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By P. BRADSHAW, B.A., and EDNA M. LOVE,
OF THE AERODYNAMICS DIVISION, N.P.L.

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Summary. Measurements of velocity magnitude and direction, static pressure, and skin friction have been made in a circular turbulent jet impinging normally on a flat surface. The speed in the jet just before impingement was 135 ft/sec and its radius was about 2·5 in. The region of increased static pressure near the stagnation point is roughly hemispherical, with a radius slightly larger than that of the jet. The maximum value of skin friction occurs at a radius approximately equal to that of the jet and is about 0·006 of the jet maximum dynamic pressure at the test Reynolds number. The virtual origin of the resulting radial wall jet is very close to the stagnation point.

1. *Introduction.* The impingement of a jet on a solid surface is of interest in many practical problems, such as paint sprays, shielded-arc welding and jet blast, particularly in connection with current schemes for vertical take-off. An impinging jet is also the most common source of the radial wall jet described by Glauert[1] and Bakke[2]. In response to several enquiries, and also because the flow seemed inherently interesting and had apparently not been explored previously, a short series of experiments has been performed on a low-speed circular jet with the aim of finding out the behaviour of the flow in the impingement region and the subsequent radial wall jet.

Experiment was, of course, restricted to the turbulent case, and no serious attempt has been made to develop a theory of the flow behaviour, other than to remark that the deflection of the jet occurs in such a small space that an inviscid-flow-plus-boundary-layer solution for the impingement region should not be wildly in error. The flow has also been discussed in Refs. 3 and 4.

2. *Apparatus.* The test rig is shown schematically in Fig. 1. The laboratory compressed-air supply was used. The velocity at exit from the pipe was approximately 350 ft/sec in the central core, with a turbulent boundary layer about 0·2 in. thick on the inner wall. The virtual origin of the jet was 19·7 in. above the plate, and the jet speed at impingement was 135 ft/sec, the profile being fully developed and about $2\frac{1}{2}$ in. in radius. Velocities were measured with a diamond-section yawmeter as shown in Fig. 1 and, in the wall jet, with a round pitot tube. Static pressure was measured at the surface tappings and with a disc static probe. Skin friction was measured with a flat pitot tube, carefully placed at different radii and calibrated in turbulent flow in a rectangular duct. The height of the pitot tube was 0·015 in., giving $\frac{u_\tau h}{v} \approx 50$ a value intended to compromise between possible calibration errors for large tubes and errors caused by inaccurate setting of a small tube.

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3. *Results.* The flow directions are shown in Fig. 2, the velocity contours in Fig. 3, the static pressure contours in Fig. 4, and the skin friction in Fig. 5. Fig. 6 shows the velocity profiles in the wall jet, plotted non-dimensionally and compared with Bakke's experimental profile[2]. Fig. 7 shows the radial variation of profile thickness and maximum velocity, and Fig. 8 the results of a temperature survey in a slightly heated jet.

Discussion. The first noticeable feature of the results is that the impingement region is quite small and that the effective origin of the radial wall-jet is very close to the centre. Most of the change from free jet to wall jet takes place within a hemisphere of about 3 in. radius, little more than the radius of the free jet, though the profile thickness is greater than that expected in the wall jet from an ideal point source for r less than about 7 in. The intercept of a best-straight-line fit to the values of $\delta_{0\cdot 5}$ is at $r = 0\cdot 6$ in. and that of a best-straight-line fit to $1/U_j$ at about $r = 1\cdot 7$ in. It had been anticipated that the flow disturbances in the wall jet, due to the decaying jet flow and the violent shearing in the impingement region, might take a considerable time to die out. In fact slight changes in the shape of the velocity profile are detectable out to the maximum radius, 20 in., at which measurements were made, but for practical purposes the wall jet is fully developed at $r = 8$ in.

Evidently, the turbulent fluctuations propagated radially from the impingement region, though possibly quite large, do not contribute much to the shear stress in the wall jet. The effect of the distortion in the inner part of impingement region would be to reduce the correlation of the free-jet turbulent components. The turbulence in the outer part of the jet is not so violently distorted in the impingement region because the magnitude of the flow velocity does not alter much during the change of flow direction (the velocity contours and streamlines are almost coincident for fluid initially more than about $1\cdot 3$ in. from the jet axis). Also, the structure of the wall-jet outer profile is much the same as that of a free jet so that the flow might be expected to change quite quickly from one to the other. The fact that the inner part of the flow also approaches equilibrium quickly is fortunate, and implies that the work of Glauert and Bakke can be applied with fair accuracy in the case of jet impingement as well as that of a jet emerging from a central source.

Although the behaviour of an equilibrium turbulence structure during and after distortion is a very important factor in the understanding of flow between boundaries of arbitrary shape, the impinging jet is not a very suitable case in which to study it because of its complicated nature: in particular hot-wire turbulence measurements would be difficult to make in the impingement region because the velocity fluctuation amplitudes are likely to be much greater than the mean, and so it seems sensible to restrict a study of this flow to the points of immediate practical interest, and to investigate distortion of an equilibrium shear flow in more suitable conditions.

The variation of skin friction with radius is unremarkable. The maximum shear stress occurs at $r = 2\cdot 5$ in. which is roughly the radius of the edge of the free jet and, more particularly, of the static pressure field, indicating that, as might be expected, the radial velocity reaches a maximum under the influence of the pressure gradient and then falls off because of radial dispersion and viscous dissipation. The skin friction coefficient based on local peak radial velocity falls from $0\cdot 0089$ at $r = 3\cdot 25$ in. to $0\cdot 0082$ at $r = 8\cdot 45$ in. and $0\cdot 0072$ at $r = 12$ in. although the Reynolds number based on peak velocity and peak height is approximately constant at 4000. Evidently the mean velocity profile tends to the wall-jet form rather more quickly than does the shear stress-profile. All these values of skin friction are rather higher than those predicted from the Blasius pipe flow formula assumed by Glauert: recent experiments with a two-dimensional wall jet have also established a skin friction law some 25 per cent higher than Glauert's.

It should be remarked that the skin friction actually measured is not necessarily a true time-mean value. The calibration of the surface tubes ensures that they will read an arithmetic mean skin friction in flows in which the turbulent fluctuations near the surface are similar to those in the calibration duct flow. However, the turbulence near the surface in the impinging jet is likely to be very intense because of the high level fluctuations transmitted from the outer jet flow and also the unsteady flow near the stagnation point, so that the tube reading for a given true mean skin friction may be higher than its calibrated reading, thus giving an overestimation of skin friction. Except near the stagnation point the error should not however be very large: in fact the experimental skin-friction curve extrapolates to quite a good zero at the origin, and the slight error can probably be attributed to the experimental necessity of mounting the tube slightly to one side of the true radius.

The skin friction distribution is of particular interest in the study of surface erosion by gas jets such as rocket motor exhausts. Very little erosion should occur on the jet axis, and the rate of erosion should also decrease very rapidly after reaching a maximum at about one jet radius from the centre. This conclusion, of course, only applies to homogeneous cool jets where the correlation between skin friction and erosion should be high and temperature effects insignificant.

In practice, jet blasts are frequently hot or loaded with some passive scalar quantity such as a small concentration of another fluid. In these cases, the distribution of temperature or concentration, as well as that of velocity, is interesting. Some attempts were made to measure the temperature distribution in a slightly heated jet. The nozzle temperature was some 35 deg C above atmospheric, falling to about 7 deg C above atmospheric at the impingement point so that the change in Reynolds number was small. The plate, being wooden, can be assumed to be nearly insulated. The radial traverse at 2·5 in. above the surface shows that, as usual, the temperature field of the jet extends further than the velocity field, to about $r = 3 \cdot 5$ in. instead of $r = 2 \cdot 5$ in. The radial traverse at 0·25 in. above the surface shows that the excess temperature in the wall jet near the surface falls off roughly as the inverse of the radius outside the impingement region, though the initial rate of decrease is quite small, and the excess temperature is still as much as half its maximum value at two jet (velocity profile) radii from the centre. In view of the high radial velocities and skin friction in this region, the area of large heat transfer must be expected to extend for at least two jet radii. The concentration of any passive contaminant varies in the same way as the temperature difference (neglecting heat transfer to the surface) and therefore decreases as $1/r$ (since the mass flow in the wall jet $\propto U_{\max}\delta r \propto r$ nearly). More complete measurements of temperature or concentration would be desirable.

Conclusions. The conclusions of the report are largely provided by the experimental results, which show that the flow is to a fair approximation the same as in an ideal wall-jet at more than two or three free-jet radii from the impingement point, but that nearer the centre the conditions are more complicated, with large pressure gradients associated with streamline curvature and a wall shear stress which rises sharply from zero at the stagnation point to a maximum at about one jet radius.

Further conclusions will doubtless be drawn by those to whom the flow is of particular practical interest, but it may be remarked that it is an excellent illustration of the way in which a turbulent flow recovers from distortion, most of the recovery taking place very quickly, followed by a slow establishment of more exact equilibrium.

LIST OF SYMBOLS

p		Static pressure
p_0		Static pressure at centre of flat surface
p_a		Atmospheric pressure
q	$=$	$\frac{1}{2}\rho U^2$
r		Radius from centre of flat surface
$r_{0\cdot5}$		Radius of free jet to $0\cdot5$ max. velocity
u_τ	$=$	$\sqrt{(\tau_0/\rho)}$
U		Velocity
U_j		Velocity at peak of wall jet profile
U_{j0}		$\sqrt{[2(p_0 - p_a)/\rho]} \doteqdot$ velocity of jet just before impingement
T		Temperature
T_a		Atmospheric temperature
y		Distance above flat surface
$\delta_{0\cdot5}$		(Larger) distance above surface at which wall jet velocity is $0\cdot5\,U_j$
ν		Kinematic viscosity
ρ		Air density
τ_0		Skin friction shear stress

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No.	*Author*	*Title, etc.*
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2	P. Bakke	An experimental investigation of a wall jet. *J. Fluid Mech.* Vol. 2, p. 467. 1957.
3	Poreh and Cermak	Flow characteristics of a circular submerged jet impinging normally on a smooth boundary. Proc. 6th Mid-West Conference on Fluid Mechanics, p. 198. 1959.
4	H. C. Levey	The back effect of a wall on a jet. *Z.A.M.P.*, 11, p. 152. 1960.

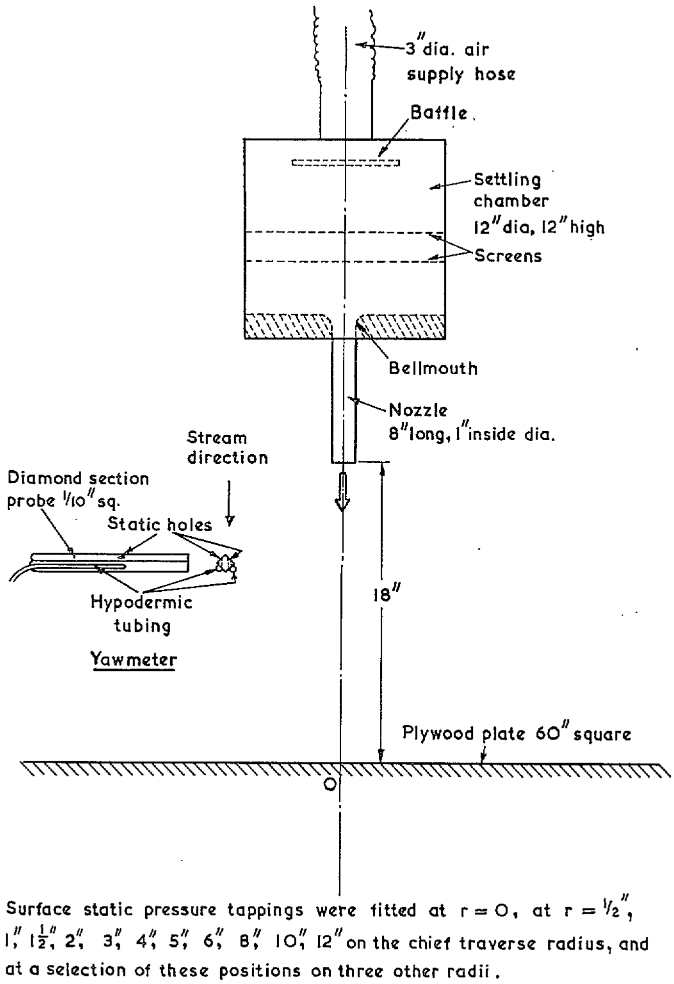

FIG. 1. Arrangement of apparatus.

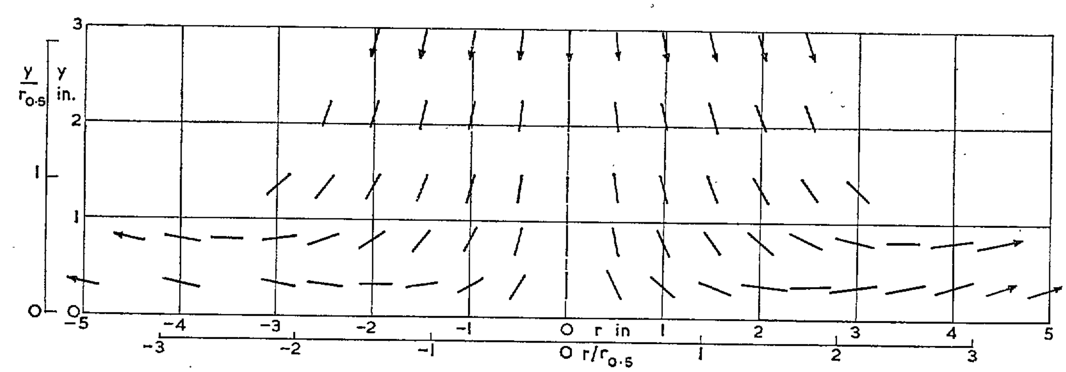

FIG. 2. Flow directions.

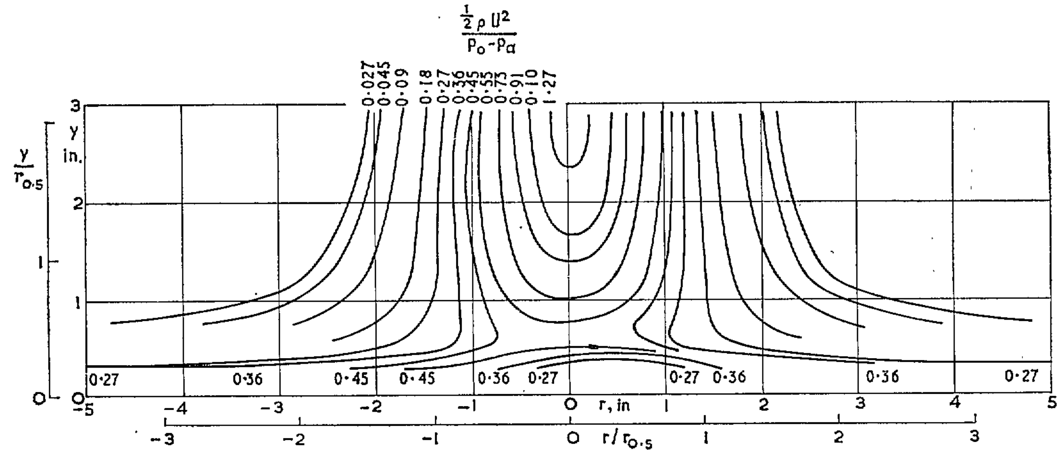

FIG. 3. Dynamic pressure contours.

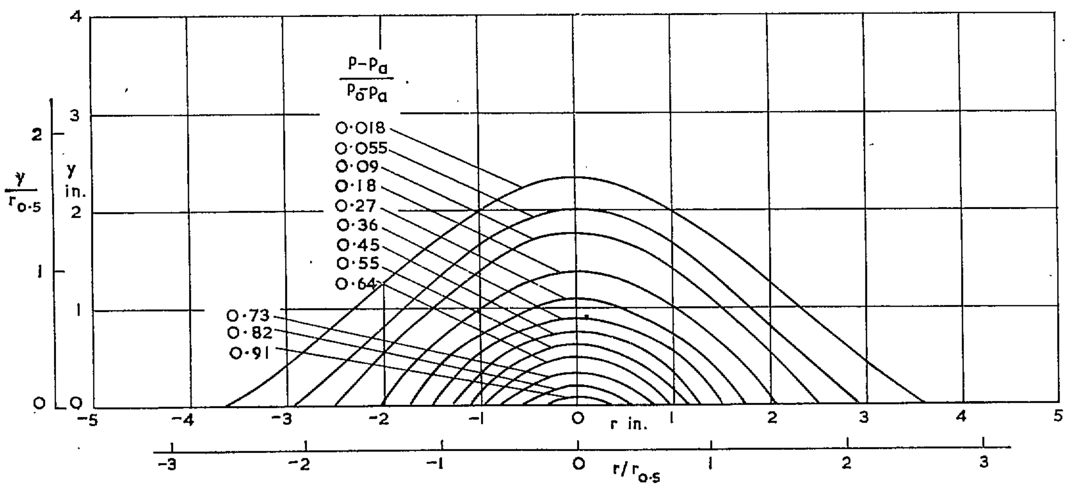

FIG. 4. Static pressure contours.

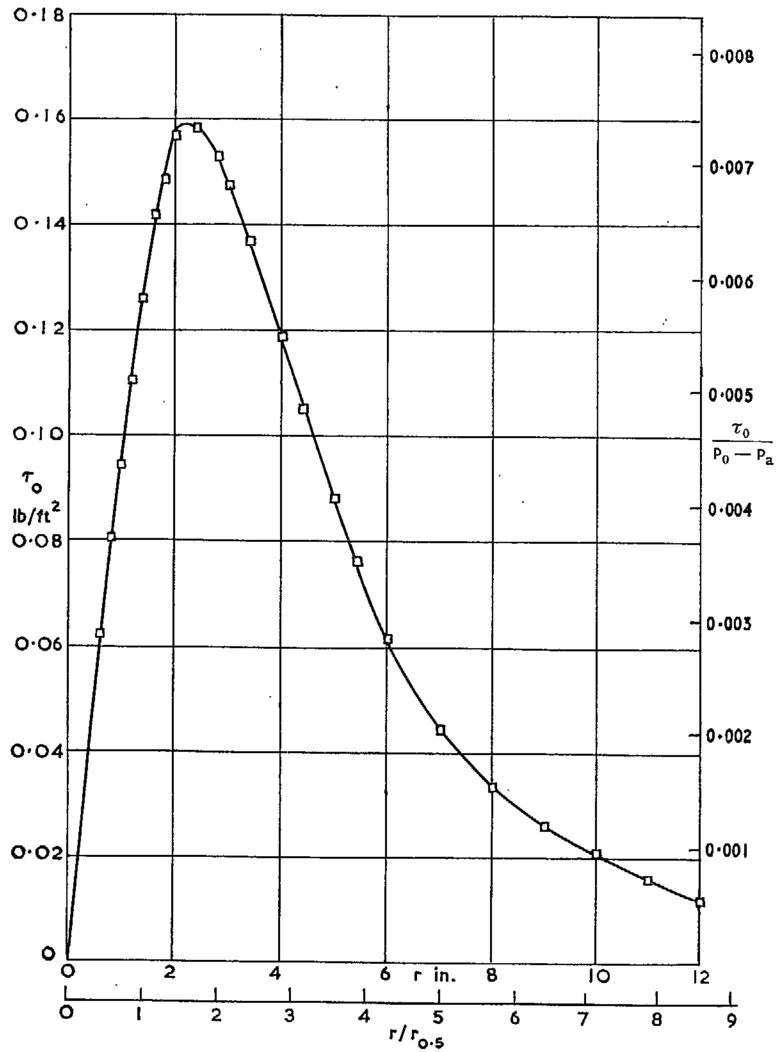

FIG. 5. Skin friction.

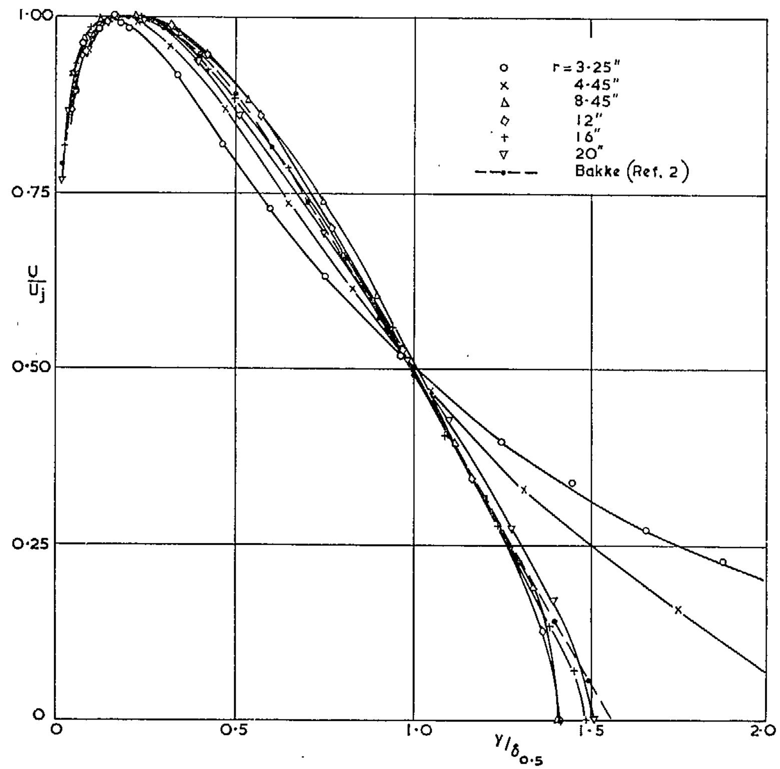

FIG. 6. Wall jet velocity profiles at different radii.

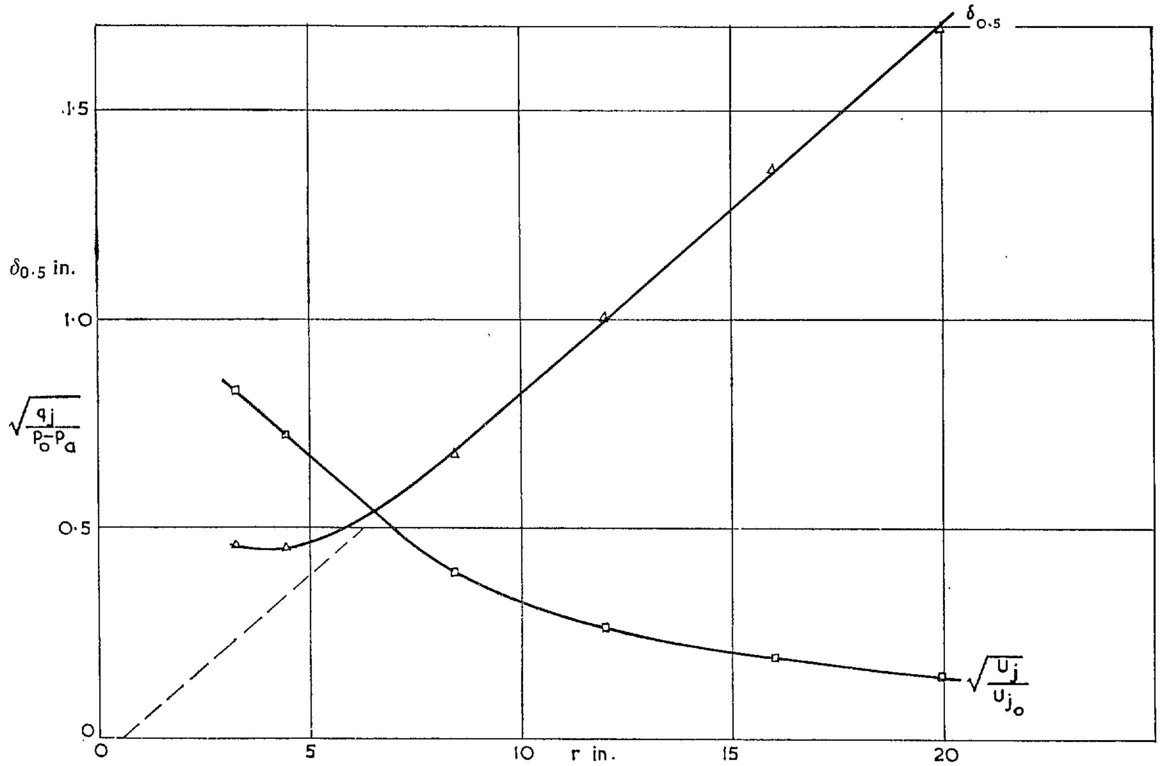

FIG. 7. Radial wall jet velocity and thickness.

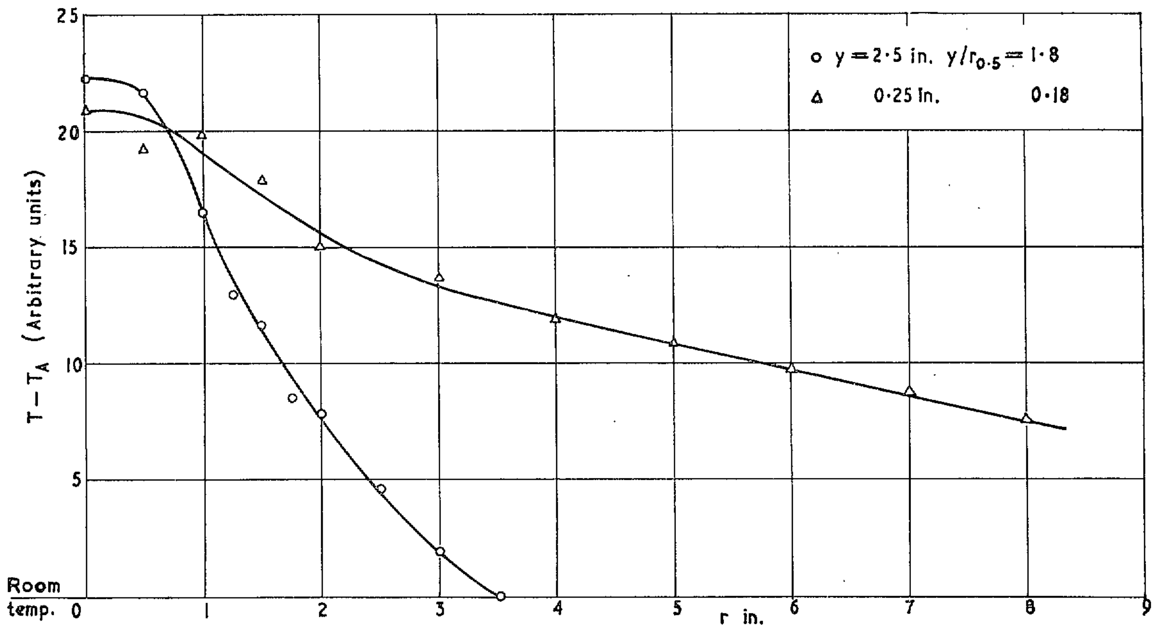

FIG. 8. Variation of temperature across warm jet.

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