. It is worth mentioning here that in practical applications, the first 10 to 20 nozzle diameters in the downstream direction are often most important for mixing and possible chemical reactions (e.g. Fondse , et. al 1983). In all experiments, the jet exit velocity was monitored and was found to be constant at its set value within ± 1%.

The sampling time during measurements was in the range of 100 to 150 seconds, depending on the flow velocity at the measurement point. The mean data rate varied from 25 Hz to 60 Hz, except for the data acquired for the spectral calculations. During spectrum measurements, the mean data rate was in the range of 6 to 7.5 kHz, depending on the local flow velocity and the measurement location inside the jet flow. A direct Fast Fourier Transform (FFT) was used to obtain the power spectrum from the LDA signal. About 30000 data points were used in calculating the spectrum. The FFT was applied to 50 successive blocks, thus resulting in an average power spectrum for the velocity.

RESULTS AND DISCUSSION

The decay of centerline velocity for all exit Reynolds number cases of the free jet (without wall) are shown in dimensionless form (U_o/U_m) in Figure (3) as a function of the dimensionless axial distance x/d. As can be seen from the figure, the fastest decay is exhibited by the lowest Reynolds number jet. It is apparent that the decay of the centerline velocity slows down with Reynolds number. Same trend was reported by Oosthuizen (1983) from his hot-wire measurements. The effect of the wall on the decay of centerline velocity is demonstrated in Figure (4) for the four Reynolds number cases. It is clearly seen that the wall slows down the decay. This is likely due to the fact that the wall restricts the interaction of the jet flow with the ambient surrounding compared with the free jet situation. Such a restricted interaction with the surroundings results in a less entrained air and, subsequently a reduced mixing. As a result, the decay of centerline velocity gets decreased. However, from the comparison of Figures (4a) to (4d) one can notice that the decay of the centerline velocity for both the free jet and the jet out of a wall are approaching each other as Reynolds number increases. This observation may be explained as follows; for the high Reynolds number case, the jet flow is more energetic compared to the low Reynolds number jet and therefore, the wall likely influences the interaction of the jet flow with the surrounding ambient in the outer region only.

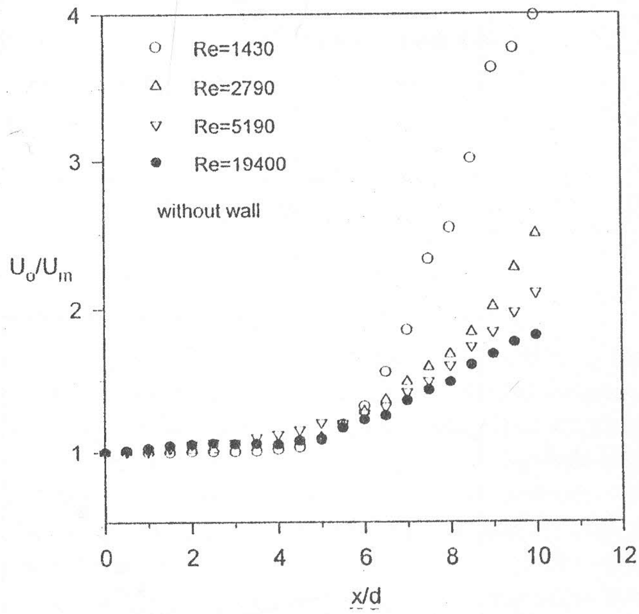


Figure 3. Decay of centerline mean velocity.

Meanwhile, the influence of the wall on the interaction of the low Reynolds number (less energetic) jet with the surrounding is felt all the way to the centerline. As a result, the centerline velocity decays faster.

In the linearly growing jet flow (Hinze 1975), the centerline velocity is given by:

$$\bar{U}_m/U_o = A\left(\frac{x}{d} - \frac{x_o}{d}\right)^{-1} \tag{3}$$

in which A is the centerline velocity decay constant and x_o is the location of the kinematic virtual origin of the jet.

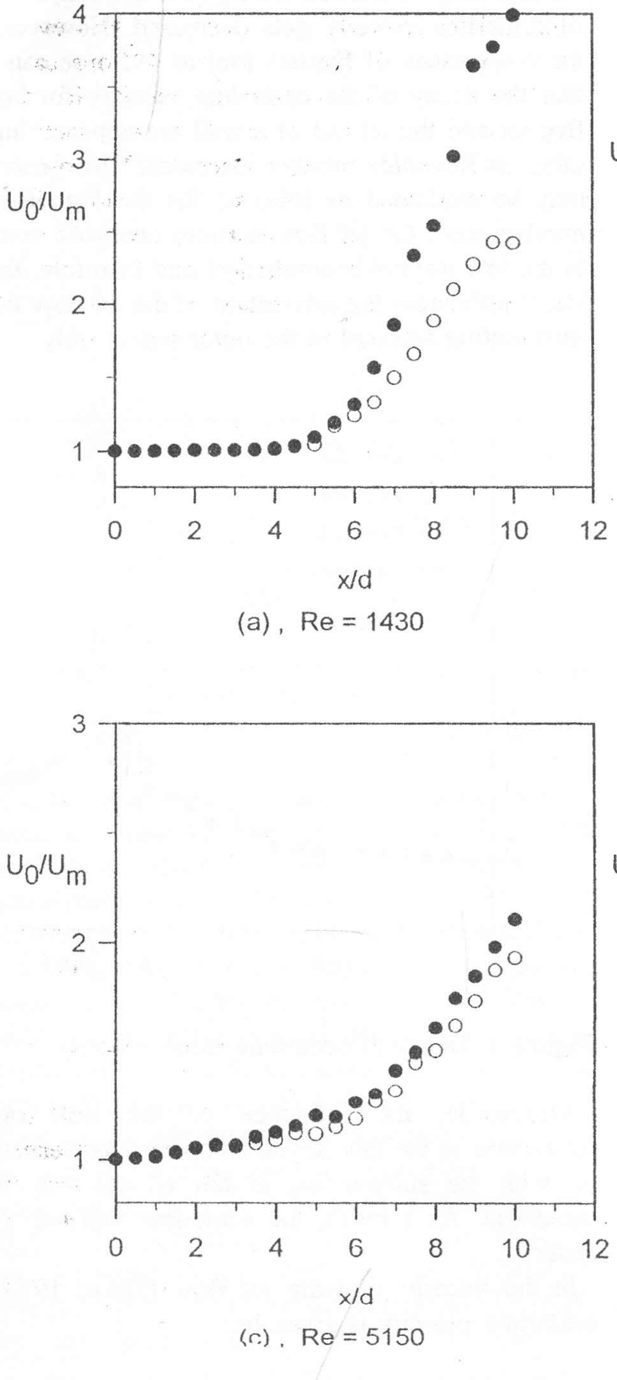


Figure 4. Effect of wall on the decay of centerline mean velocity
● without wall ○ with wall

Table (1): measured values of A and x_0/d

Exit Reynolds number	A (95% conf.)		x_0/d (95% conf.)	
	no wall	wall	no wall	wall
1430	1.35 ± 0.54	2.92 ± 0.56	4.45 ± 1.50	2.55 ± 1.35
2790	2.96 ± 0.60	4.82 ± 0.70	2.83 ± 1.04	0.22 ± 0.70
5190	4.27 ± 0.43	5.10 ± 0.45	1.10 ± 0.39	0.16 ± 0.28
19400	6.11 ± 0.31	5.95 ± 0.29	-1.44 ± 0.42	-0.88 ± 0.35

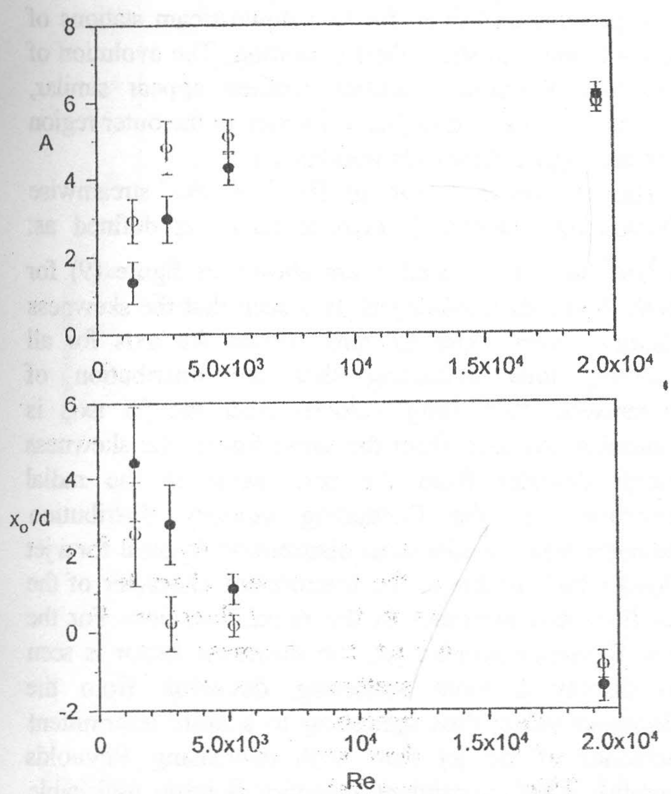


Figure 5. Variation of A and x_0/d exit Reynolds number • without wall o with wall.

Using equation (3), the values of A's and x_0's have been determined from the data of figure (4) for $x/d \geq 8$ and given in Table (1). In so doing, it is implicitly assumed that the mean jet data by $x/d \geq 8$ follow the self-preserving decay law given by equation (3). Therefore, the calculated values of A and x_0 may be considered, at least qualitatively, representations of the self-preserving regions of the jets. The variation trend of both A and x_0, reported in Table (1), is presented graphically in Figure (5) where a gradual increase in A and a gradual decrease in x_0/d with Reynolds number can be seen. The values of A for the jet out of a wall are seen to be higher than those for the free jet case. In the meantime, the values of x_0/d are seen to be lower than the corresponding values of the free jet case. These two observations are consistent with the notion that the free jet interacts more with the surroundings. It should be mentioned here that Monkewitz, et. al (1990), from their pitot tube measurements in the first 10d stations in two round jets of Re = 7500 and 47000, have shown that the low Reynolds number jet exhibits faster centerline velocity decay and shorter potential core than the high Reynolds number jet. At this point, one may conclude that lowering the Reynolds number results in a less uniformity of the jet flow and consequently more mixing with the surroundings takes place. Accordingly, the entrainment process gets enhanced and, as a result, the decay of centerline velocity increases. In the meantime, using a wall at the nozzle exit results in a less mixing with the surroundings and subsequently a decrease in the decay rate of centerline velocity.

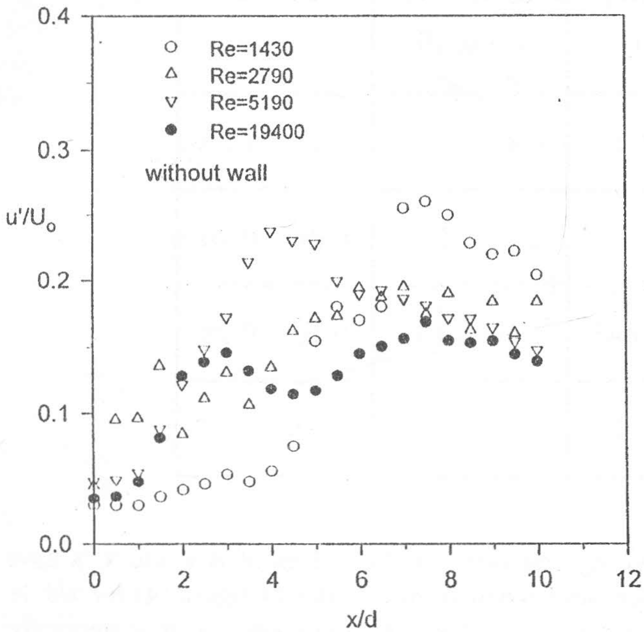


Figure 6. Variation of turbulence intensity along the jet axis.

The variation of the streamwise turbulence intensity along the jet centerline is shown in Figure (6) for the free jet. The turbulence intensity level is seen to increase with decreasing Reynolds number, particularly for the region downstream of the potential core (x/d > 6). This is in agreement with the faster decay of the mean velocity as the Reynolds number decreases (refer to Figure 3). The turbulence intensity level in the potential core region (up to x/d $\cong$ 6), on the contrary, is seen to decrease as the Reynolds number decreases. This is expected, anyhow, since the velocity in the potential core region is constant and the turbulence level, therefore, represents the initial turbulence level of the jet flow. Figure (7) presents the same information presented by Figure (6), but for the case of the jet out of a wall. The behavior of turbulence intensity with Reynolds number is seen to be very similar to that of the free jet case. No noticeable effect for the wall on the turbulence level along the jet centerline can be seen.

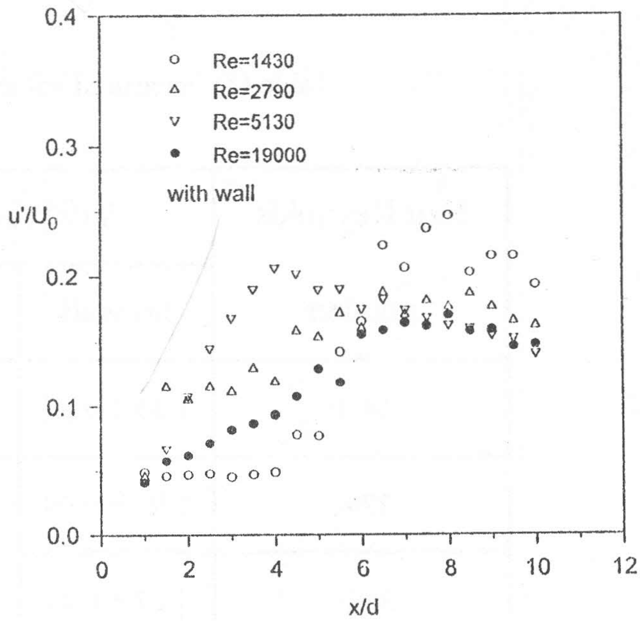


Figure 7. Variation of turbulence intensity along the jet axis.

Figure (8) shows the streamwise mean velocity profiles for exit Reynolds numbers of 3000 and 4800. The profiles are given for two downstream stations of x/d = 6 and 8 to show their evolution. The evolution of the two Reynolds number profiles appear similar, except for observed higher velocities in the outer region for the higher Reynolds number jet.

The skewness factor profiles of the streamwise fluctuating velocity (skewness factor is defined as: $\bar{u}^3/u'^3$ at x/d = 6 and 8 are shown in figure (9) for both Reynolds number jets. It is seen that the skewness factor is very close to zero around the axis for all profiles, thus indicating that the distribution of streamwise fluctuating velocity near the jet axis is Gaussian. As seen from the same figure, the skewness factor deviates from the zero value in the radial direction, i.e. the fluctuating velocity distribution deviates from the Gaussian distribution (typical for a jet flow) which is due to the intermittent character of the jet flow that increases in the radial direction. For the low Reynolds number jet, the skewness factor is seen to display a more scattering deviation from the Gaussian value, thus indicating to a more intermittent behavior of the jet flow with decreasing Reynolds number. This intermittent behavior is more noticeable at x/d=8 compared to that at x/d=6, thus indicating that the intermittency increases in the downstream direction.

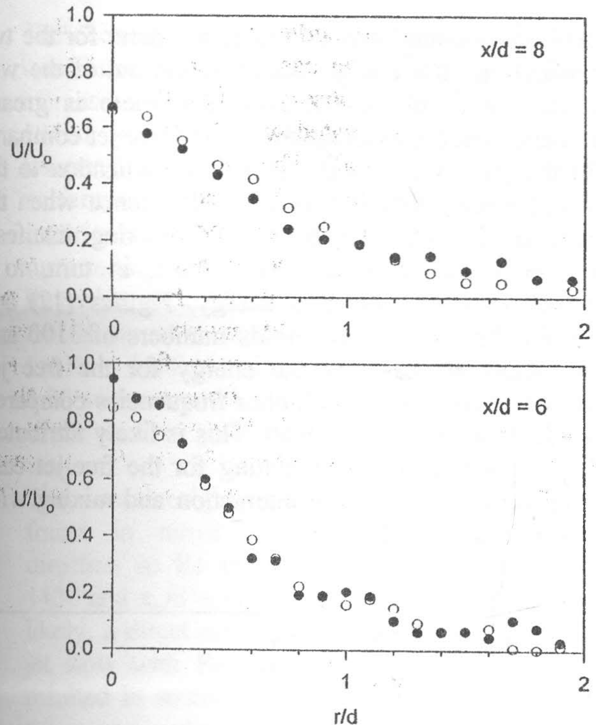


Figure 8. Radial profiles of streamwise velocity (without wall).

o Re = 3000 • Re = 4800

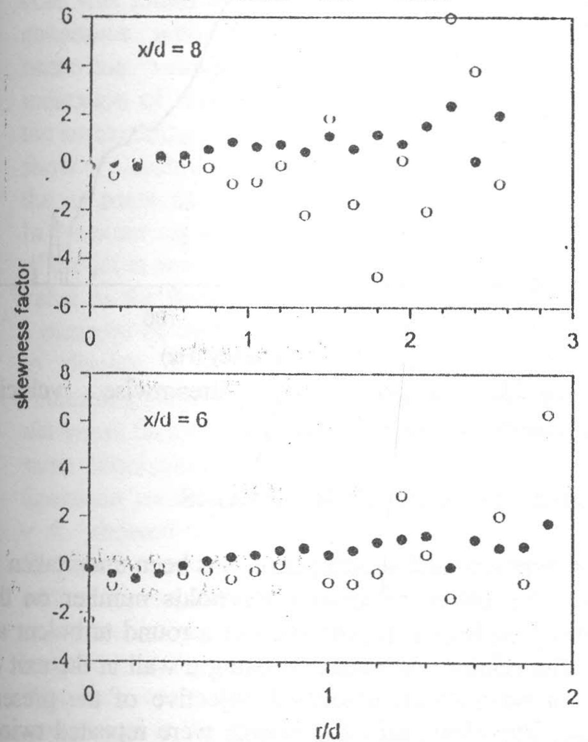


Figure 9. Variation of skewness factor across the jet flow (without wall).

o Re = 3000 • Re = 4800

Figure (10) shows the profiles of the flatness factor of the fluctuating velocity (defined as: $\overline{u^4}/u'^4$ for both Reynolds numbers at x/d = 6 and 8. It is seen that the flatness factor approaches the values 3 (Gaussian value) close to the jet axis, then start to deviate from this value in the radial direction. In general the flatness factor profiles emphasize the observations made from the skewness factor profiles (Figure 9). That is, the jet flow tends to have a more intermittent character with decreasing Reynolds number. This intermittent character becomes more pronounced with the main direction of the jet flow.

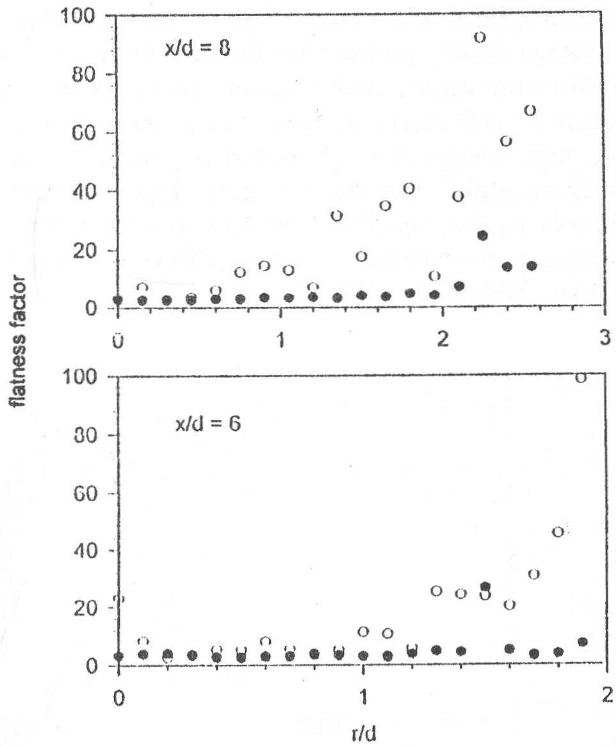


Figure 10. variation of flatness factor across the jet flow (without wall).

o Re = 3000 • Re = 4800

Power spectrum density taken at x/d = 6 for the four Reynolds number cases appears in Figure (11). Each spectrum, as mentioned before, is an average of at least 50 individual 512 point realizations of signal traces, reproduced at even time intervals to reduce the bias error in the velocity estimates (Buchave, et. al 1990). In order to determine accurately the contributions to the power spectrum of a random signal from a digital sample of the signal, the data rate must be at least twice as great as the highest frequency component which contains significant power (Nyquist criterion). If the data rate is less than this data rate the power spectrum will be "aliased". Further, Tropea (1987) has shown that the spectrum is subject to positive bias in the low frequency range and to negative bias in the high frequency range when the average data rate is less than 2.5 times that determined from the Nyquist criterion. Therefore, the traces for the power spectrum were generated from the raw data traces at 40% of the mean arrival time of the particles (equivalent to data rate of 2.5 times that determined from Nyquist criterion) to avoid the bias in the spectrum estimates as described by Tropea. A direct Fast Fourier Transform was then applied to successive blocks, thus resulting in an average power spectrum for the velocity. As can be seen from the figure, there is greater energy at the high frequencies with increasing Reynolds number. Because these high frequencies correspond to smaller eddies, thus demonstrates that smaller eddies appear at higher Reynolds number which is consistent with the notion of increased vortex stretching at higher Reynolds number (Wei and Wilimarth 1989).

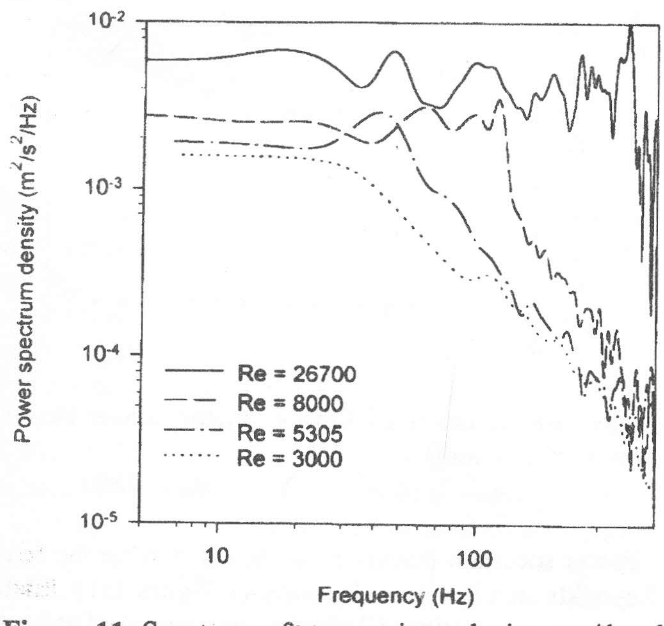


Figure 11. Spectrum of streamwise velocity at x/d = 6 (without wall).

Figures (12), (13) and (14) represent the power spectrum density for Reynolds number of 3100, 5305 and 8000. Each figure includes the power spectrums for the free jet and the jet out of a wall. In the three figures, it is seen that the frequency of the main-energy-containing eddies is the same for the two jet situations; the free jet case and the out of the wall jet case. It is to be observed that there is greater turbulence energy associated with the free jet compared with the jet out of a wall. This is an indication to the reduced mixing that the jet flow experience when the wall is used. Of course, the reduced mixing manifests itself in a less turbulence level and, in turn, to a relatively lower turbulence energy. Figures (12) and (13), for the two low Reynolds numbers of 3100 and 5305, show further that the energy for the free jet (without wall) extends to higher frequencies compared with that for the jet with wall. This is likely attributed to the increased vortex stretching for the free jet case due to the relatively more interaction and mixing with the surrounding ambient.

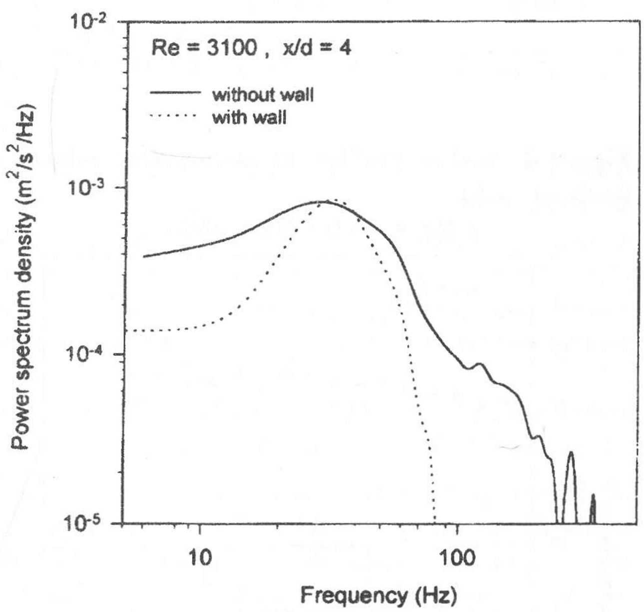


Figure 12. Spectrum of streamwise velocity fluctuations at the jet centerline.

SUMMARY AND CONCLUSIONS

An experimental investigation has been undertaken to study the effect of jet-exit Reynolds number on the developing region (up to 10d) of a round turbulent air jet. The relative influence of using a wall at the exit of the jet nozzle was a second objective of the present study. Therefore, all experiments were repeated twice; once for the free jet situation, and once more after placing a wall at the nozzle exit. Using a LDA system, measurements were performed for jet flows having exit Reynolds numbers in the range of 1400 to 20000.

- The decay of centerline mean velocity of the free jet was found to slow down as exit Reynolds number increases: for Re = 1430, A = 1.35 and for Re = 19400, A = 6.11. Therefore, one may conclude that lowering the Reynolds number results in a less uniformity of the jet flow, thus making the jet experiences more mixing and interaction with the surrounding environment relative to the high Reynolds number jet. Placing a wall at the nozzle exit is shown to slow down the decay (for instance, for Re = 1430, A = 2.92 compared with the value of 1.35 without wall) due to the restricted interaction of the jet flow with the surrounding imposed by the wall.
- The virtual origin of the jet flow (x_o/d) has been found to move continuously in the upstream direction as Re increases: x_o/d = 4.45 for Re = 1430 and x_o/d = -1.4 for Re = 19400. This is, most likely, a direct result of the decreased spread of the jet flow with Reynolds number. Placing the wall resulted in smaller values for x_o/d's compared with the corresponding values for the free jet (x_o/d=2.55 for Re = 1430 and x_o/d = -0.88 for Re = 19400).
- The turbulence intensity level beyond the potential core was found to increase as Re decreases. This is consistent with the faster decay of the mean centerline velocity with decreased Re, and an indication of the more mixing of the jet flow with the surrounding with decreased Re. The wall did not show noticeable influence on the turbulence level at the jet centerline.
- In the outer region of the jet flow, the flatness factor of the jet is seen to deviate much from the Gaussian value as Re decreases. Using the flatness factor as a measure of intermittency, the jet flow can be said to display a more intermittent character with decreasing Reynolds number. The distribution of the skewness factor across the jet flow complements the same conclusion.
- Spectrum measurements at the jet centerline for x/d = 6 showed that the energy content at the high frequencies increases as Re increases; i.e. smaller eddies appear at higher Reynolds number which is consistent with the notion of increased vortex stretching at higher Reynolds number. Such vortex stretching mechanism was decreased when a wall was placed at the nozzle exit. This was indicated by a lower energy at the high frequencies for the jet out of a wall.

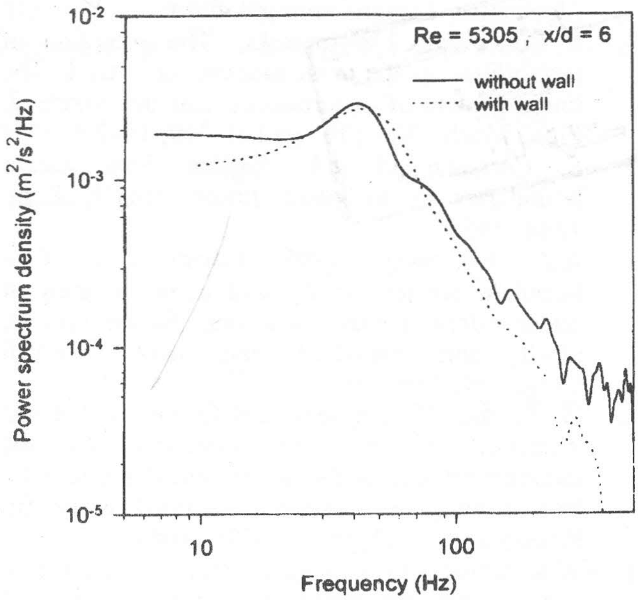


Figure 13. Spectrum of streamwise velocity fluctuations at the jet centerline.

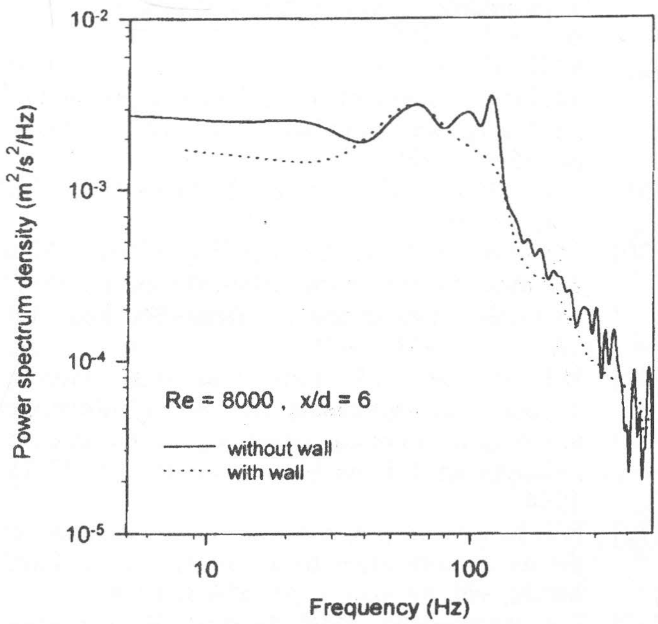


Figure 14. Spectrum of streamwise velocity fluctuations at the jet centerline.

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