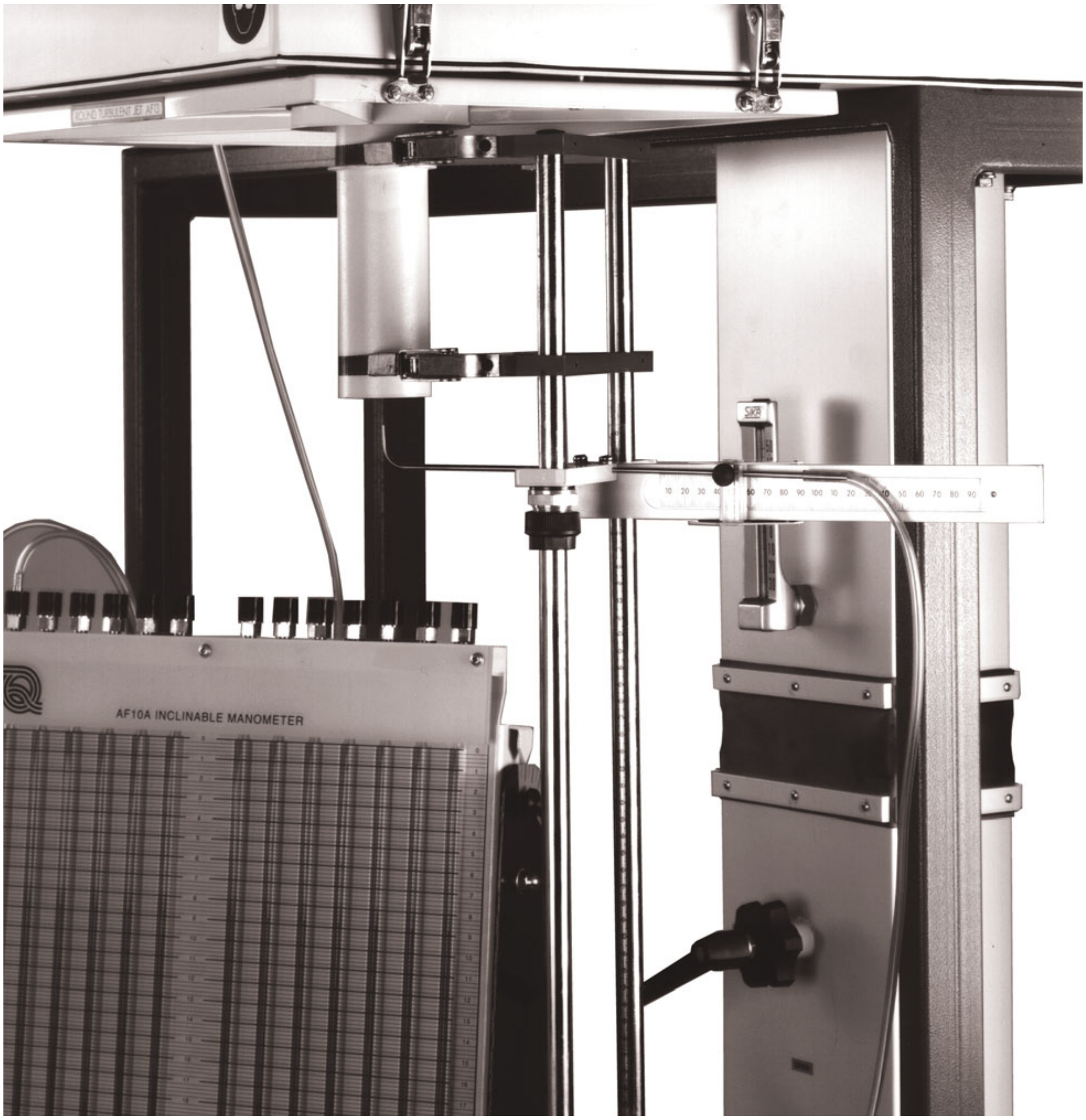
6. THE ROUND TURBULENT JET



AF13 Round Turbulent Jet Apparatus

Introduction

The behaviour of a jet as it mixes into the fluid which surrounds it has importance in many engineering applications. The exhaust from a gas turbine is an obvious example. In this experiment we establish the shape of an air jet as it mixes in a turbulent manner with the surrounding air. It is convenient to refer to such a jet as a 'submerged' jet to distinguish it from the case of the 'free' jet where no mixing with the surrounding medium takes place, as is the case when a smooth water jet passes through the atmosphere.

If the Reynolds number of a submerged jet (based on the initial velocity and diameter of the jet) is sufficiently small, the jet remains laminar for some length - perhaps 100 diameters or more. In this case the mixing with the surrounding fluid is very slight, and the jet retains its identity. Laminar jets are important in certain fluidic applications, where a typical diameter may be 1 mm, but the vast majority of engineering applications occur in the range of Re where turbulent jets are produced.

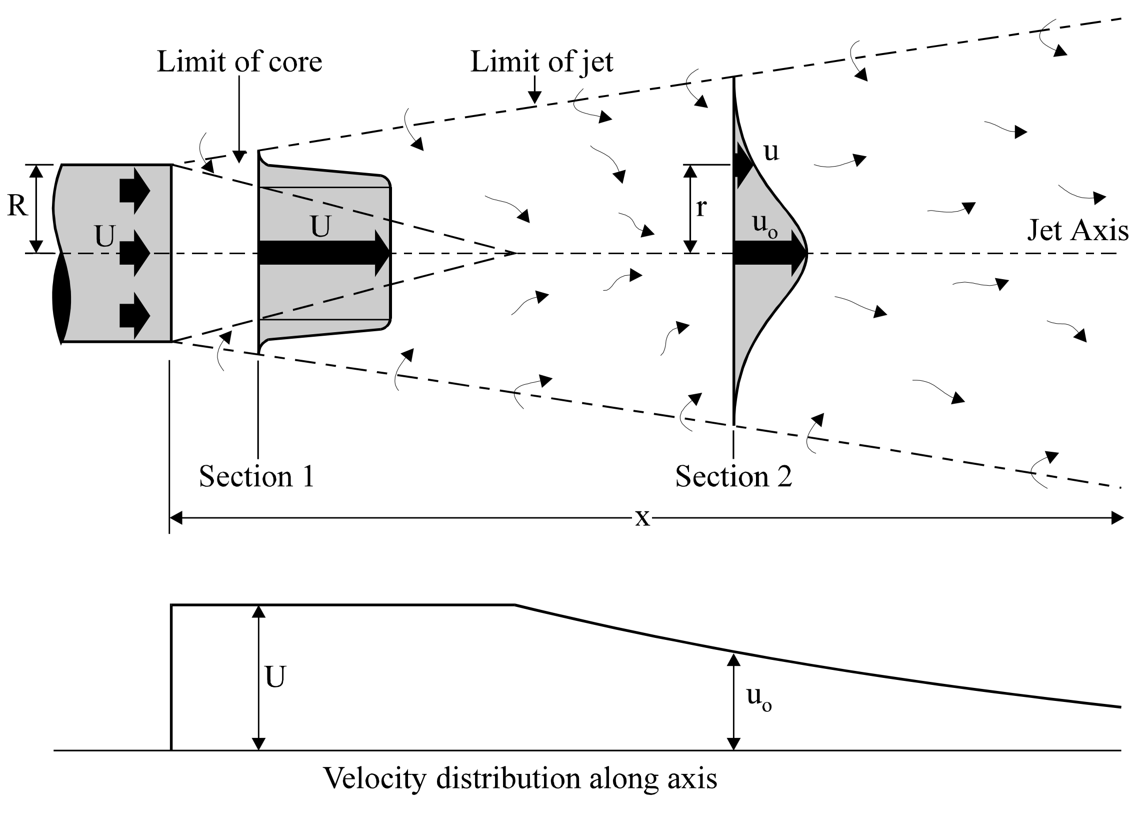


Figure 6.1 Schematic Representation of a Round Turbulent Jet

The essential features of a round turbulent jet are illustrated in Figure 6.1. The jet starts where fluid emerges uniformly at speed U from the end of a thin-walled tube, of cross-sectional radius R, placed in the body of a large volume of surrounding fluid. The sharp velocity discontinuity at the edge of the tube gives rise to an annular shear layer which almost immediately becomes turbulent.

The width of the layer increases in the downstream direction as shown in the diagram. For a short distance from the end of the tube the layer does not extend right across the jet, so that at section 1 there is a core of fluid moving with the undisturbed velocity U, the velocity in the shear layer rising from zero at the outside to U at the inside. Further downstream the shear layer extends right across the jet and the velocity u_o on the jet axis starts to fall as the mixing continues until ultimately the motion is completely dissipated.

There is entrainment from the fluid surrounding the jet by the turbulent mixing process so that the mass flux in the jet increases in the downstream direction. The static pressure is assumed to be constant throughout, so there is no force in the direction of the jet. The momentum of the jet is therefore conserved. The kinetic energy of the jet decreases in the downstream direction due to the turbulent dissipation. It should be emphasised that the velocity profiles indicated in Figure 6.1 are mean velocity distributions, and that the very severe turbulence in the jet will cause instantaneous velocity profiles to vary considerably from these mean ones.

Velocity Distribution and Momentum Flux

Consider the jet of Figure 6.1. If we assume that the flow pattern is independent of Reynolds number, then we might expect the velocity on the jet axis to depend on position in the dimensionless form

$$\frac{u_o}{U} = f\left(\frac{x}{R}\right) \tag{6-1}$$

In the core of the jet, we have already observed that

$$\frac{u_o}{U} = 1$$

Far downstream, when the length of the core ceases to have influence, there is some theoretical justification (supported by experiment) for expecting the centreline velocity to decay inversely as x, i.e.

$$\frac{u_o}{U} = \frac{c}{x} \tag{6-2}$$

where c is a constant.

The velocity u at any position (r, x) in the jet may also be written in the dimensionless form

$$\frac{u}{u_o} = g\left(\frac{x}{R}, \frac{r}{x}\right) \tag{6-3}$$

Consider now the velocity distribution over a section far downstream, i.e. where $\frac{x}{R}$ is large. We might reasonably expect that the velocity distribution across the section would not depend appreciably on the precise detail of the flow near the tube exit, so we might ignore the dependence upon $\frac{x}{R}$ and simply write

$$\frac{u}{u_o} = g\left(\frac{r}{x}\right) \tag{6-4}$$

far downstream. Velocity profiles of this type, in which the velocity ratio depends on a parameter, are frequently called 'similar', in the sense that a single expression is used to characterise the velocity distribution at any number of chosen sections. Using certain assumptions about the nature of the turbulent processes, it is possible to show that Equation (6-4) should take the form

$$\frac{u}{u_o} = \frac{1}{\left\{1 + 0.25\left(\frac{\lambda r}{x}\right)^2\right\}^2} \tag{6-5}$$

where λ is a constant which is to be determined by experiment.

Values of u/u_o computed from this expression are presented in Table 6.1. The value $\lambda r/x = 1.287$ is included, as this makes $u/u_o = 0.5$. When comparing with experimental results it is useful to have this value, since the radius at which $u/u_o = 0.5$ is easily identified on the velocity profile.

λr/x	**u/u_o**
0	1.000
0.2	0.980
0.4	0.925
0.6	0.842
0.8	0.743
1.0	0.640
1.287	0.500
1.4	0.450
1.6	0.372
1.8	0.305
2.0	0.250
2.25	0.195
2.5	0.152
3.0	0.095
4.0	0.040

Table 6.1 Calculated Velocity Profile of Round Jet

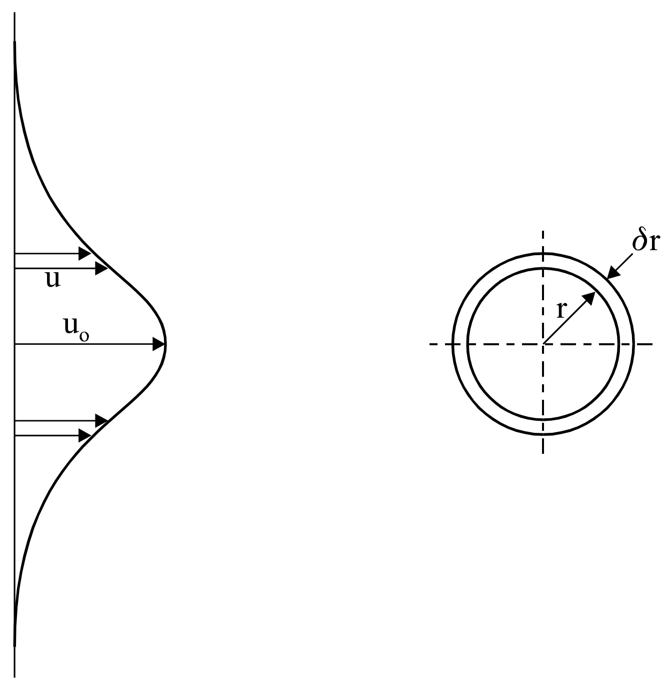


Figure 6.2 Annular Element of a Round Jet

Coming now to mass, momentum and energy flux, we see in Figure 6.2 an annular element of the jet through which fluid of density ρ is flowing with velocity u. The area of the element is

$$\delta A = 2\pi r\, \delta r$$

So the mass flux $\delta\dot{m}$ through it is

$$\delta\dot{m} = 2\pi\rho u r\, \delta r$$

The total mass flux $\dot{m}$ through the section of the jet is

$$\dot{m} = 2\pi\rho \int_0^\infty u r\, dr$$

(6-6)

The momentum flux J through the section is similarly found to be

$$J = 2\pi\rho \int_o^\infty u^2 r\, dr$$

(6-7)

and the kinetic energy flux E to be

$$E = 2\pi\rho \int_o^\infty \tfrac{1}{2} u^3 r\, dr$$

(6-8)

It is convenient in many instances to relate these to the corresponding fluxes at the tube exit, as follows:

$$\dot{m}_o = \pi\rho U R^2$$

$$J_o = \pi\rho U^2 R^2$$

$$E_o = \pi \tfrac{1}{2}\rho U^3 R^2$$

with the results

$$\frac{\dot{m}}{\dot{m}_o} = 2\int_0^\infty \left(\frac{u}{U}\right)\left(\frac{r}{R}\right)d\left(\frac{r}{R}\right)$$

(6-9)

$$\frac{J}{J_o} = 2\int_0^\infty \left(\frac{u}{U}\right)^2\left(\frac{r}{R}\right)d\left(\frac{r}{R}\right)$$

(6-10)

$$\frac{E}{E_o} = 2\int_0^\infty \left(\frac{u}{U}\right)^3\left(\frac{r}{R}\right)d\left(\frac{r}{R}\right)$$

(6-11)

Description of Apparatus and Procedure

The round jet is produced by discharging air from the airbox through a short tube as indicated in Figure 6.3. The inlet of the tube is rounded to prevent separation so that a substantially uniform velocity distribution is produced at the tube exit.

A traversing mechanism is supported on the tube so that a Pitot tube may be brought to any desired position in the jet. Measurements are normally made in one plane, but if it is necessary to check on the symmetry of the jet about the axis, the traversing mechanism may be rotated as a whole to any position.

The Pitot tube is first brought into the plane of the exit of the jet tube and the scale readings are noted for which the axial position x and the radial position r are zero. The latter may be obtained by taking the average of the readings when the tube is set in line with one side and then the other side of the tube. The pressure P_o in the airbox is then brought to a convenient value and traverses are made at various axial stations along the length of the jet. The readings of total pressure P fluctuate violently because of the turbulence and some damping is required; however, excessive damping must not be used. It is recommended that graphs of total pressure P against radius r be plotted as the experiment proceeds to ensure that the profile is well-established by a sufficient number of readings in the critical regions.

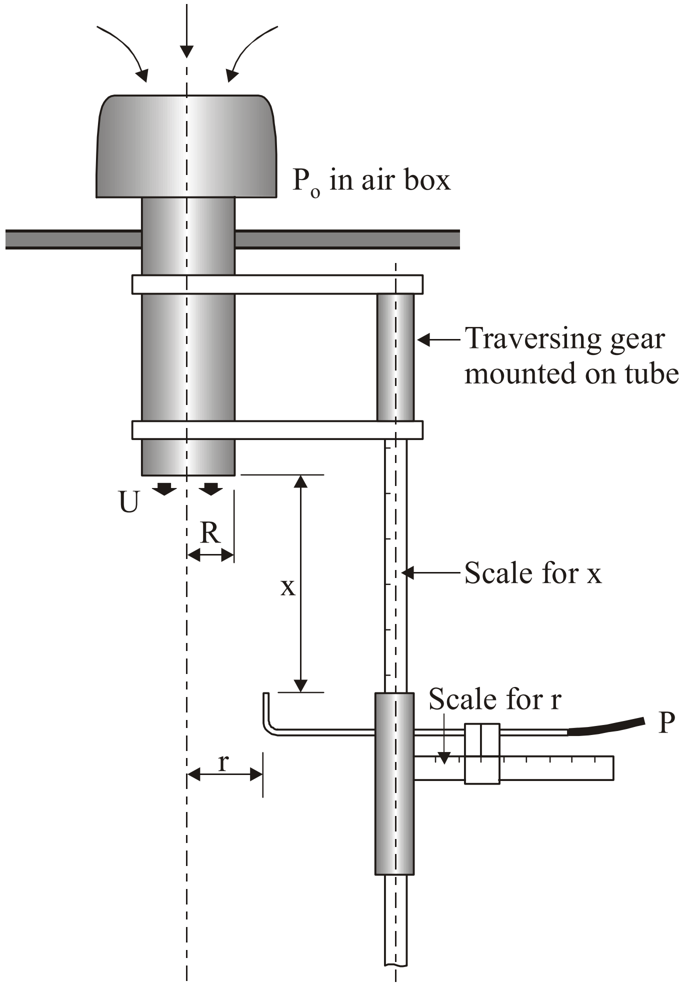


Figure 6.3 Arrangement of Jet Apparatus

Results and Calculations

Diameter D of jet tube	51.6 mm		
Radius R	25.8 mm		
Pressure P_o in airbox	900 N/m^2		
Air temperature	22^oC	=	295 K
Barometric pressure	1025 mb	=	1.025×10^5 N/m^2
Air density ρ	$\dfrac{1.025 \times 10^5}{287.2 \times 295}$	=	1.210 kg/m^3
Coefficient of viscosity, μ		=	1.82×10^{-5} kg/ms

Coefficient of kinematic viscosity, $\nu \quad = \quad \dfrac{\mu}{\rho} \quad = \quad 1.50 \times 10^{-5}\ \mathrm{m^2/s}$

Velocity U at tube exit, $\quad \frac{1}{2}\rho U^2 \quad = \quad 870\ \mathrm{N/m^2}$

$$\therefore \quad U \quad = \quad \sqrt{\frac{2 \times 870}{1.210}} \quad = \quad 37.9\ \mathrm{m/s}$$

Reynolds number Re at tube exit $\quad Re \quad = \quad \dfrac{UD}{\nu} \quad = \quad \dfrac{37.9 \times 0.0516}{1.50} \times 10^5$

$$Re \quad = \quad 1.30 \times 10^5$$

The velocity along the axis of the jet was first found by traversing axially, the results being presented in Table 6.2 and Figure 6.4.

x (mm)	**P (N/m^2)**	$\dfrac{u_o}{U}$
0	870	1.00
50	860	0.99
75	845	0.99
100	835	0.98
125	830	0.98
150	810	0.96
175	775	0.94
200	730	0.92
225	675	0.88
250	620	0.84
300	505	0.76
350	430	0.70
400	340	0.63

Table 6.2 Velocity Distribution along Jet Axis

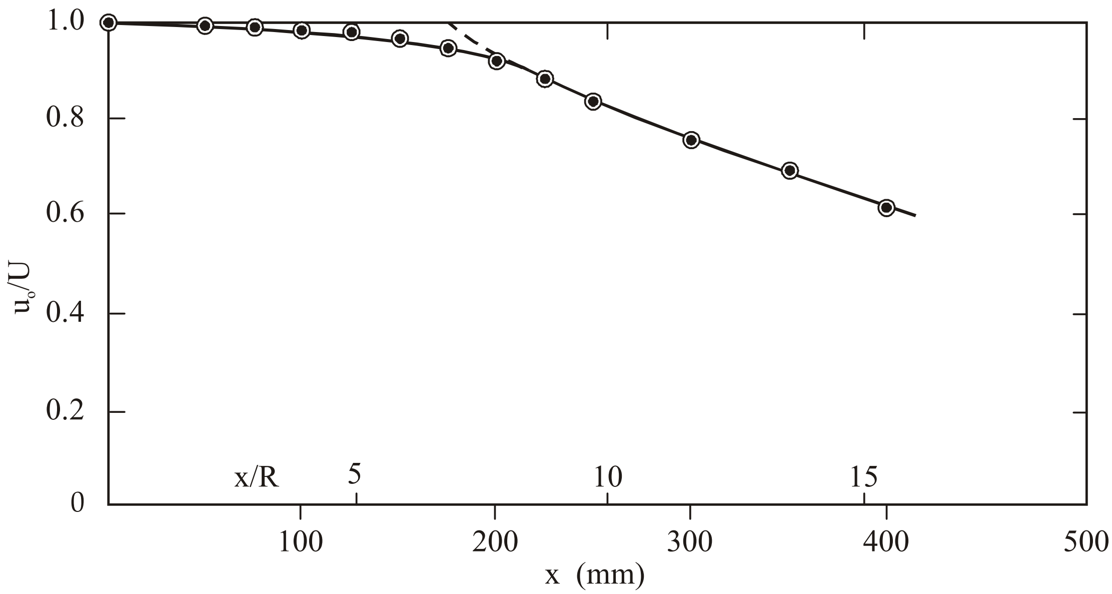


Figure 6.4 Centreline Velocity along Jet

For the initial portion the centreline velocity u_o is seen to be almost constant, and further downstream it starts to fall more rapidly as the shear layer extends to the centre. Extrapolating the falling curve backwards to the line $u_o/U = 1$ shows the length of the core to be

$$x_c = 175 \text{ mm} \qquad \text{or} \qquad x_c/R = 6.8$$

The results of radial traverses made at various values of x are shown in Table 6.3 and in Figures 6.5(a) to 6.5(d). It may be noted that for x = 300 mm a check was made to find whether the velocity distribution was symmetrical about the axis, and this established that there was no appreciable departure from roundness. The profile at x = 75 mm shows a distinct region of constant velocity in the core, and at x = 150 mm there is still some evidence of a flat top to the profile. Further downstream, however, this has disappeared. In Figure 6.6 a dimensionless comparison of the profiles is made by dividing the radius by the radius at which the velocity ratio is 0.5. If you take a set of readings further downstream than x = 300 mm and plot the velocity profile, it will be very similar to the x/R = 11.6 curve. This shows a similar profile. The transition from the square-topped profile at the tube exit to the similarity profile is clearly demonstrated. The curve calculated from Equation (6-5) as shown in Table 6.1 is also plotted. There is good agreement with the similarity profile near the centre of the jet, but Equation (6-5) over estimates u/u_o at the outer edge.

r (mm)	x = 75 mm P (N/m²)	x = 75 mm u/u₀	x = 150 mm P (N/m²)	x = 150 mm u/u₀	x = 300 mm P (N/m²)	x = 300 mm u/u₀
0	840	1.00	810	1.00	520	1.00
5	840	1.00	800	0.99	520	1.00
10	840	1.00	770	0.97	495	0.98
15	835	1.00	720	0.94	450	0.93
17.5	810	0.98				
20	755	0.95	590	0.85	375	0.85
22.5	630	0.87				
25	465	0.74	430	0.73	330	0.80
27.5	275	0.57				
30	160	0.44	250	0.56	245	0.69
32.5	50	0.24				
35	5	0.08	135	0.41	185	0.60
40	0	0	70	0.29	155	0.55
45			25	0.18	110	0.46
50			10	0.11	75	0.38
55			5	0.08	45	0.29
60			0	0	30	0.24
65					20	0.20
70					15	0.17
75					5	0.10
80					0	0
85						
90						

Table 6.3 Velocity Distribution at Various Sections of the Jet

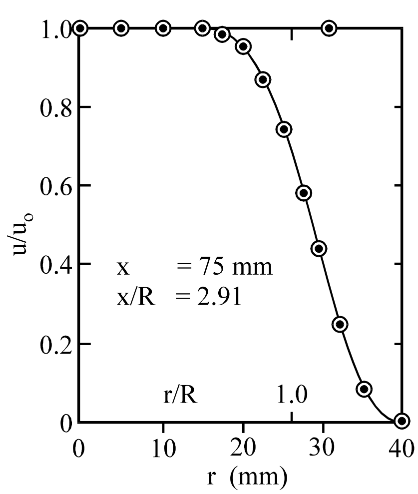


Figure 6.5(a)

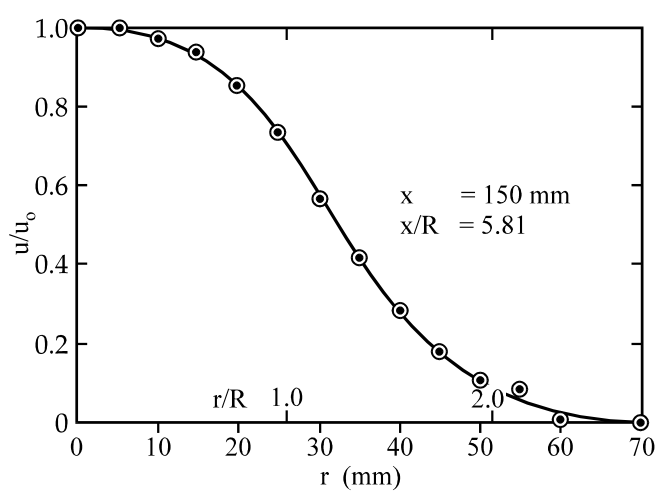


Figure 6.5(b)

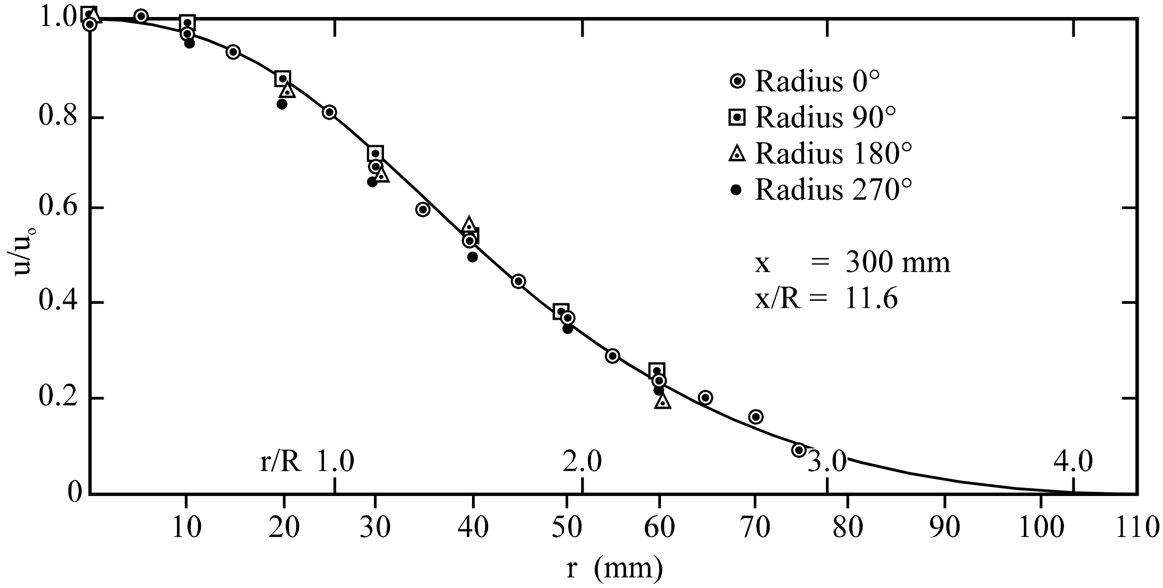


Figure 6.5(a)-(c) Velocity Profiles in Jet at Various Distances Downstream

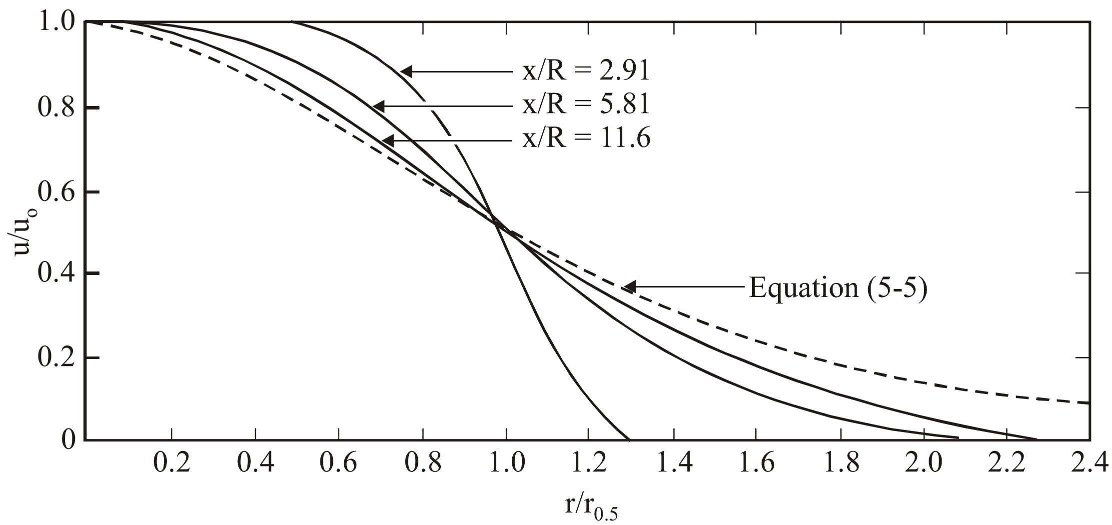


Figure 6.6 Dimensionless Velocity Profiles in the Jet

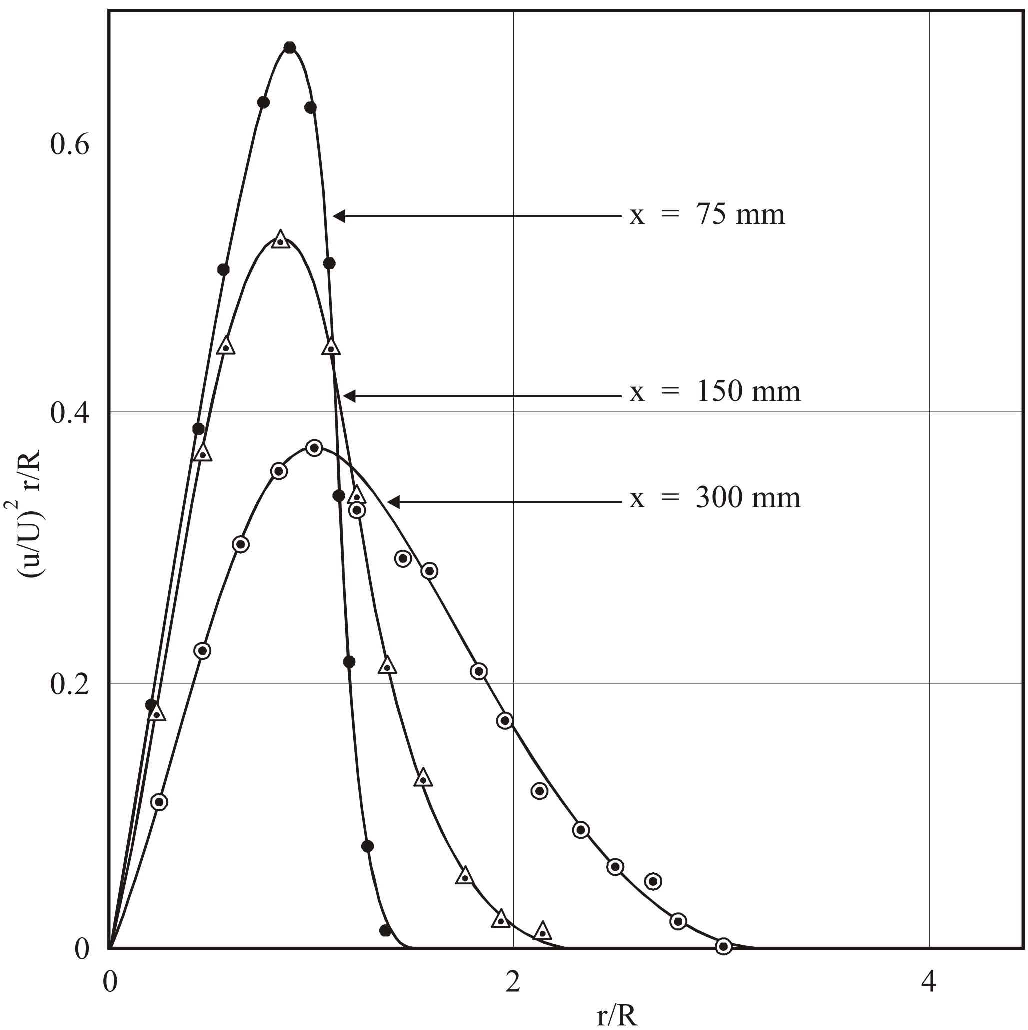


Figure 6.7 Momentum Flux in the Jet

A check on momentum conservation may be made by application of Equation (6-10). On Figure 6.7 the curves of $\left(\frac{u}{U}\right)^2 \frac{r}{R}$ are drawn as functions of $\frac{r}{R}$ for each of the sets of radial traverses. The areas under these curves represent the integrals

$$\int_0^\infty \left(\frac{u}{U}\right)^2 \left(\frac{r}{R}\right) d\left(\frac{r}{R}\right)$$

and so are a measure of momentum flux. The measured areas lead to the results of Table 6.4.

The values do not remain constant at 1.0 as expected, but rise significantly as the jet develops. There can be no doubt that the momentum flux does not increase since there is no force acting in the direction of the jet, so the apparent rise must be due to experimental error. The most likely source is turbulence which could have the effect of giving an excessive mean velocity pressure.

x (mm)	**x/R**	$2\int\left(\frac{u}{U}\right)^2\left(\frac{r}{R}\right)d\left(\frac{r}{R}\right)$
75	2.91	1.01
150	5.81	1.10
300	11.6	1.15

Table 6.4 Momentum Flux in Jet

Conclusion

The diffusion of a turbulent air jet into the surrounding atmosphere has been measured by velocity traverses along the centreline and along several radii. The first part of the jet is found to have a central core of almost constant velocity which extends for a length $x_c = 6.8R$ along the axis. Thereafter the centreline velocity reduces and the velocity profile rapidly tends to similarity, that is to a profile which may be characterised by the single parameter r/x. The momentum flux in the jet, which must be constant in a constant-pressure atmosphere, appears to rise by approximately 15% along its length. The discrepancy is attributed to measurement error due to turbulence.

Suggestions for Further Experiments

1. Obtain the angle at which the jet spreads by establishing the trajectory along which $u/u_o = 0.5$.

2. Compare the variation of centreline velocity with Equation (6-2).

3. Investigate the effect of initial turbulence in the jet by placing a wire gauze over the exit of the tube and comparing the results with those obtained with a plain exit.