# MEASUREMENT OF REYNOLDS STRESSES IN DUCT FLOW BY HOT-WIRE ANEMOMETRY

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## Introduction

The determination of all components of the Reynolds stresses for turbulent in-line single phase flow through complex cross-section ducts is a major experimental task, even if limited to the developed flow region. The system outlined in this paper used hot-wire anemometry for the turbulence measurements, with fully automated probe traversing, signal processing and rig control by a PDP computer. The time required for a fixed Reynolds number study of the developed flow region was reduced from months, when manually performed, to continuous operation and completion in several days.

The automated system significantly improved the accuracy of the Reynolds stress measurement, by continuously monitoring the hot-wire probe performance. Changes in the small-signal sensitivity of the hot-wire sensors could readily be detected. A constant duct Reynolds number was maintained by monitoring the ambient air temperature and pressure, and by resetting the rig operating point to a new reference axial pressure drop when significant changes occurred.

## Experimental Method

The duct mean axial velocity distribution was determined by pitot probe traverse, and the velocity data stored in reference files. The computer stored reference velocity profiles are to be scaled by

$$U(x,y) = U_r(x,y)\ (\upsilon/\upsilon_r) \qquad (1)$$

to determine the local mean velocity when subsequently using hot wire probes. The selected rig axial pressure drop is calculated by

$$\Delta p = \Delta p_r . (\rho/\rho_r) . (\upsilon/\upsilon_r)^2 \qquad (2)$$

in order to maintain a constant duct Reynolds number. The kinematic air viscosity is $\upsilon$, and subscript r refers to the reference mean velocity study.

A simple form of hot wire correlation (1) was selected, with the bridge voltage E of a wire normal to the mean flow U given by

$$E^2 = E_o^2 + B\ U^n \qquad (3)$$

where both B and n are functions of the mean velocity. The inclined wire response is given by

$$E_\alpha^2 = E_{o\alpha}^2 + B\ U^n \cos^m(\alpha) \qquad (4)$$

where $\alpha$ is the angle between the normal to the wire and the mean velocity. Davies and Davis [1] and Bruun [2] have shown that the functional relationship of the indicies m and n with velocity is constant for a limited range of probe slenderness ratios, wire material and probe overheat ratios if the sensor is isolated from the probe support forks. A standard single inclined wire and single normal wire probe was developed, using 2 mm long 5 μm tungsten wire sensors, which were isolated from the support forks by 2 mm of copper plating.

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The use of equation (4) for the inclined wire response, rather than the correlations developed by Champagne et al. [3] which use an optically measured angle, requires that a yaw calibration be made to determine $\alpha$. The inclined probe is yawed to known angles $\beta$ in a low turbulence intensity parallel air jet at the same mean velocity as the experimental duct, and the effective inclined wire angle $\alpha$ calculated from

$$\alpha = \tan^{-1} \left[ \cot\beta - \mathrm{cosec}\beta . \left[ \frac{E_{\alpha+\beta}^{2} - E_{o\alpha}^{2}}{E_{\alpha}^{2} - E_{o\alpha}^{2}} \right]^{\frac{1}{m}} \right] \quad . \tag{5}$$

Twelve individual estimates of $\alpha$, using $\beta$ in the range $\pm$ 15°, defined the effective probe angle $\alpha$ to a standard deviation of 0.5°.

The use of small signal expansions of the unlinearised probe steady state response equations (3) and (4), to calculate the Reynolds stresses, has been shown by [4] to generate Reynolds stress distributions in developed axi-symmetric pipe that are in close agreement with accepted data. Several redundant measurements were made by taking the normal and inclined wire signal variance, and the covariance of the signal cross-product, in a normally 7 segment axial probe rotation sequence. The probe was rotated in 45° increments, and the redundant equations used to test the accuracy of the small signal approximations.

The axial component of the Reynolds stress is

$$\overline{u^2} = 4\, E^2\, U^2/(n^2(E^2 - E_o^2)^2) \,.\, \overline{e^2} \tag{6}$$

and application of the inclined wire equation

$$(u + m/n \tan(\alpha)\, v)^2 = \overline{e_\alpha^2} \,.\, 4\, E^2\, U^2/(n^2(E_\alpha^2 - E_{o\alpha}^2)^2) \tag{7}$$

to five rotation positions determines the six Reynolds stresses.

## Duct Measurements of Mean Velocity and Reynolds Stresses

In conclusion, a study simulating the fluid dynamics of a single phase coolant in a power reactor core is presented. The flow was fully developed (i.e. the axial derivative of the data presented is zero), and symmetry was used to further limit the measurement area shown in the duct cross section, figure 1. The axial mean velocity (fig. 2 (a)) is normalised by the average velocity for this area, the turbulence intensities (figs. 2 (b), (c) and (d)) by the mean wall friction velocity, and the Reynolds shear stresses (figs. 2 (e) and (f)) by the mean wall shear stress. Approximately 450 data points (about 150 hours of measurement) were used to generate these contour plots [5], with the experimental time being reduced by a factor of approximately fifty when compared to manual operation.

## References

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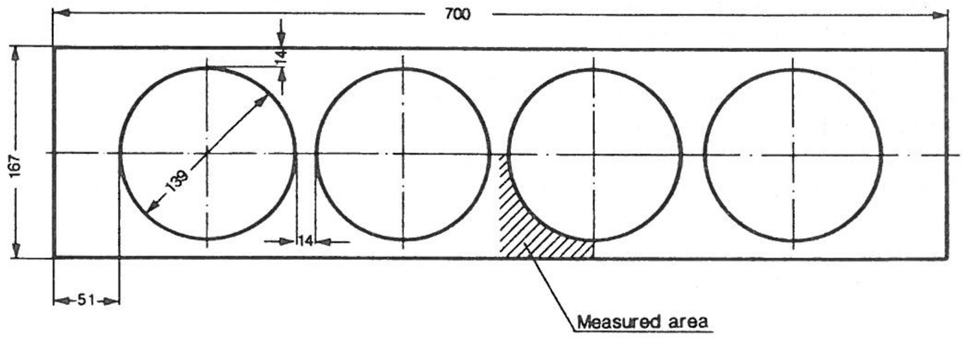
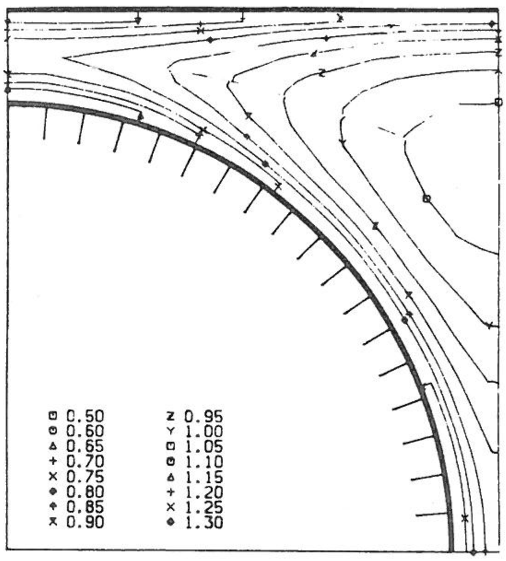



Figure 1: Cross-section of duct.



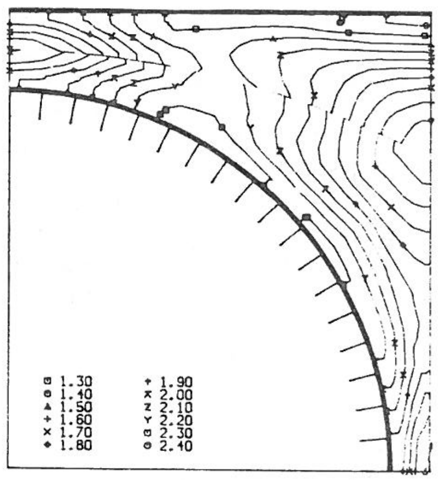




Figure 2: (a) Mean axial velocity (b) Axial turbulence intensity

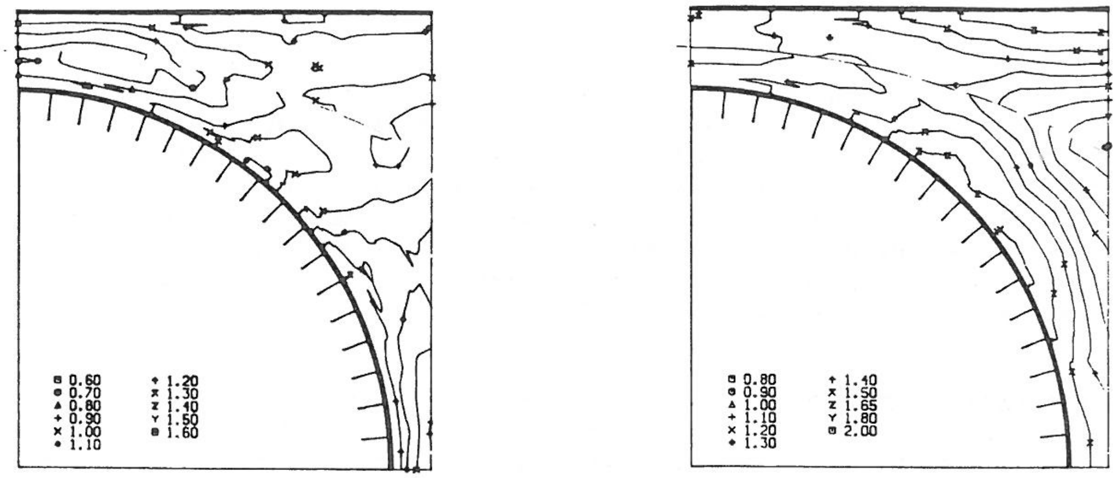



Figure 2: (c) Radial turbulence intensity. (d) Azimuthal turbulence intensity.

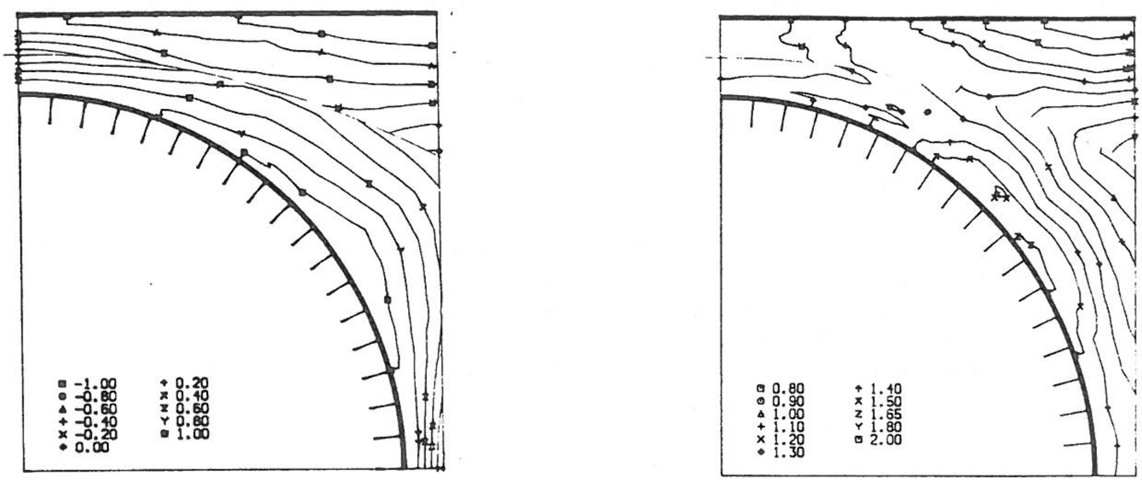



Figure 2: (e) Radial Reynolds shear stress. (f) Azimuthal Reynolds shear stress.