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Deflexion of a submerged round jet to increase lateral spreading

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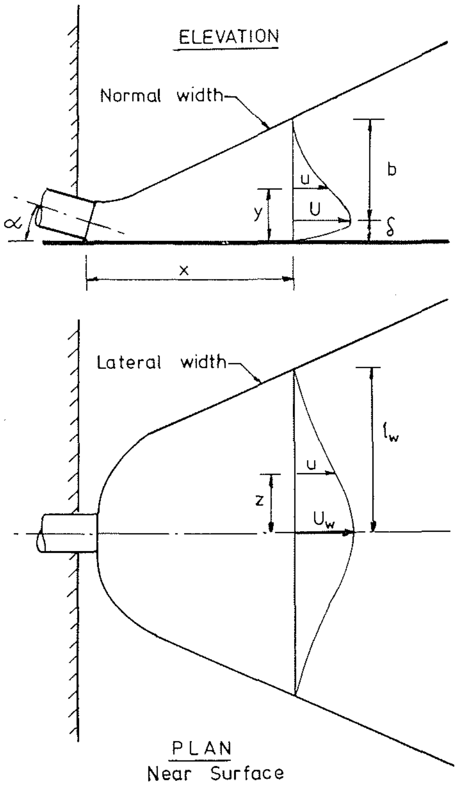
Introduction

A jet or a stream of air blown into the atmosphere mixes with the latter and spreads out linearly in accordance with well known laws. In the case of a jet issuing from a nozzle or an orifice and is directed at an angle to a plane surface, it is transformed into a thin stream with wide lateral boundaries at a short distance downstream of the outlet, as shown in Fig. 1. The increased surface of the jet becomes available for mixing and energy dissipation which results faster reduction of the velocity and energy of the jet than in the case of the free jet. Between this stream and the surrounding fluid, a turbulent mixing region is formed having normal and lateral boundaries b and l. The normal velocity profile at any section consists of a wall boundary layer and an outer jet layer, which is similar in character to that of the wall jet analysed by Glauert [1] and the parallel wall jet recently investigated by the author [2].

The behaviour of the deflected jet is of importance in many industrial designs, including combustion chambers, furnaces, jet exhaust systems, stilling basins of pipe chutes and fish passes of the pool type. In the last two cases if the pipe outlet or orifice is inclined downwards, the floor of the pool takes the place of the deflecting plane and this leads to a more rapid velocity reduction than if the outlet or orifice is horizontal. This allows for a shorter length of pool than that required with a horizontal outlet.

Another aspect of the inclined jet design is the steadying effect it has on the flow in the stilling basin of a pipe outlet. It was observed that a round water jet discharging into a rectangular channel produces both unsymmetrical and unsteady flow. For semi-submerged flow, the jet is sucked laterally and adheres to one side of the channel, with a long circulation zone forming on the other side. At higher depth of submergence, the jet changes into a state of sustained oscillatory movement from one side of the channel to another. Attempts to stabilize the flow without altering its character were unsuccessful. However, reasonably steady and symmetrical flow was obtained when the jet was directed at 45° angle to the channel bed.



1/ Flow in a deflected round jet.

The data on deflected jets are few and are scattered in a number of publications. Chester et al [3] carried out experiments on an air jet from a 25 mm diameter orifice and from a 6.5 mm rectangular slot of the same area which were directed over a plane wooden surface. The jets were examined for each aperture with the plane set both parallel to the jet axis and at an impinging angle of 15° to the direction of discharge. For the circular orifice, they found inclination of the jet to the surface causes the angle of boundary divergence across the surface to increase from 50° to 68°.

Nemenyi and White [4] investigated the design of fish passes with submerged orifices given a downward slope of 45°. They found immediately after issue the jet fanned out to 90° on the floor of the pool and ran up the side walls very smoothly, practically the whole of its excess energy being dissipated before it reached the next orifice. This produced a saving in length of pool of about 50 per cent.

Recently, the author has investigated the spreading and development of turbulent jets and streams [5 to 9] including a round air jet projected parallel to a wall [2]. Experiments were carried out to establish the shape of the velocity profiles, the decay of maximum velocity and the rate of growth of the jet. It was found that the jet consists of an inner half extending from the wall to the centre line of the jet where the flow resembles that along a flat plate and an outer half which is similar in character to that of a free air jet discharging into the atmosphere. In the outer half the rate of spreading parallel to the wall is about six to eight times greater than that normal to it. The present research was undertaken to extend this work by studying the flow characteristics of the jet impinging at 15, 30 and 45 degrees to a plane smooth surface.

Experimental method

A jet of air, 25.4 mm diameter, was produced by a blower with a rheostat for adjusting the speed of the fan. The jet was directed at different angles to a smooth wooden surface. Except of the small boundary layer on the inside of the nozzle, the velocity profile was practically uniform across the exit section.

A shielded pressure probe [10] with a central sting was used for velocity measurements. The probe has been found to be insensitive to direction changes through a range of angles ± 45 degrees for a 1 per cent error limit. Near the wall, the velocity profiles across the surface were measured by a total-head tube 1 mm inside diameter. Each probe was clamped into a micrometer screw transversing mechanism graduated to 0.05 mm.

Analysis of turbulent round jet

The theoretical aspects of the dispersion of a round jet into the stationary atmosphere are covered in numerous papers and only a brief survey is given here to help explaining the trends of the present experimental results.

Tollmien [11] using Prandtl's mixing length theory, solved the fundamental equations of turbulent motion of a round submerged jet originating from a point source. He established the shape of the velocity profiles and showed that the central velocity of the jet U is inversely proportional to the distance x,

$$\frac{U}{U_1} = K \frac{d}{x} \tag{1}$$

Where U_1 is the initial velocity of the jet, K is a constant for the jet, and d is the orifice diameter. The value of K has been found experimentally to be variable depending on the effect of the boundary layer in the nozzle. Based on theoretical and experimental results, Squire [12] recommends a mean value of 6.5.

The analysis also gives the outer boundary of the jet by the following:

$$b = c_1 x \tag{2}$$

the value of c_1 is 0.214, which makes the angle of divergence approximately 12° with the jet axis.

Kuethe [13] extended Tollmien's work to the case of a jet with a finite source and established the length of potential core is about 5 diameters from the orifice. This result agrees with experiments over a wide range of Reynolds numbers.

The flow of a round jet impinging on a plane surface and spreading radially over it has been analysed by Glauert [1]. He termed the flow as a radial wall jet for which he obtained approximate similar solutions in regions far downstream of the point of impingement.

The analysis near the wall was based on Blasius law for pipe flow, while Prandtl's mixing-length hypothesis was used further out. An experimental investigation of the radial wall jet has been carried out by Bakke [14]. Measurements of velocity profiles were made at distances 10 to 20 times the jet diameter. At these distances, the profiles were similar, and rate of spreading and decay of the jet followed power laws:

$$b \propto x^{1.02}$$

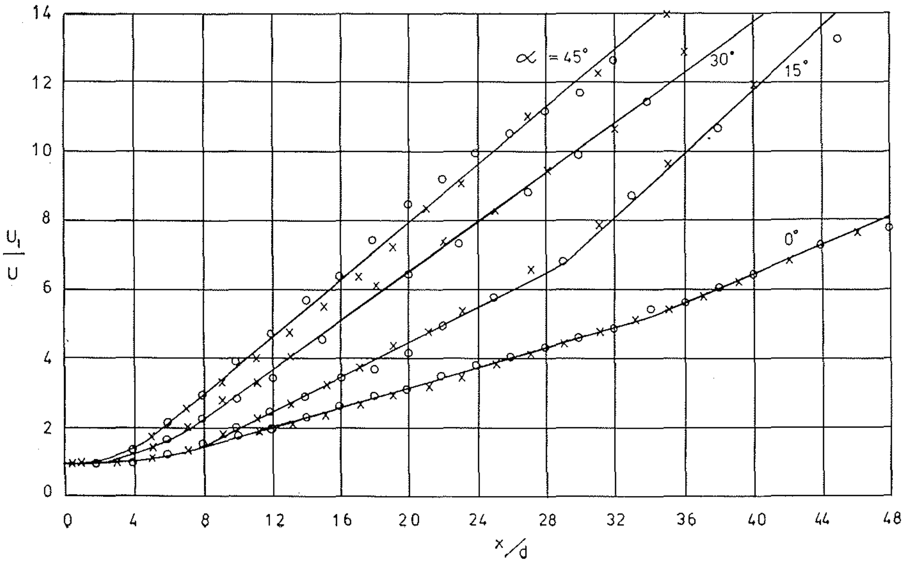
$$U_c \propto x^{-1.11}$$

These are in fair agreement with Glauert's predictions.

Variation of maximum velocity

The variation of maximum velocity of the jet for different angles of deflection are plotted non-dimensionally in Fig. 2. As for the parallel wall jet [2] the velocity for the case of 15° deflection is seen to be constant over 2 diameters followed by a transitional length up to 8 diameters which joins to a straight line up to 30 diameters and this is followed by another line of greater slope. With increasing deflection angle the length of transition decreases from 8 to 6 diameters, and the velocity beyond this length decreases linearly up to 40 diameters.

The length of the potential core is seen to be independent of the deflection angle and it is about 2 diameters compared with 5 diameters for the free round jet. As expected, the presence of the wall on one side of the jet increases lateral mixing and hence reduces the length of the potential core. However, the length of the transition region for the 15° deflection is seen to be such that the linear distribution



2/ Decay of maximum velocities.

begins at a distance of 8 diameters as for a free jet. It seems that the impingement region is relatively small and the deflection of the jet is completed within the potential core.

The following relationships between maximum velocity and distance are derived :

ANGLE	RELATIONSHIP	DISTANCE
0°	$U/U_1 = 7 \ d/(x + 2.5)$	$8 < x/d < 33$
	$U/U_1 = 5 \ d/(x - 8)$	$33 < x/d < 53$
15°	$U/U_1 = 4 \ d/(x - 2)$	$8 < x/d < 29$
	$U/U_1 = 2.2 \, d/(x - 14)$	$29 < x/d < 45$
30°	$U/U_1 = 2.8 \, d/(x - 2)$	$7 < x/d < 40$
45°	$U/U_1 = 2.4 \, d/(x - 1)$	$6 < x/d < 36$

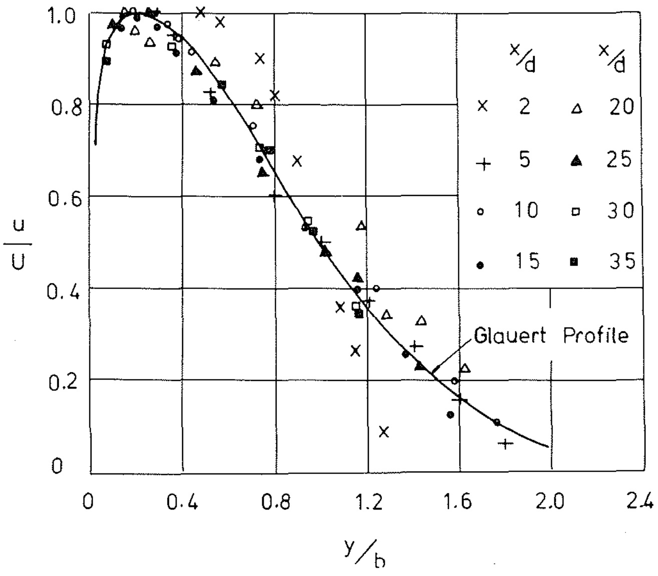
The origin for each relationship was located by extrapolating the straight line thus obtained to meet the x-axis.

As for the free air jet and the parallel wall jet, four regions of flow are apparent in the 15° deflected jet: (*i*) Region I of potential core extending about 2 diameters from the orifice; (*ii*) Region II of transition flow that extends up to 8 diameters and in which the velocity apparently varies parabolically with distance; (*iii*) Region III of established flow which extends to about 30 diameters and (*iv*) Region IV of terminal flow in which the residual velocity decays rapidly as a result of large scale turbulence to that of the surrounding air.

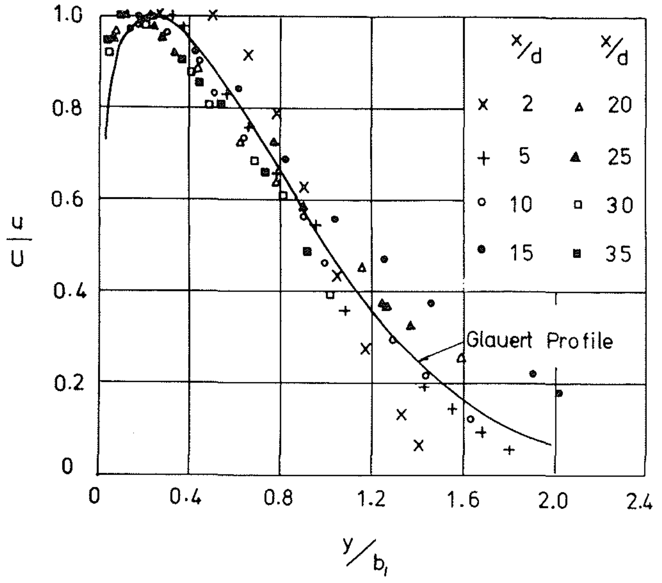
Because of the greater rate of spreading and hence mixing for the 30° and 45° deflected jets, the rate of decay of maximum velocity is much faster than for the other jets, being about two and a half times that for the parallel wall jet. Also, it appears that downstream of transition Region II, there is only one region of fully developed flow with velocity decay characteristics nearly the same as in Region IV of terminal flow for the 15° deflected jet.

Velocity profiles

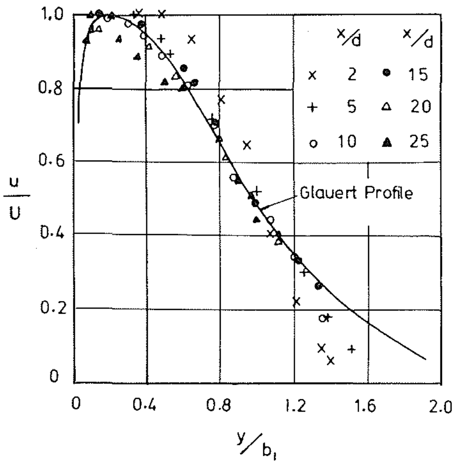
The velocity profiles in various regions of the flow are plotted non-dimensionally in Figs. 3 to 8. Concerning the normal profiles along the centre plane of the jet, for regions $5 < x/d < 35$ they lie nearly on one curve and therefore are similar despite the different rates of decay of maximum velocity in the three regions of the jet. The profiles are also seen to be in some agreement with Glauert's profile for the radial wall jet, and thus the two flows are similar.



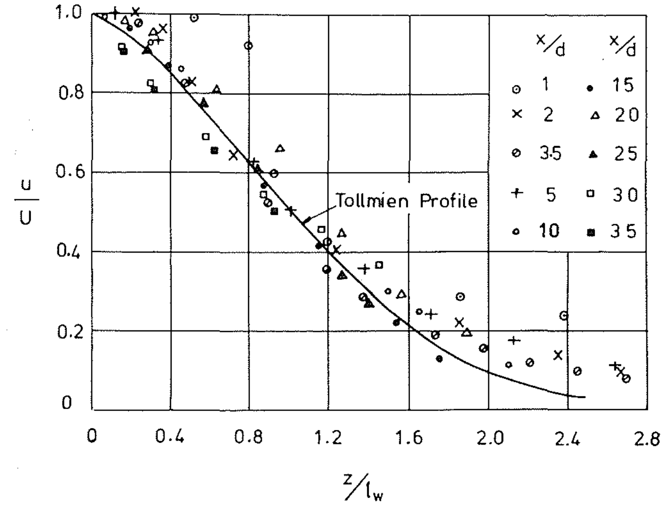
3/ Normal velocity profiles for $\alpha = 15°$.



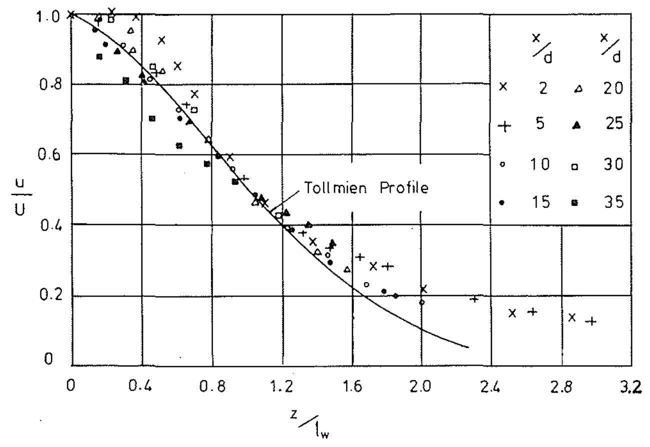
4/ Normal velocity profiles for $\alpha = 30°$.



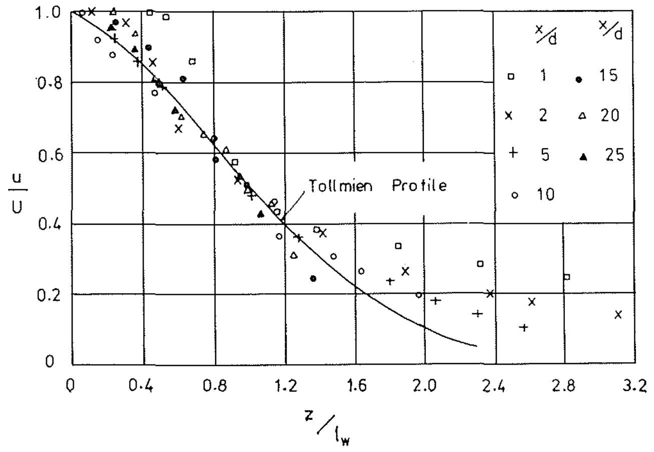
5/ Normal velocity profiles for $\alpha = 45°$.



6/ Lateral velocity profiles near the wall for $\alpha = 15°$.



7/ Lateral velocity profiles near the wall for $\alpha = 30°$.



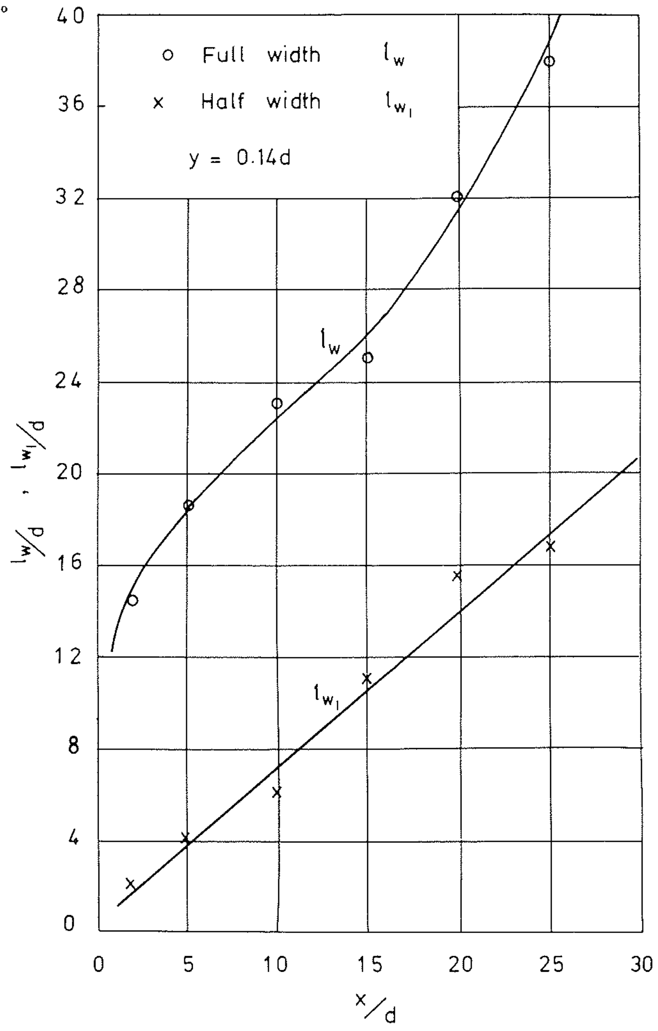
8/ Lateral velocity profiles near the wall for $\alpha = 45°$.

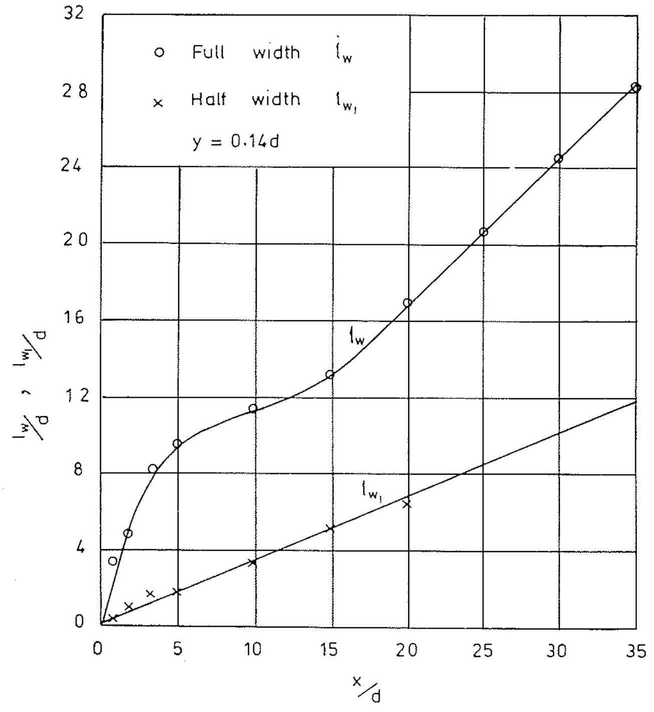
However, in the outer layer of the jet and near the position of maximum velocity, there is a difference in the velocity profile from that of the wall jet. This is caused primarily by the spreading effect of the wall on the jet and the effect of the inner wall layer on the outer layer. The lateral velocity profiles near the wall for $5 < x/d < 35$ show some variation with distance especially at the outer edge of the jet, where it is seen that the velocity falls more slowly than in the case of the free jet. It should be noted, however, that a large part of this discrepency may be due to inaccuracy of measurements in this region of flow. The profiles compare reasonably with Tollmien's curve for the free jet.

Spreading of boundaries

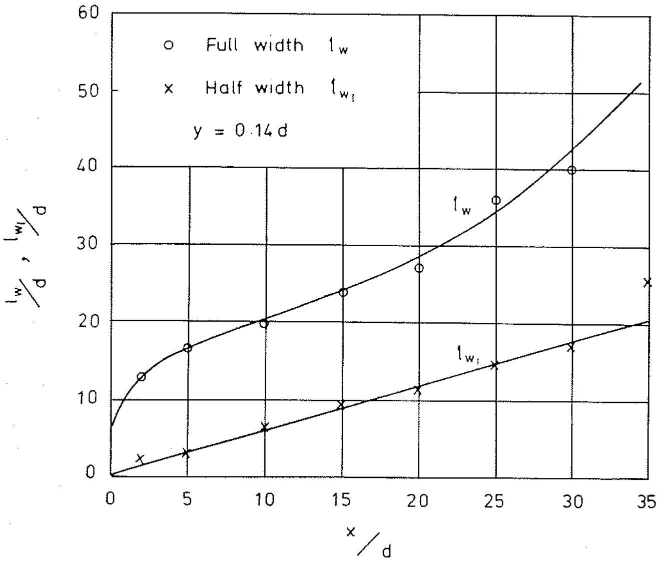
The normal and lateral widths of the jet for different deflection angles are plotted non-dimensionally in Figs. 9 to 14. On impact the jet spreads out rapidly over the wall, reaching a wide lateral width l_w at a short distance downstream of the nozzle. Using smoke and fine strings as tracers, it was observed that at about 30° deflection angle the jet fans out to 90° on the surface of the wall

11/ Lateral width of the jet for $\alpha = 45°$

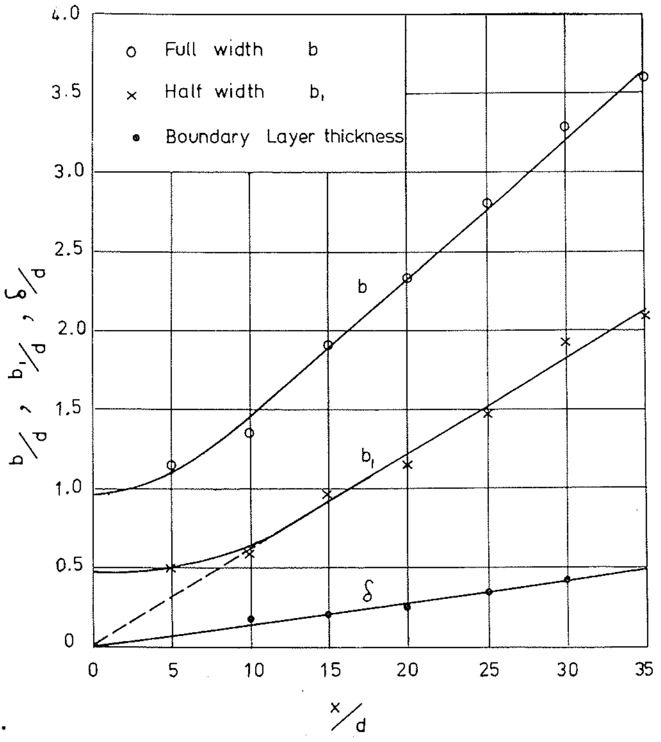




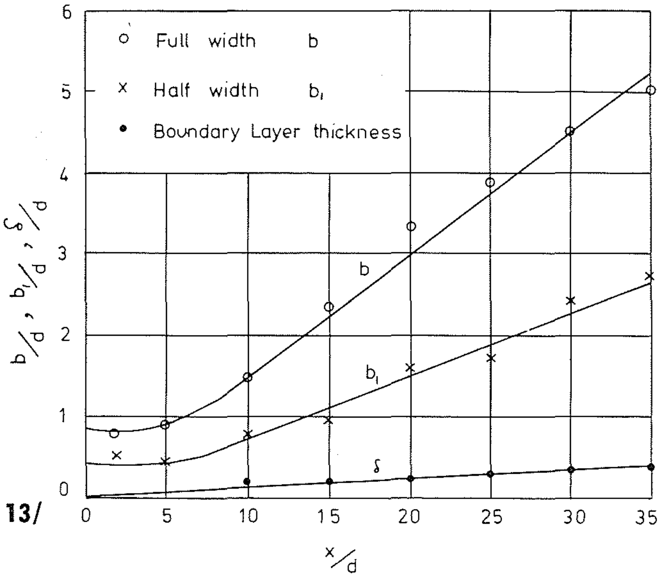
9/ Lateral width of the jet for $\alpha = 15°$.



10/ Lateral width of the jet for $\alpha = 30°$.



12/ Lateral width of the jet for $\alpha = 15°$.



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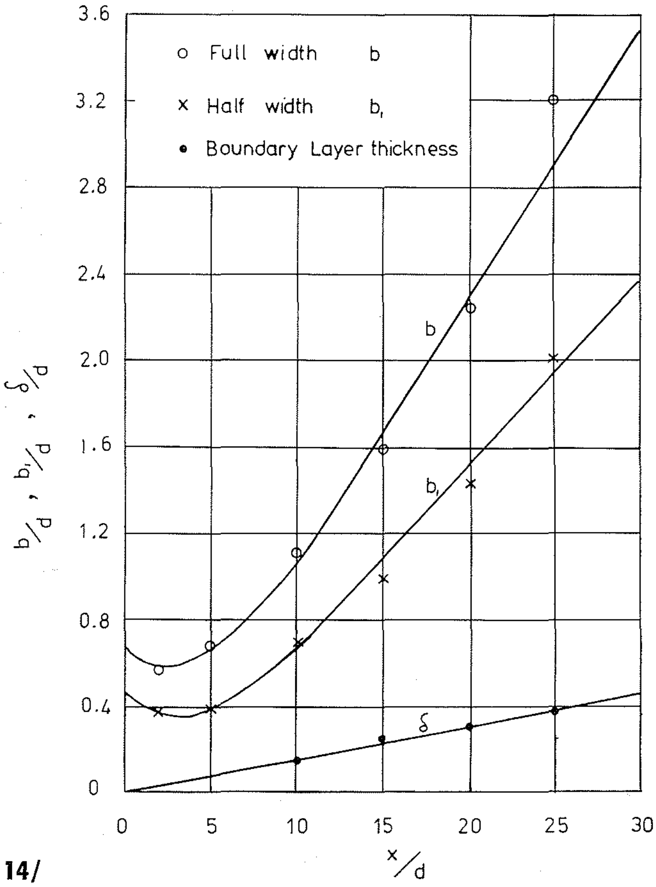
13/ Normal width of the jet for α = 30°.

14/ Normal width of the jet for α = 45°.

15/ Flow in the jet for different angles of impingement.

16/ Comparison of lateral widths of the jets.

17/ Boundary layer growth in the jets.



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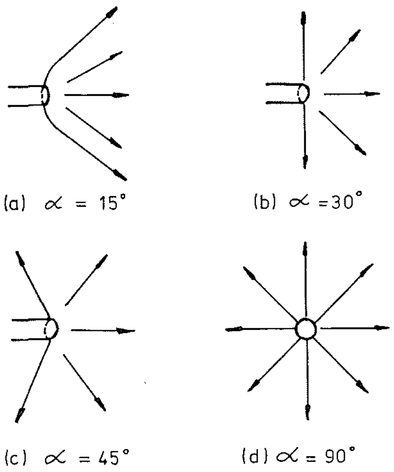

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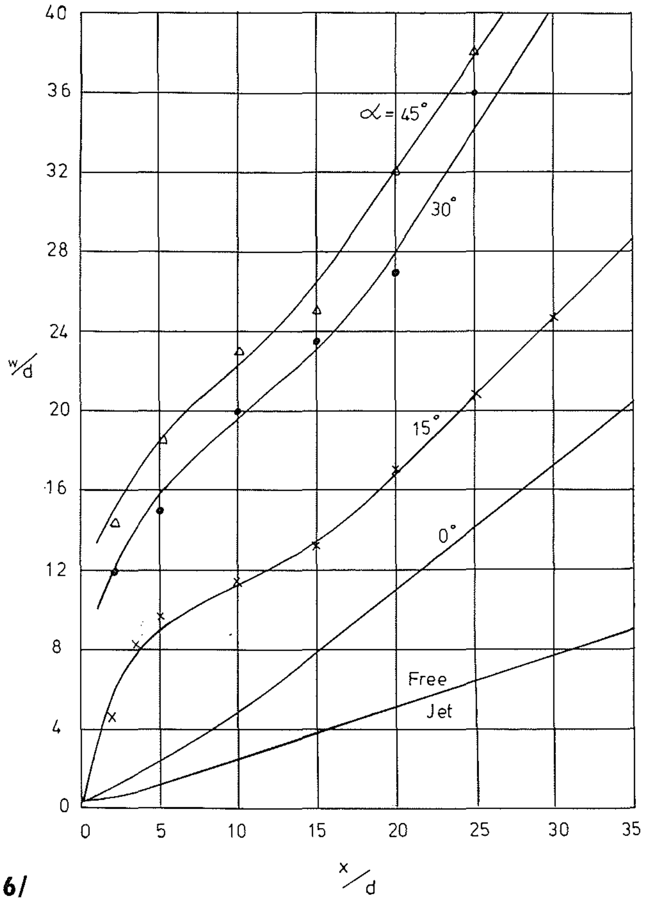

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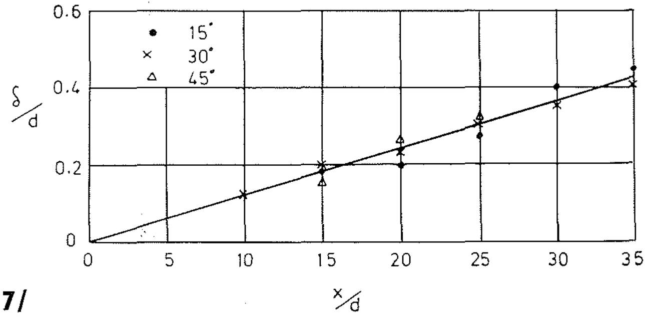

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(Fig. 15). With increasing deflection angle upstream flow occurs (Fig. 15 *c*), until when the jet impinges vertically on the surface, it spreads out radially in all directions (Fig. 15 *d*) as in the case of the radial wall jet. This explains the considerable increase in lateral width of the jet at impact for the 30° and 45° deflection angles and may also account for the similarity of decay of maximum velocity in both cases. Downstream of flow Region II, the lateral width follows a curve which then joins to a straight line of large divergence angle. As expected, the divergence angles for the 30° and 45° deflected jets are the same, about 60°. The widths are compared with that for the round free jet in Fig. 16, which shows the considerable increase in lateral width with increasing deflection angle.

The normal widths, b, along the centre plane are plotted in Figs. 12 to 14. It is seen in the impingement Region, the jet contracts slightly and then spreads linearly with maximum slope of about 13° for the 30° deflected jet. The angles of normal and lateral boundary divergence Θ and Φ in the regions of fully developed flow are given in the table below.

BOUNDARY	ANGLES OF DIVERGENCE			
	0° Deflection	15° Deflection	30° Deflection	45° Deflection
Normal width b	4.75°	5.2°	12.7°	7 °
Normal half-width b_1 ..	2.3 °	2.6°	4.4°	4.9°
Lateral width l_w	28 °	37 °	59.5°	59.5°
Lateral half-width l_{w1} ..	14 °	17.5°	20 °	34 °

The rate of spreading parallel to the wall is seen to be about 5 to 7 times that normal to it. This is due to the effect of the wall in broadening the jet on impact and transforming it into a thin wide stream. The increased surface area of the stream becomes available for mixing which results in faster reduction of velocities and greater expansion of the boundaries than in the case of the free jet. The half-widths l_{w1} and b_1 also vary linearly with distance for the jets.

The development of the bounday layer, extending from the wall to the point of maximum velocity in the profile, is shown in Fig. 17. The points lie closely on a straight line passing through the origin, which is represented by the following equation:

$$\frac{\delta}{d} = 0.012\left(\frac{x}{d}\right) \tag{3}$$

The value of the constant is considerably less than the average value of 0.067 found experimentally for the plane wall jet [15]. This is a further illustration of the deflection effect of the solid surface in transforming the jet into a very wide shallow stream.

Notation

The notation used is illustrated in Fig. 1 and is given below.

b	Normal width of jet.
b_1	Normal half-width of jet.
d	Jet diameter.
l_w	Lateral width of jet near the wall.
l_{w1}	Lateral half-width of jet near the wall.
K	Constant defined by equation (1).
U_1	Jet exit velocity.
U	Maximum profile velocity.
U_w	Maximum profile velocity near wall.
y	Normal distance measured from the wall.
z	Lateral distance measured from centreline.
x_0	Distance from point source to the exit section.
δ	Boundary layer thickness.
Θ	Angle of normal boundary divergence.
Φ	Angle of lateral boundary divergence.

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