TECHNICAL NOTE

Measurements of turbulent developing flow in a moderately curved square duct

M. M. Enayet, M. M. Gibson and M. Yianneskis*

Laser–Doppler measurements in the turbulent flow in a right-angled bend of square cross-section, radius/duct-width ratio 7.0, are presented and show the development of secondary circulation in cross-stream planes. Distributions of the streamwise and radial components of the mean velocity and turbulence intensity, and the corresponding Reynolds shear stress, are presented as contour plots and are intended for use in the further development of numerical flow prediction methods

Key words: *flow measurement, turbulence, ducting*

This note is a postscript to the longer and more detailed account of laser–Doppler measurements of laminar and turbulent flow in a strongly curved pipe bend[1]. Measurements are reported here of turbulent flow in a more moderately curved bend of square cross-section which were made using the same experimental arrangements and instrumentation as previously[1]. A principal objective of this research has been the recording of basic data suitable for testing numerical calculation methods; in addition, the flow exhibits a number of interesting features.

Detailed measurements of the flow in strongly curved bends[1–4] show that the main secondary motion develops over an appreciable distance and that it is more complicated than originally expected or suggested by the idealized diagrams of the textbooks. Investigations of laminar and turbulent flow in right-angled bends of square section have been carried out[2–4], and the effects of changes in inlet conditions have been established[4]. Details of the flow in an equivalent round bend have been published[1] and these studies recently have been extended to flow in an S-bend of moderate curvature[5]. This note contains the results of similar measurements in turbulent flow in a right-angled square bend of lesser curvature, with a radius/duct-width ratio of 7.0 compared to that of 2.3 in the previous experiments.

Experimental

The geometry and dimensions of the test bend are shown in Fig 1. It was manufactured from 20 mm thick perspex with a cross-section of 40×40 mm^2. The curved surfaces were machined from solid perspex to radii of 260 and 300 mm. The tolerance on each of these dimensions was ±0.1 mm. The bend was fixed in the horizontal plane at the end of a straight duct 300 mm long and discharged into another straight duct 200 mm long. The complete assembly was attached to the water flow rig described previously[1]. The bulk velocity was 0.88 m/s giving a Reynolds number based on the bulk velocity and duct width of 35 200. The boundary layers in the bend inlet plane were turbulent and ≈0.14 duct widths thick. Measurements were made in the 45°

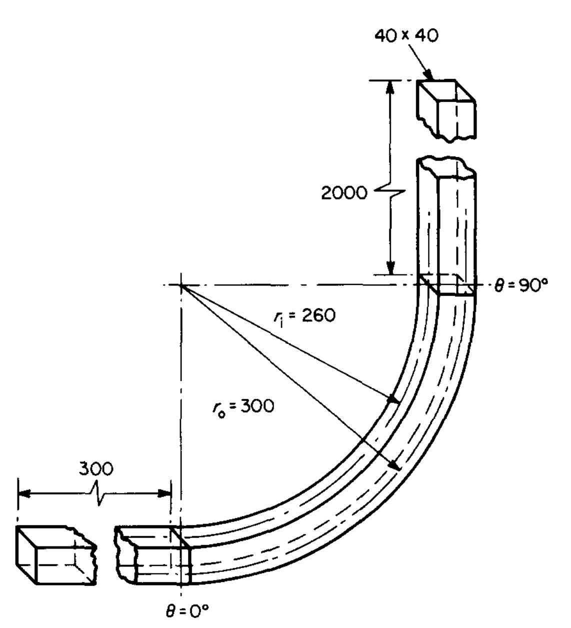

Fig 1 Duct bend geometry (dimensions in mm)

* Mechanical Engineering Department, Imperial College of Science and Technology, Exhibition Road, London, UK, SW7 2BX
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Notation

r_i	Inside radius of curvature of bend
r_0	Outside radius of curvature of bend
U	Circumferential component of mean velocity
U_B	Bulk viscosity
V	Radial component of mean velocity
u', v'	rms fluctuating velocity components
$\overline{uv}$	Reynolds shear stress
θ	Angle subtended at centre of curvature

and exit (90°) planes, the optical axis being vertical. Measurements in the inlet plane were made with an 'S'-bend fitted to the rig as reported previously[5]. The laser–Doppler anemometer system and associated equipment have been fully described elsewhere[1].

Results and discussion

The results consist of the streamwise and radial mean velocity components U and V, the corresponding turbulence intensities u' and v' and the Reynolds shear stress $\overline{uv}$. Measurements in the inlet plane for a Reynolds number of 40 000 were made by Taylor *et al*[5] when an 'S'-bend was fitted to the water rig. It is assumed that the inlet conditions do not differ significantly in the present bend flow and the data from Taylor *et al*[5] are reproduced in Fig 2. These show reasonably uniform inlet boundary layers with an appreciable potential core. The radial component of the mean velocity, which is not presented, never exceeded $0.07U_B$ and the shear stress levels, also not presented, appear to be consistent with the intensities, but the boundary layers were too thin for more detailed measurements of the cross-correlation in the high shear regions adjacent to the walls. The measurements in the 45° and exit planes (Figs 3–7) may usefully be compared with the equivalent data[3,4] from the more strongly curved bend. As in these previous experiments, the flow responds in two ways to the imposition by the bend of a radial pressure gradient. Initially, the peak velocity in the core moves towards the inside of the bend as required for radial equilibrium in the centre, but further downstream the development of secondary flows results in a shift of this peak to the outside region. Both these effects are very evident in the tight bend flow[3,4] but the former is not apparent in the measurements made here where the transverse pressure gradients are considerably smaller and less influential. The secondary flows, the presence of which is evident in the mean velocity contours at 45°, effectively displace the velocity maximum to the outside of the bend and result in an accumulation

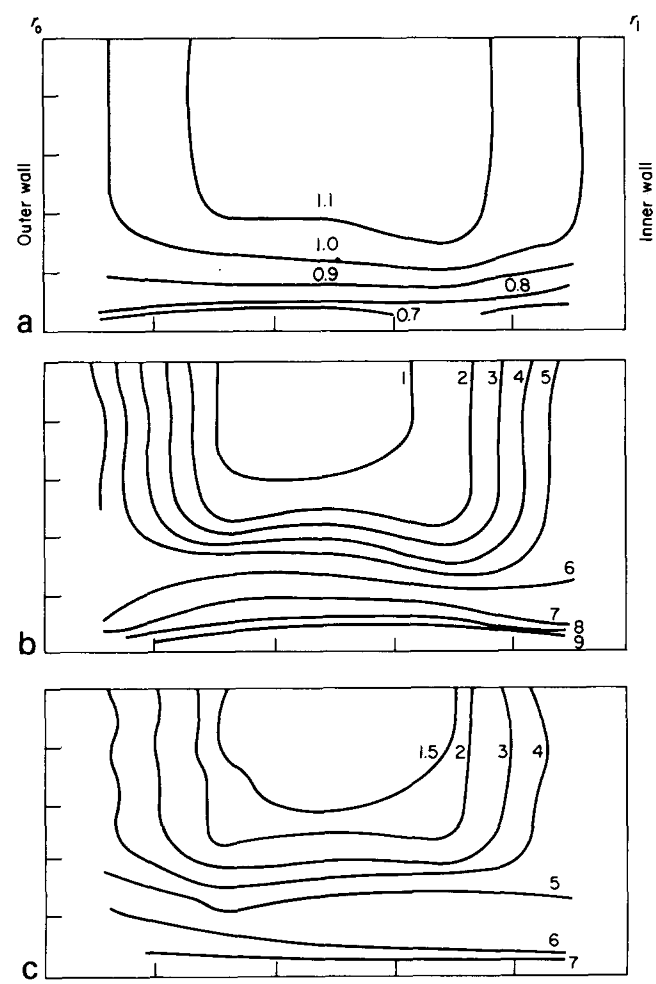

Fig 2 Contours of mean velocity and rms turbulence intensity in the inlet plane: (a) U/U_B *(b)* $u'/U_B \times 10^2$ *(c)* $v'/U_B \times 10^2$. *(Data from Taylor* et al[5]. Re = 40 000)

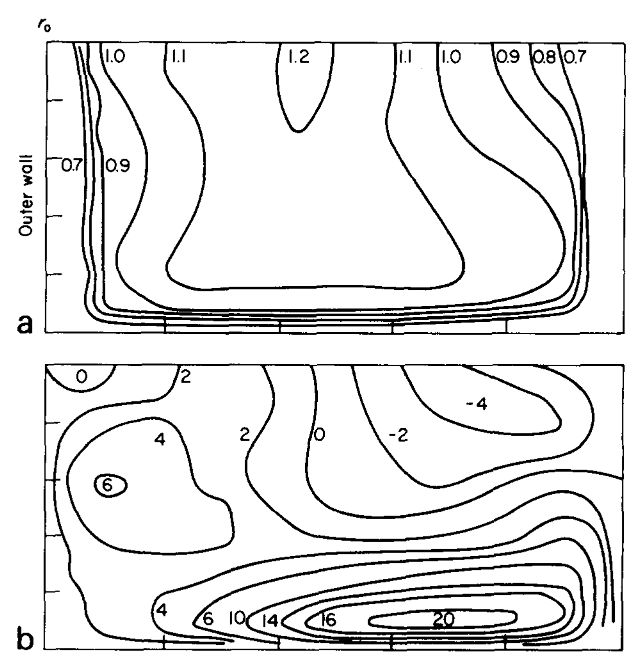

Fig 3 Contours of mean velocity in the 45° plane: (a) U/U_B *(b)* $V/U_B \times 10^2$

of slow moving fluid on the inner wall. The inward flows at the side-walls ensure that the boundary layers there remain thin. As the flow approaches the bend exit it is accelerated on the outer wall and retarded on the inner one. The adjustment to rectilinear flow is rapid: the measurements in Fig 4 show that in the exit plane the transverse mean velocities have decreased to approximately half their values at 45° while the much distorted contours of U simply record the history of the flow. Profiles of the transverse component V, plotted in Fig 5, show strong inward flow in the inner part of the duct and also suggest the presence of a weak secondary circulation of the opposite sense in the outer part of the duct. These circulations presumably arise from the destabilizing action of concave curvature on the outer wall boundary layer and persist because the curvature is sufficiently mild for it not to be swept into the main pressure-driven secondary motion of the opposite sense.

Contours of the rms turbulence intensities u' and v' and the Reynolds shear stress $\overline{uv}$ are plotted in Figs 6 and 7. The distortion of the nearly symmetrical inlet contours, Fig 2, is very evident and generally consistent with the development of local high shear zones in the mean flow. The high levels of v' measured near the inner corner in the exit plane are rather surprising and in contrast with the strong curvature results[3,4] where peak values of v', of the same order as u', were distributed in the outer part of the exit plane. The shear stress plots contain less detail but generally show higher levels near the inside of the bend consistent with high shear and turbulence activity there. There appears to be no evidence of significant damping or amplification of turbulence due to longitudinal curvature as observed in the strongly-curved bend[3] and the position of zero shear stress coincides approximately with that of the maximum mean velocity.

Conclusions

The measurements show the development and decay of cross-stream flows in a 90° moderately curved bend. The flow behaviour is consistent with that previously observed in more strongly curved bends and differences in the details of the two flows are accounted for by the differences in curvature: here, the secondary cross-stream velocities are only one half of those measured in the strongly curved bend. The results are seen as a contribution to the data base available to developers of turbulence models and computer flow prediction methods.

Acknowledgement

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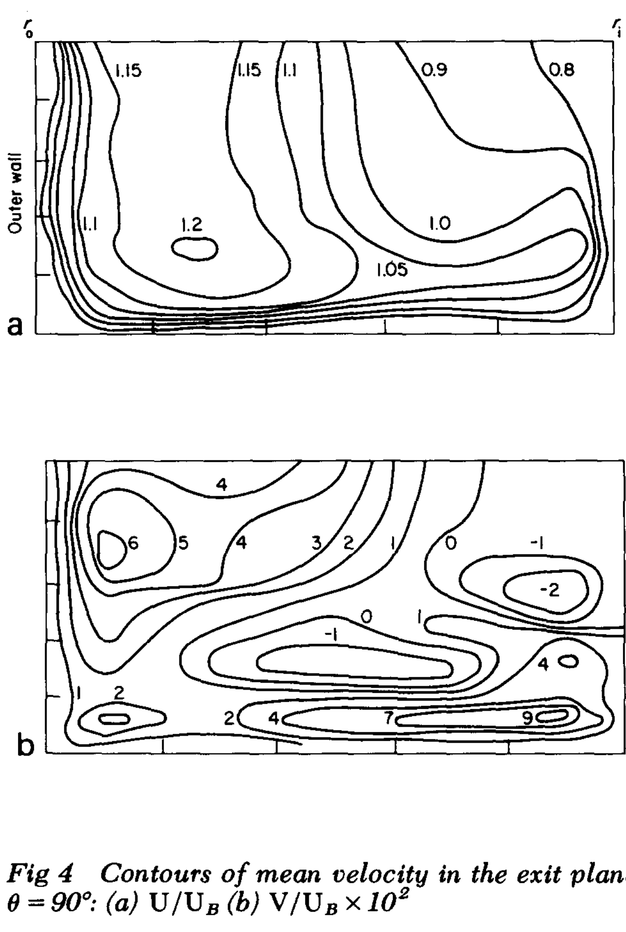

Fig 4 Contours of mean velocity in the exit plane, $\theta = 90°$: (a) U/U_B (b) $V/U_B \times 10^2$

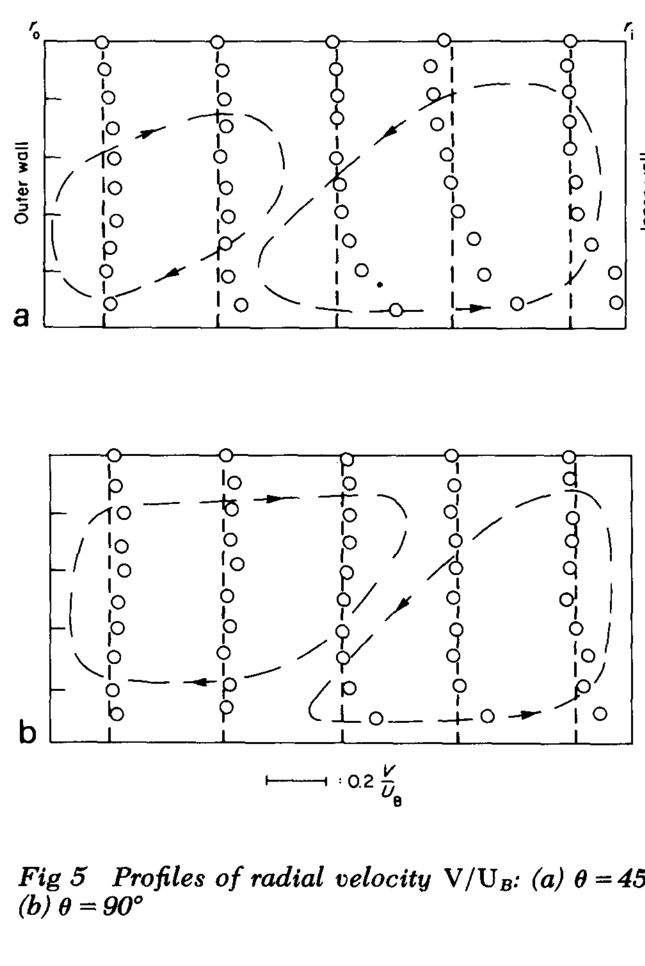

Fig 5 Profiles of radial velocity V/U_B: (a) $\theta = 45°$ (b) $\theta = 90°$

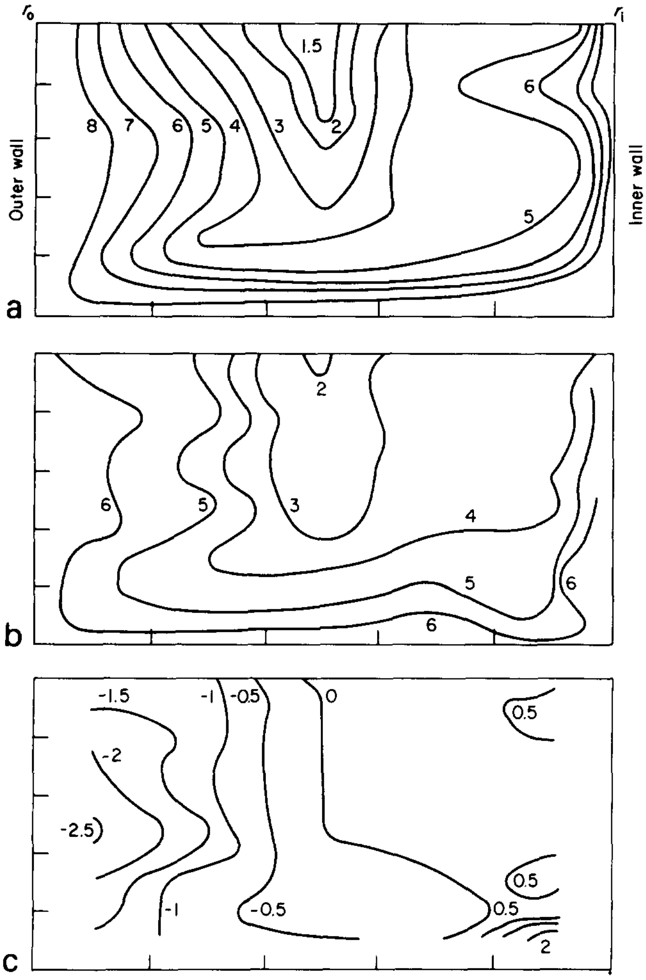

Fig 6 Turbulence measurements in the 45° plane: contours of (a) $u'/U_B \times 10^2$ *(b)* $v'/U_B \times 10^2$ *(c)* $\overline{uv}/U_B^2 \times 10^3$

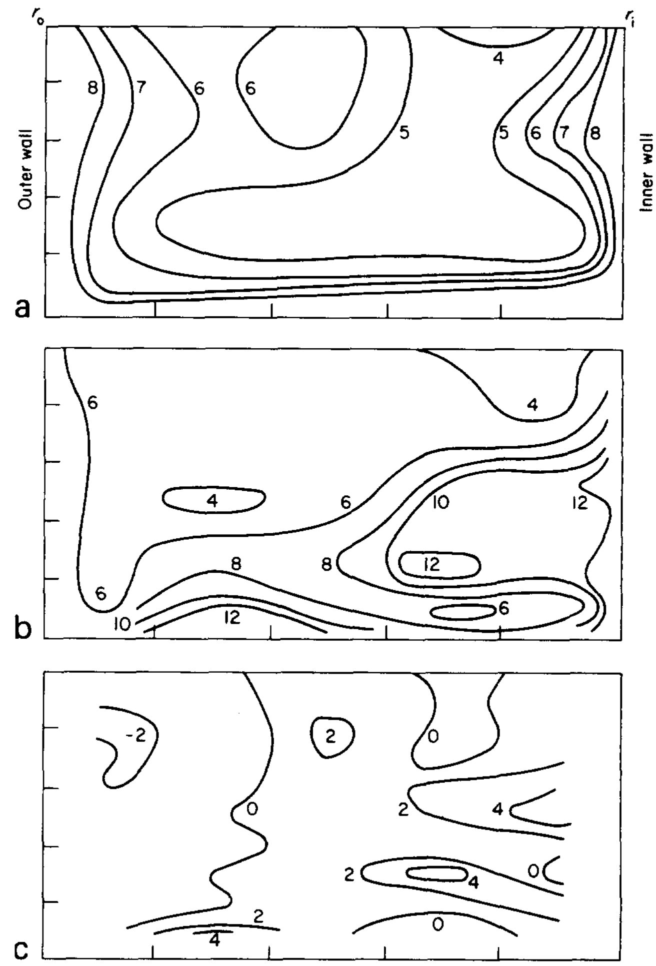

Fig 7 Turbulence measurements in the exit plane: contours of (a) $u'/U_B \times 10^2$ *(b)* $v'/U_B \times 10^2$ *(c)* $\overline{uv}/U_B^2 \times 10^3$

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