An experimental investigation of a wall jet

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Summary

This paper deals with an experimental investigation of a turbulent low-speed jet of air spreading out radially over a flat smooth plate: a flow which has been discussed by Glauert (1956) in his theory of the wall jet.

The aim of the experiments has been to determine the mean velocity distribution and rate of growth of the jet. It is found, within the experimental range and accuracy, that the velocity profiles are similar and that the rate of change of velocity and width of the jet can be expressed by simple power-laws.

1. Introduction

The term 'wall jet' was introduced by Glauert (1956) to describe the flow that develops when a jet, consisting of a fluid similar to that of its surroundings, impinges on a plane surface and spreads out over the surface. Glauert studied such a flow in two dimensions and in three dimensions with axial symmetry, and pointed out that it has features common to both the free jet and the ordinary boundary layer; thus, the spreading fluid is retarded by frictional resistance of the wall and the inner part of the flow may be expected to show a certain structural similarity to a boundary layer, whereas entrainment of quiet fluid occurs near the outer edge of the flow which accordingly is likely to resemble a free jet in character.

This idea of a hybrid structure led Glauert to a solution of the turbulent wall jet by introducing an eddy viscosity distribution near the wall consistent with the Blasius power-law velocity-profile, and a constant eddy viscosity in the outer part of the flow. From this solution, which involved one disposable constant, it was concluded that exact similarity of the flow at all distances x from the origin—the 'point' of impingement of the jet—could not exist, since the eddy viscosities in the inner and outer parts of the flow varied in a slightly different manner with x or, what amounts to the same thing, with Reynolds number. As a consequence, if the local rates of change with x of maximum velocity and jet width are expressed by simple power laws, the exponents of these laws will themselves vary slowly with x. However, it appears from the analysis that for any particular jet the variation is so slow that it would be undetectable experimentally.

The experiments described in this paper were made with a turbulent, round, low-speed jet which spread radially over a smooth, plane surface.

Velocity distributions were measured and, as foreshadowed by the theory, were found to be similar, within the limits of experimental accuracy; they were also consistent with the shape of profile predicted by the theory.

2. Arrangement of the experiment

The experiment arrangement is shown diagrammatically in figure 1. The wall was a flat plate of bakelite 125 cm × 125 cm, placed horizontally on a steel frame.

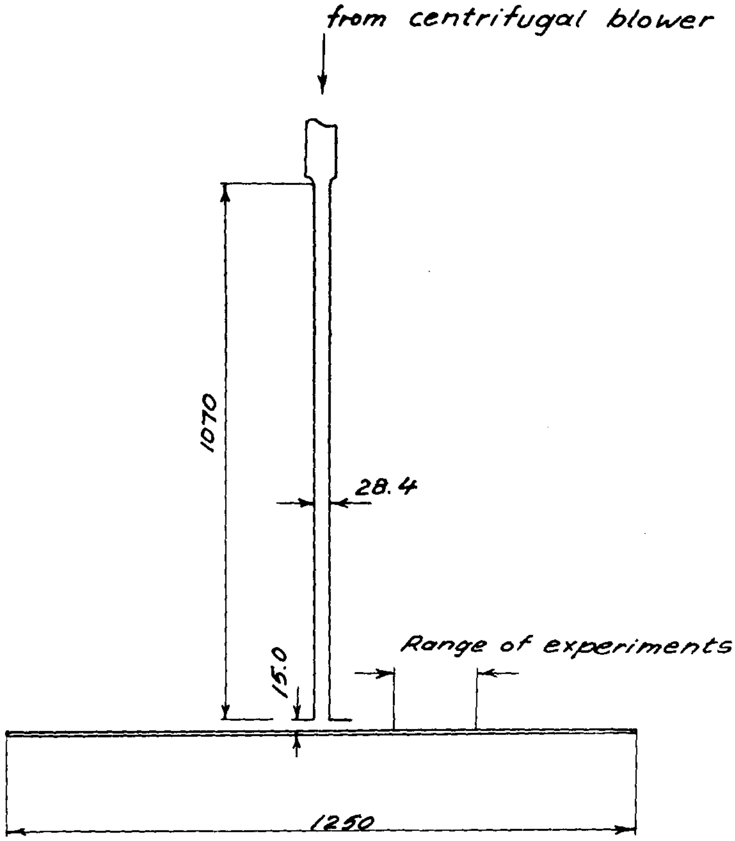

Figure 1. Arrangement of apparatus. All lengths in mm.

The air was supplied by a centrifugal blower connected to a rubber tube of internal diameter 56 mm and length 2·8 m, which terminated, by way of a smooth contraction, in a pipe of 28·4 mm diameter and 1·07 m length. A flange of 126 mm diameter was attached to the end of the pipe. The reason for installing this flange was partly to prevent the generation of large scale disturbances at the pipe exit, and partly to get a closer approximation to the form of source assumed by Glauert. During all experiments the pipe was placed at right angles to the bakelite plate with the exit 15·0 mm above the plate. Preliminary measurements showed a fully developed turbulent velocity profile at the pipe exit with a peak velocity of 34 m/s. With a previous arrangement in which the rubber tube had a 90° bend the velocity profile at the pipe exit was not symmetrical. The deviation was consistent with a secondary flow due to the bending of the tube and disappeared when the rubber tube was straightened.

The velocity distribution along the plate was measured by means of a 1 mm external diameter total-pressure tube connected to a 'Casella' U-tube manometer, the measuring accuracy being 0·01 mm water. The time required to obtain a reading with this accuracy was about 15 minutes.

3. Experiments

The velocity distributions were measured at distances of 143 to 303 mm from the origin. At each station a Pitot traverse was made perpendicular to the plate and the velocities were computed by assuming the static pressure to be atmospheric everywhere. Each of the traverses consisted, on the average, of 20 readings at about 0·3 mm intervals near the wall and intervals of about 1·5 mm in the outer part of the flow. The accuracy of setting the Pitot tube was 0·05 mm.

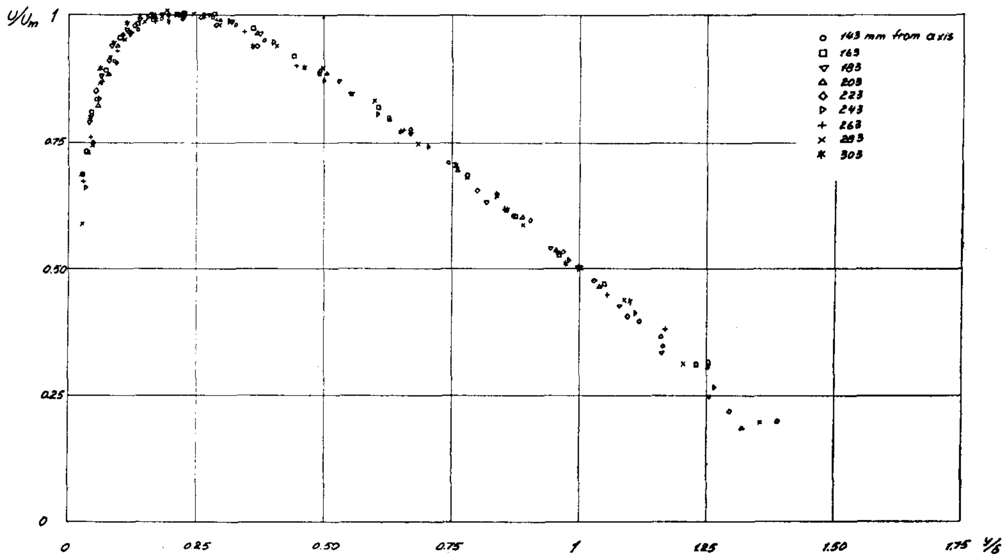

Figure 2. Experimental velocity profiles.

In the range mentioned the maximum velocity varied from 6·10 m/s to 2·60 m/s. The width of the jet, measured from the plate to the point where the velocity had decreased to half the maximum velocity, varied from 11 to 23 mm.

Figure 2 is a dimensionless plot of velocities obtained from nine traverses. The horizontal axis indicates the height y above the plate measured in terms of δ, where $U(\delta) = \frac{1}{2}U_m$ and U_m is the maximum velocity. The vertical axis gives the measured velocities, U, in terms of U_m. Points corresponding to values of U/U_m below 0·2 in the outermost parts of the flow have been omitted. With the previously quoted estimate for the accuracy of a pressure measurement, the percentage velocity error is $7{\cdot}5/U^2$, where U is measured

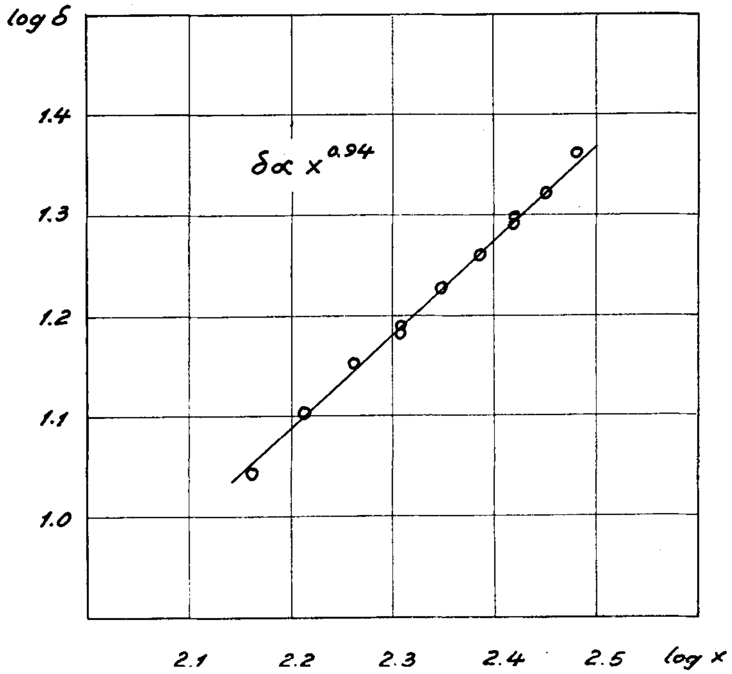

Figure 3. Variation of width of jet with distance from origin.

in m/s. For the largest velocity presented in figure 2, 6·10 m/s, the error is 0·2%; for the smallest velocity, which occurs at the outer edge of the flow at a point furthest from the origin, the accuracy of velocity measurement is 28%. Apart from errors in pressure measurement, there is a source of error at the outer edge where U tends to zero; the transverse inflow velocity tends to a finite value which results in a yawed flow relative to the Pitot tube. A rough estimate indicates that there is no yaw effect at $U/U_m = 0{\cdot}5$, whereas at $U/U_m = 0{\cdot}2$ the true values are of the order 20% less than the plotted ones. The points within a few Pitot-tube diameters from the wall are also subject to error.

Figures 3 and 4 respectively are plots of $\log U_m$ (U_m in m/s) and $\log \delta$ (δ in mm) *vs* $\log x$, where x is the distance from the origin in mm. The simple power laws quoted in the figures correspond to the least-square estimated inclination of a straight line through the points. The estimated accuracy is $\pm 0{\cdot}03$ for $-1{\cdot}12$ and $\pm 0{\cdot}02$ for 0·94.

Returning to figure 2, the experiments show no detectable departures from similarity of the velocity profile. Whether this observation holds for larger distances from the origin was not investigated due to the limitation set by the measuring accuracy of the apparatus.

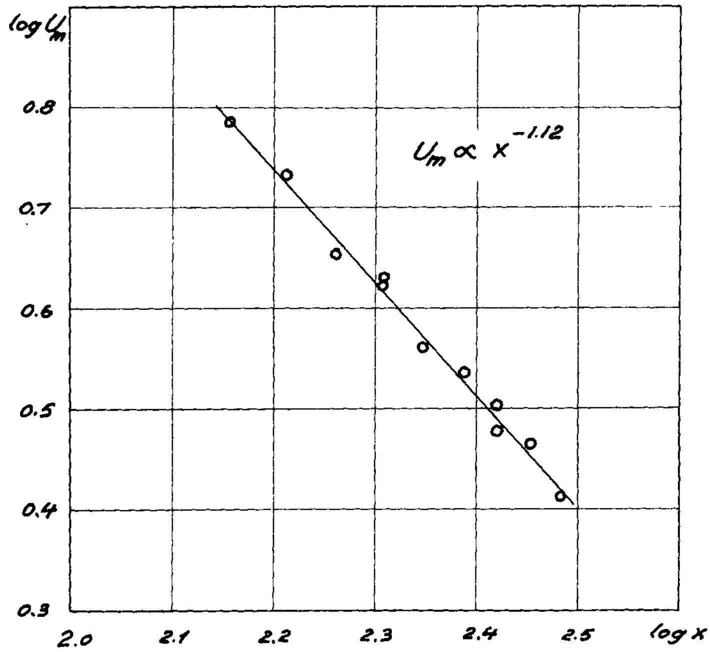

Figure 4. Variation of maximum velocity of jet with distance from origin.

4. Comparison with Glauert's theory

The shape of the velocity profile given by Glauert depends on a single parameter α, which is uniquely related to $\kappa R^{1/4}$. κ is an empirical constant related to the eddy viscosity in the outer layer, and R $(= U_m \delta_t/\nu)$ is the jet Reynolds number, where δ_t, consistent with Glauert's definition, is the distance between the points at which $U = U_m$ and $U = \frac{1}{2}U_m$. The relation between α and $\kappa R^{1/4}$ is given in Glauert's table 1.

Figure 5 shows the experimental profile and Glauert's solution for $\alpha = 1{\cdot}3$ $(\kappa R^{1/4} = 0{\cdot}102)$. This value of α was chosen to give the best agreement with experiment. The jet Reynolds number of the experiment was 3500. This corresponds to $\kappa = 0{\cdot}013$. This figure differs slightly from the value quoted by Glauert, $\kappa = 0{\cdot}012$, which was based on a preliminary experiment at $R = 5000$. The deviation between the experimental velocity profile and Glauert's solution is negligible except at the outer edge. However, this is analogous to the case of a free jet where the assumption of constant eddy viscosity leads to too large velocities in this region. The experimental points closest to the wall are certainly in error, and should be discounted.

Corresponding to $\alpha = 1{\cdot}3$, the predictions given by Glauert's table 1 are that $U_m \propto x^{-1{\cdot}14}$ and $\delta \propto x^{1{\cdot}02}$, whereas the present experiments give for these similarity exponents, $-1{\cdot}12 \pm 0{\cdot}03$ for U_m and $0{\cdot}94 \pm 0{\cdot}02$ for δ. The agreement in the case of U_m is reasonable. For δ on the other hand, Glauert gives values greater than unity for all values of α.

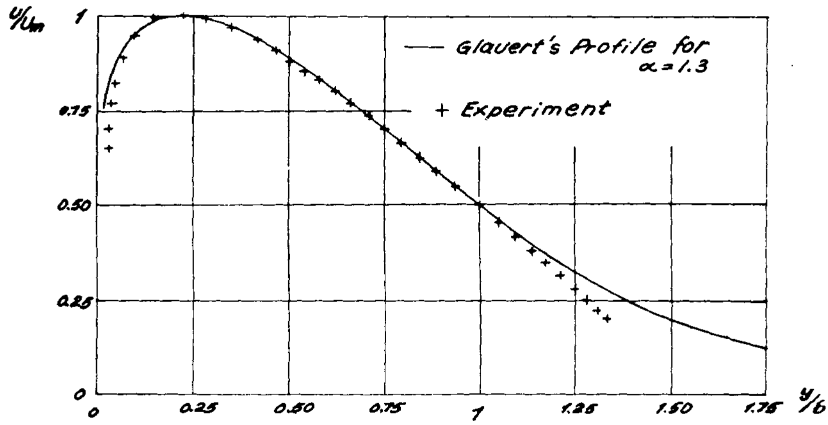

Figure 5. Comparison of M. B. Glauert's theoretical velocity profile and experiment.

In the present experiment the Reynolds number varies as $x^{-0{\cdot}18}$. By Glauert's theory this would increase the value of y/δ at the velocity maximum by 0·003 for x varying from 143 to 303 mm. Considering the experimental accuracy, one could not expect to detect such a small change of velocity profile.

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