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NUMERICAL SIMULATION OF HOT-WIRE BEHAVIOUR IN THE VISCOUS SUBLAYER

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SUMMARY When hot-wire anemometers are used in the viscous sub-layer adjacent to a solid wall an error arises in the velocity indicated by the instrument. This effect is due to the difference between the usually uniform velocity flow in which the hot-wire anemometer is calibrated and the heavily sheared flow with adjacent wall in the viscous sub-layer. Heat transfer from the hot-wire is modified by the presence of the wall and by the effects of the velocity gradient across the cylinder on the flow field.

The most common arrangement of hot-wire anemometer may be modelled as a cylinder normal to the flow direction and parallel to the wall, which permits a two-dimensional model to be used. A Galerkin finite element computer program is employed to calculate the flow fields. Results are presented for a range of Reynolds numbers and range of velocity gradients. The effect of the wall on the flow field is demonstrated by considering both cases in which a solid wall is near the hot-wire and cases in which it is removed.

1 INTRODUCTION

Hot-wire anemometry is the most commonly used technique of aerodynamic velocity measurement and one of its great strengths is the precision with which readings can be taken in the immediate vicinity of boundaries. The calculation of velocities from these readings depends on a knowledge of the effect of the proximity of the wall on the rate of heat loss, as compared with the rate in the free stream in which the hot-wire is calibrated (Zemskaya et al. (1979)). Two cases of changes in the heat flux are suggested: firstly, near a wall the wire is in a strong shear flow and secondly, the wall may act as a large heat sink. Interaction between the two is also probable. There is some disagreement on the empirical behaviour of the necessary corrections: Wills (1962) found it to depend on the ratio of distance from the wall y_w to diameter d and not on Reynolds number Re while Repik and Ponomareva, reported by Zemskaya et al. (1979), found it affected mainly by y_w and Re.

The wall effect on hot-wire measurements is almost confined to the laminar sublayer of the turbulent boundary layer (Zemskaya et al. (1979)) in which the velocity distribution is strictly linear. As part of a combined experimental and numerical programme it is proposed to compute the effects on the heat flux from a hot wire in the laminar sublayer. The thermal effects may be separated into forced convection and heat-driven effects on the flow. As a first step, the isothermal flow around a wire is considered, to give an insight into the effects of the flow on convection from the wire.

The hot-wire is represented by a cylinder normal to the direction of flow and the velocity gradient, and hence parallel to the wall. This yields a two-dimensional flow geometry. It is not possible to consider other wire orientations, such as occur with crossed wires, because of present limitations of computer size.

Isothermal flow near a cylinder with a constant velocity at infinity has been extensively studied, both experimentally and numerically (Prandtl (1927), Apelt (1961)), but computation of flow near a cylinder in a shear flow has been neglected. This may be partly due to problem size: the symmetry of the uniform flow is no longer present. Bretherton (1962) has examined this problem analytically. The contrasting problem of heat flow from a cylinder in uniform unsteady flow has been treated by Apelt and Ledwich (1979).

2 HOT-WIRE ANEMOMETRY NEAR A WALL

Typical measured and expected velocities obtained from hot-wire readings near a wall are shown in Fig. 1, obtained by the second author. The wire diameter d is 5μm, friction velocity u_τ is 0.40m/s and kinematic viscosity is 1.55×10^{-5} m/s. Velocity and distance are nondimensionalised by the expressions

$$u^+ = u/u_\tau \qquad (1)$$

and

$$y^+ = y_\tau u/\nu. \qquad (2)$$

The expected velocity distribution in the sub-layer is

$$u^+ = y^+. \qquad (3)$$

For the arrangement described the wall distance to wire diameter ratio is

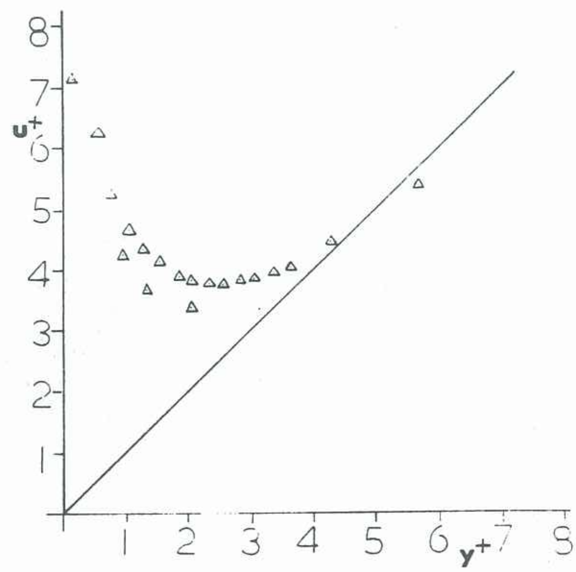

Fig 1. Uncorrected non-dimensionalised velocity measurements with hot-wire anemometer near a wall compared with expected distribution (solid line). Wire 5μm, friction velocity 0.40m/s, overheat ratio 1.8.

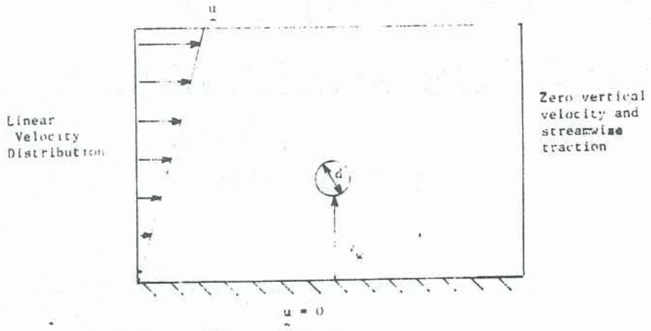

Fig. 2. Computational boundary conditions for cylinder in isothermal shear flow.

$$\frac{y}{d} = 7.75\, y^+ \quad (4)$$

and the Reynolds number based on wire conditions is

$$Re = \frac{y^+}{7.75} \,.$$

The measured and expected velocities are very close for y^+ greater than 5, which corresponds to a distance/diameter ratio of 39. The Reynolds number based on wire diameter and the velocity at the wire is less than 1.

3 COMPUTATIONAL METHOD

The computations were performed with a modified version of the AXFINR program (Nickell et al. (1974)). This is a Galerkin finite element program with quadratic velocity and linear pressure elements, capable of simulating steady Newtonian and non-Newtonian laminar flows up to quite high Reynolds numbers. The geometry and boundary conditions used are shown in Fig. 2: velocity conditions are imposed everywhere except on the downstream boundary, where zero normal traction conditions are imposed. The 18 by 38 element grid has the elements concentrated near the cylinder.

We have computed flows for Reynolds numbers of 0.1 and wall distance to wire diameter ratios of 50, 10 and 5. An additional computation was performed for a strong shear corresponding to a wall distance of 5 but with the wall removed to a distance ratio of 50.

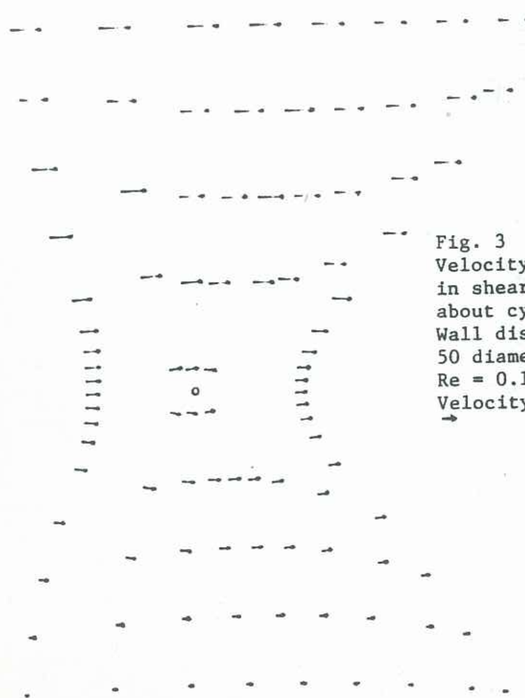

Fig. 3
Velocity vectors in shear flow about cylinder. Wall distance is 50 diameters, Re = 0.1.
Velocity = 1 units.

4 DISCUSSION

A selection of computed velocity vectors for the various situations is shown in Figs. 3, 4, 6, 8, 10. With the wall distance equal to 50 (Fig. 3,4) the shear rate $\frac{\partial u}{\partial y}$ is relatively low. It can be seen that the velocity distribution is fairly symmetrical about the cylinder. The perturbation from a uniform flow past a cylinder is not strong.

Bretherton (1962) concluded that the perturbation velocity in an infinite shear flow past an obstacle should decrease as the two-thirds power of distance. The perturbation velocity in the plane of the cylinder normal to the shear is shown in Fig. 5. For comparison a line inversely proportional to the two-thirds power of distance is also shown. The agreement with the analytic result is good except for one point at intermediate distance.

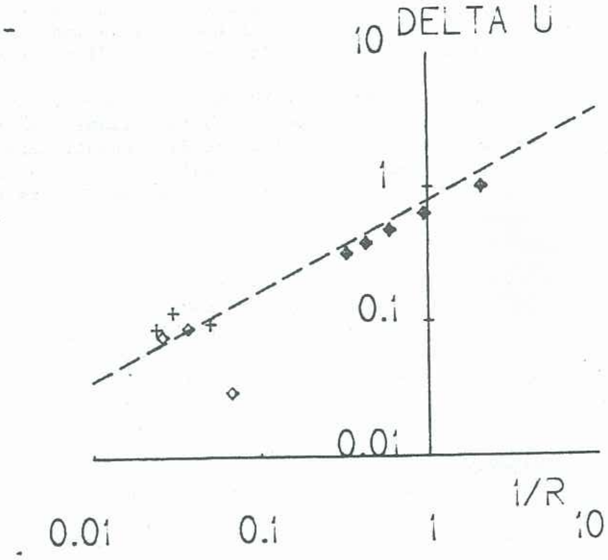

Fig. 5. Perturbation Delta u from free stream shear velocity against distance R from cylinder, in plane of cylinder. Wall distance is 50 diameters, Re = 0.1.
— — $\alpha\ R^{-2/3}$.

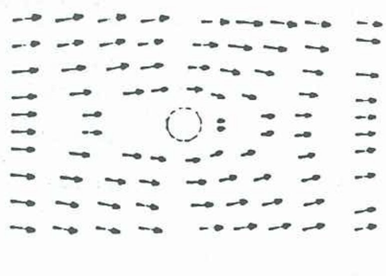

Fig. 4. Velocity vectors in shear flow about cylinder. Wall distance is 50 diameters, Re = 0.1.
⟶ Velocity = 1 unit.

In Fig. 6 the velocity vectors near the cylinder are shown for a wall distance of 10, corresponding to y^+ = 1.29. Although the asymmetry of magnitude due to the shear is apparent, the directions of the vectors are symmetrical. The wake extends directly downstream from the cylinder. The perturbation velocity for this case (Fig. 7) shows considerable divergence from the infinite region analytic model. On the side nearer the wall the perturbation velocity should certainly be low as the no-slip condition forces the perturbation to zero at the wall. The explanation of the high perturbation at large distance away from the wall is not clear.

Velocity vectors near the cylinder for a wall distance of 5, (y^+ = 0.65) (Fig. 9) display considerable asymmetry in both magnitude and direction. On the wall side of the cylinder the wake flow deviates substantially away from the wall, while further out the flow is virtually undeviated from the free stream direction. The wake is substantially diverted away from the wall. The perturbation velocity (Fig. 8) follows the two-thirds power curve only very approximately at large distances away from the wall.

The asymmetry noticeable in Fig. 8 is still more clearly seen in Fig. 9, which is for a flow with the same value of $\partial u/\partial y$ as for a wall distance of 5, but with the walls removed to a large distance. The Reynolds number in this case is 4. The perturbation velocity (Fig. 11) approximately follows the two-third power law.

It is clear that one of the significant aspects of shear flows past cylinders is the deviation of the wake towards the higher velocity fluid. This deviation increases with the free-stream shear rate. The non-dimensional free-stream shear rate increases with proximity to the wall but that proximity also tends to partially suppress the wake deviation.

The deviation of the wake towards the higher velocity flow provides a partial explanation of the velocity error encountered with a hot-wire anemometer near a wall. Convection away from the cylinder will occur at a rate appropriate to a velocity greater than that at the cylinder position and will cause the heat loss to

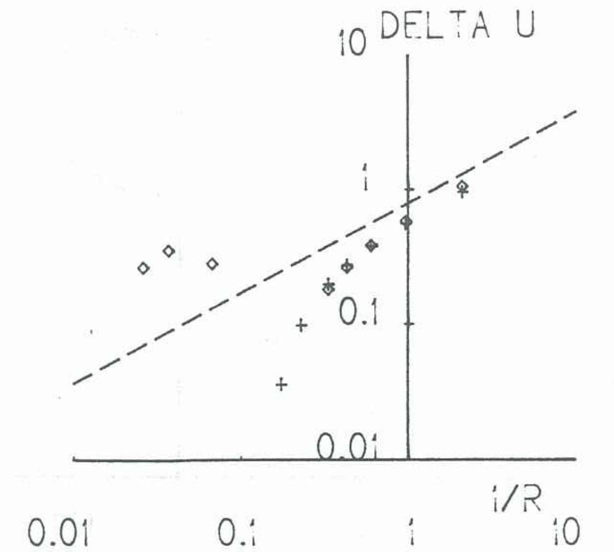

Fig. 7. Perturbation Delta u from free stream shear velocity against distance R from cylinder, in plane of cylinder. Wall distance is 50 diameters. Shear rate equivalent to wall distance 5 diameters.
Re = 0.1. — — $\alpha R^{-2/3}$

be larger than expected for a uniform stream of the same velocity. The effect will increase with shear rate, that is, inversely as the distance to the wall. However, this mechanism is not sufficiently strong to fully explain the errors that occur, as the deviation of the wake is not marked at a wall distance of 10 (y^+ = 1.29) where the heat loss difference is quite substantial. It would appear that heat transfer from a cylinder is also substantially affected by modifications to the isothermal flow pattern, most probably caused by variation in material properties, and possibly by heat loss through the wall.

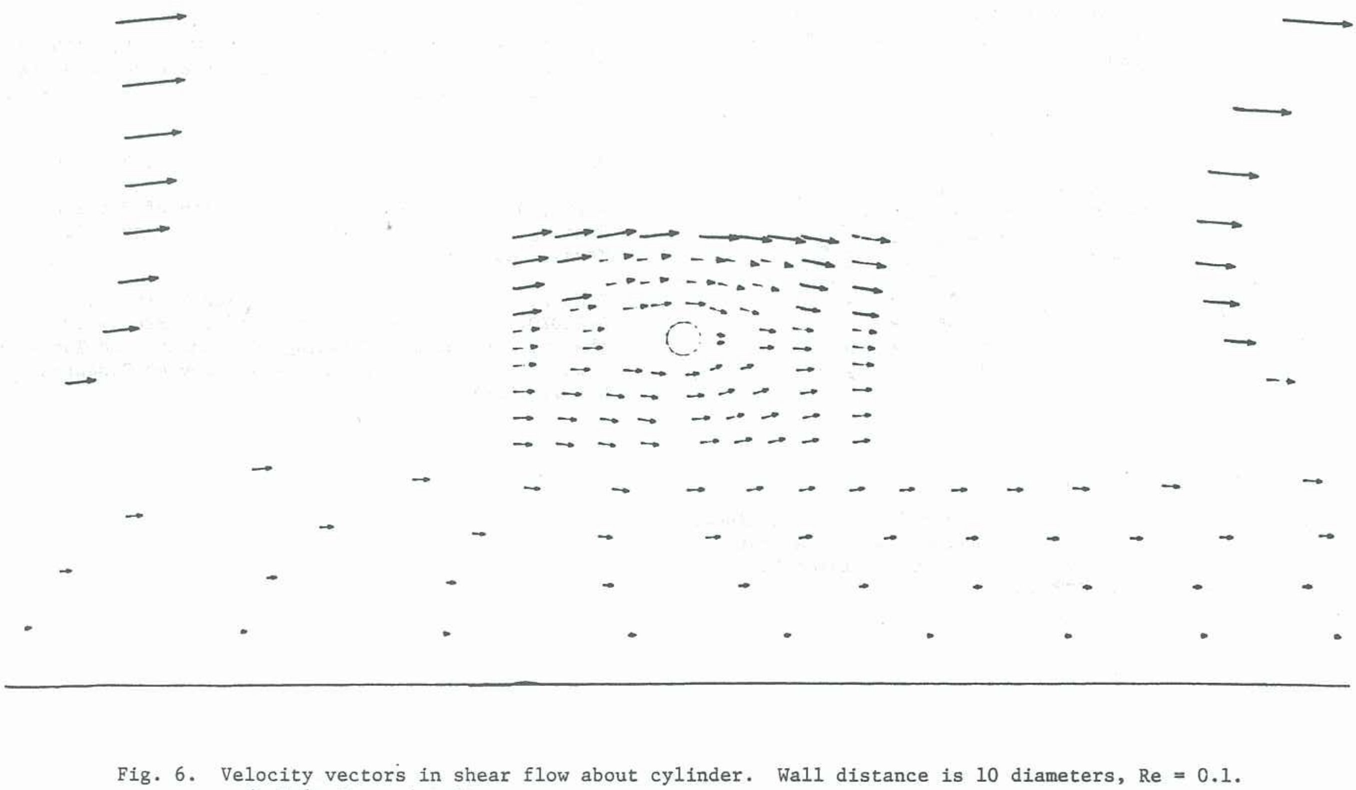

Fig. 6. Velocity vectors in shear flow about cylinder. Wall distance is 10 diameters, Re = 0.1.
⟶ Velocity = 1 unit.

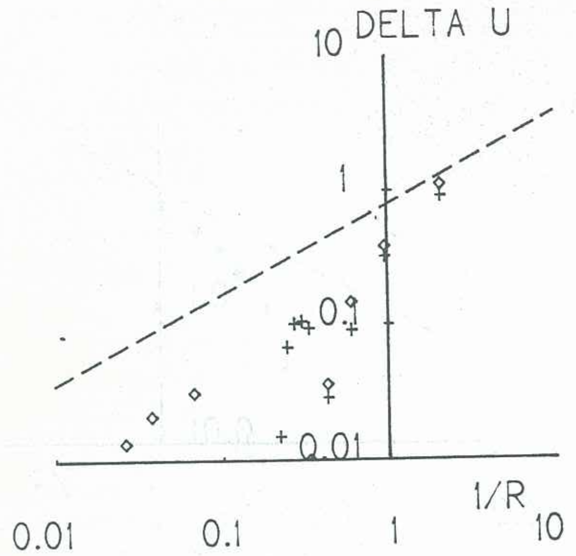

Fig. 8. Perturbation Delta u from free stream shear velocity against distance R from cylinder, in plane of cylinder. Wall distance is 5 diameters. Re = 0.1 — — $\alpha R^{-2/3}$.

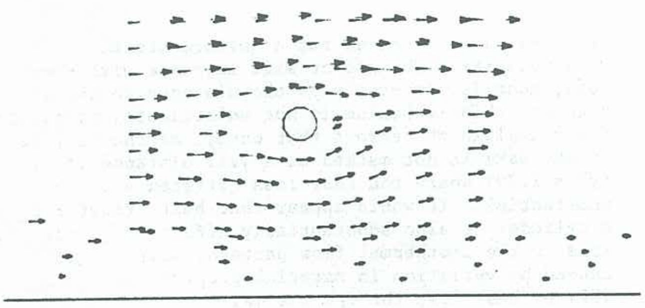

Fig. 9. Velocity vectors in shear flow about cylinder. Wall distance is 5 diameters. Re = 0.1. ⟶ Velocity = 1 unit.

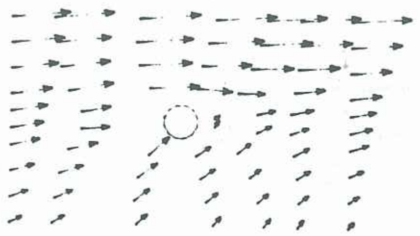

Fig. 10. Velocity vectors in shear flow about cylinder. Wall distance is 50 diameters. Shear rate equivalent to wall distance 5 diameters. Re = 4.0. ⟶ Velocity = 1 unit.

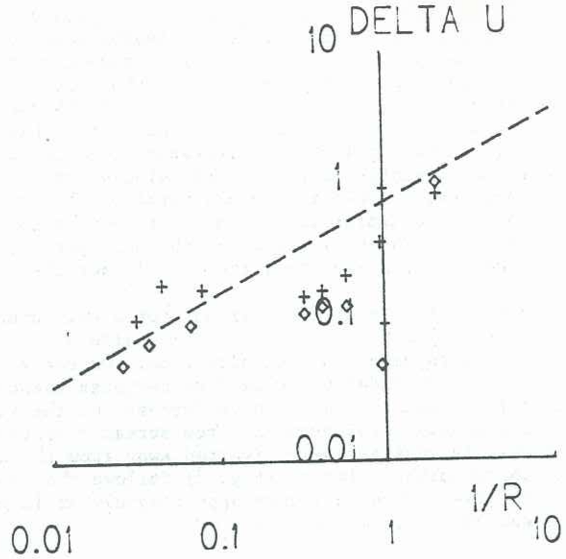

Fig. 11. Perturbation Delta u from free stream shear velocity against distance R from cylinder, in plane of cylinder. Wall distance is 50 diameters. Shear rate equivalent to wall distance 5 diameters. Re = 4.0. — — $\alpha R^{-2/3}$.

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