THE INFLUENCE OF REYNOLDS NUMBER AND A GRADIENT CORRECTION METHOD FOR FIVE-HOLE PRESSURE PROBES

by

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ABSTRACT

The influence of Reynolds number on the calibration characteristics of a conical five-hole probe has been tested in a closed wind-tunnel. The calibration was performed at three Reynolds numbers for the Mach numbers 0.6 and 0.8. The results indicated that the probes have to be calibrated at both correct Reynolds and Mach numbers for accurate measurements.

A numerical method for correcting measuring errors due to pressure gradients has been developed. The basis for this method involves calculating the distances of the sensing holes to an imaginary streamline through the centre hole of the five-hole probe. The method was tested by measuring a cylinder wake at the Mach number 0.7.

INTRODUCTION

For investigating the influence of Reynolds number on conical five-hole probes, systematic tests have been performed in a closed wind-tunnel circuit where the Reynolds number could be varied.

In the same test rig a cylinder wake was measured to verify the usefulness of a new method for gradient correction. The method will be presented in the later part of this paper.

TEST EQUIPMENT

Wind-tunnel

The test equipment is shown in Fig. 1. The five-hole probe was calibrated in a pipe flow. The inner diameter of the measuring pipe was 163 mm. In the closed wind-tunnel circuit the density of the air and thus the Reynolds number could be varied.

The probe was mounted in the measuring pipe so that the tip of the conical body remained at the same point in the flow at all angles of yaw and pitch. The static pressure was measured from four wall-static tappings in the measuring cross-section.

Five-hole probe

For the tests a conical type of five-hole probe was chosen that can be used in turbomachines, Fig. 2. The stem of the probe was relatively thick in order to avoid deformations at high speeds. Two variants with different types of sensing holes were investigated. The same probe had as variant 1, holes of 0.6 mm in diameter in the axial direction, and as variant 2, holes of 0.2 mm bored at right-angles to the conical surface.

Definitions

The definition of the two angles for the flow direction in the xyz-coordinates of the probe is given in Fig. 3. The z-axis is in the direction of the stem. The angle α (yaw) lies in the xy-plane and the angle β (pitch) is defined in the cz-plane where c is the vector of velocity. This definition is the most practical for the calibration of the probe. In Fig. 3 the positive angles α and β are drawn, and the numbering of the holes given.

CALIBRATION OF THE FIVE-HOLE PROBE

Reynolds number

The five-hole probe was calibrated for three Reynolds numbers between 18600 and 63300 referring to the diameter of the conical body, by constant Mach number. The density of the air in the wind tunnel was varied by changing the pressure level. The highest pressure level was obtained when the wind-tunnel circuit was opened against the atmosphere on the pressure side of the compressor; a middle pressure level by opening on the suction side; and the lowest one by evacuating the circuit with an auxiliary compressor. In this way it was possible to vary the Reynolds number and still having identical test- and measuring devices.

Mach number

The calibration was performed at the Mach numbers 0.6 and 0.8. The Mach number was regulated with the aid of the total pressure in the settling chamber, this being measured by a pitot tube, and the static pressure in the measuring cross-section, which was the mean pressure from four wall tappings. The measurements were performed with 25 different flow directions. The turbulence level was 0.9...1.0 perc. by Ma = 0.6 and 1.4...1.6 perc. by Ma = 0.8.

RESULTS

To get comparable quantities, a dimensionles pressure ψ was calculated with the dynamic pressure as unit:

$$\psi_i = \frac{p_t - p_i}{p_t - p} \qquad i = 0...4 , \qquad (1)$$

The pressure p_i is the measured pressure in hole i. The Figures 4...11 are shown as examples ψ_1 and ψ_3 for both variants of the probe. The results are presented in detail in Ref. 1.

The greatest difference obtained by the variant 1 at the three Reynolds numbers was $\Delta\psi$ = 0.074, which was measured for ψ_2 at Ma = 0.6 and $\alpha = 20^0$, $\beta = -20^0$. The influence of Reynolds number was of the same magnitude by the variant 2 except for hole 3, see Fig. 10 and 11. It was noticed, that the hole 3 had partially broken edges. This caused the greatest measured difference of $\Delta\psi$ = 0.148.

Dynamic pressure

The dynamic pressure will be determined with aid of the pressure difference between hole 0 and the mean pressure in the sideholes $(p_{1...4})$:

$$p_t - p = K(p_0 - p_{1...4}) \qquad (2)$$

where K denotes a calibration factor. The influence of Reynolds number on this difference was up to 2 per cent of the dynamic pressure by variant 1 and 5 per cent by variant 2, which had holes with partially broken edges.

The investigated probe was manufactured in the usual way. The results show that the type of holes is not essential for the influence of Reynolds number, but the holes have to be bored with the greatest care. For accurate measurements the probes must be calibrated at both correct Reynolds and Mach numbers.

GRADIENT CORRECTION

When a probe is used in a non-uniform flow, gradients of velocity, static pressure and total pressure lead to measuring errors. Firstly because the sensing holes lie at a certain distance from each other and secondly because the flow around the probe is not identical in non-uniform and uniform flows, Ref. 2. The first effect can be corrected numerically.

By using this numerical method for gradient correction of five-hole probes, the distances of the side holes to the centre hole are calculated in the flow field. The pressure distributions of the sensing holes in the direction of the gradient should be measured. According to these distances, the pressures that the holes had sensed if they had lain at the same point, can be calculated by interpolation from the pressure distributions. The results are calculated with these pressures. Since the distances depend on the flow direction, the calculation is iterative.

Definitions

The direction angles and the coordinates of the five-hole probe are shown in Fig. 3. For the application of the gradient correction by measurements in turbomachines, the angles α_0 and μ, and the coordinates qtn are introduced, see Fig. 12. The coordinate axes z and q coincide. The angle α_0 indicates the rotation of the xyz-coordinates around the q-axis. The angle μ is the angle between the x-axis and the center line of the conical body.

It is possible to derive geometrically correct expressions for the distances of the side holes to an imaginary streamline through the centre hole by studying two cases:
1. the gradient in the q-direction, the flow being assumed to be uniform in the t-direction; and 2. the gradient in the t-direction and the q-direction being uniform.

GRADIENT IN THE q-DIRECTION

The flow is assumed to be uniform in the t-direction. The notations are indicated in Fig. 12. The derivations of the expressions are presented in Ref. 1.

The distance of hole 1 to the imaginary streamline, which would pass through hole 0 is:

$$\Delta q_1 = \frac{\delta_{12}}{2}\left\{\frac{\sin\mu}{\tan\phi} - \left[\frac{\cos\mu}{\tan\phi}\cos\alpha_0 - \sin\alpha_0\right]\frac{\tan\beta}{\cos(\alpha_0-\alpha)}\right\} -$$

$$\delta_{0K}\left[\sin\mu - \frac{\cos\mu\ \cos\alpha_0\tan\beta}{\cos(\alpha_0-\alpha)}\right] \qquad (3)$$

The distance for hole 2 can be calculated from:

$$\Delta q_1 - \Delta q_2 = \delta_{12}\ \sin\alpha_0\ \frac{\tan\beta}{\cos(\alpha_0-\alpha)} \qquad (4)$$

The corresponding expressions for holes 3 and 4 are:

$$\Delta q_3 = \frac{\delta_{34}}{2\sin\kappa}\left[\sin(\kappa-\mu)+\cos(\kappa-\mu)\ \cos\alpha_0\ \frac{\tan\beta}{\cos(\alpha_0-\alpha)}\right] +$$

$$\delta_{0K}\left[\sin\mu - \frac{\cos\mu\ \cos\alpha_0\tan\beta}{\cos(\alpha_0-\alpha)}\right] \qquad (5)$$

$$\Delta q_3 + \Delta q_4 = \delta_{34}\left[\cos\mu+\sin\mu\ \cos\alpha_0\ \frac{\tan\beta}{\cos(\alpha_0-\alpha)}\right]$$

GRADIENT IN THE t-DIRECTION

The flow is assumed to be uniform in the q-direction. For the distances of the holes corresponding expressions as above were obtained:

$$\Delta t_1 = \frac{\delta_{12}}{2}\left\{\cos\alpha_0 + \frac{\cos\mu}{\tan\phi}\sin\alpha_0 - \left[\frac{\cos\mu}{\tan\phi}\cos\alpha_0 - \sin\alpha_0\right]\tan(\alpha_0-\alpha)\right\} - \delta_{0K}\cos\mu\left[\sin\alpha_0 - \cos\alpha_0\tan(\alpha_0-\alpha)\right] \quad (6)$$

$$\Delta t_1 + \Delta t_2 = \delta_{12}\left[\cos\alpha_0 + \sin\alpha_0\tan(\alpha_0-\alpha)\right] \quad (7)$$

$$\Delta t_3 = \left[\frac{\delta_{34}}{2\sin\kappa}\cos(\kappa-\mu) - \delta_{0K}\cos\mu\right]\left[\sin\alpha_0 - \cos\alpha_0\tan(\alpha_0-\alpha)\right] \quad (8)$$

$$\Delta t_3 - \Delta t_4 = \delta_{34}\sin\mu\left[\sin\alpha_0 - \cos\alpha_0\tan(\alpha_0-\alpha)\right] \quad (9)$$

REMARKS

The expressions for the distances of the holes contain the distances between the symmetrically lying holes 1 and 2 and the holes 3 and 4. It is not necessary for these pairs to be in the same plane. Thus the method can be used for all kinds of symmetrical probes. There is no need for the gradients to be known beforehand. The correction can be included permanently in the calculation procedure for the probe measurements.

MEASUREMENT OF A CYLINDER WAKE

As an experimental verification of the gradient correction a measurement was performed, where the five-hole probe was traversed through a cylinder wake. A cylinder rod was stuck in the measuring pipe ahead of the probe, see Fig. 13. The rod could be moved like a pendulum in front of the probe. The diameter of the cylinder was 2.5 mm and the distance of its centerline to the tip of the probe was 4.5 diameters. The Mach number in the pipe was 0.702 and the Reynolds number of the cylinder 43800.

The measured pressures are drawn in Fig. 14. The pressure gradient is about 10 kPa/mm. It is remarkable that the pressure distributions of p_1 and p_2 do not have their minima at the centre of the wake. The justification of the gradient correction appears here clearly.

The measured normal velocity c_n is in Fig. 15 compared with Schlichting's fare-wake correlation, Ref. 3. It has been shown with laser velocimeter measurements by NASA, Ref. 4, that this correlation can also be used in the near-wake region. In Fig. 15 the measured points are calculated both with and without gradient correction close to the theoretical curve.

The effect of the gradient on the results is most noticeable for the tangential velocity c_t, Fig. 16. The theoretical curve has been derived from the Schlichting's correlation. This figure clearly shows how the gradient correction improves the results.

The flow field was not quite two-dimensional. As shown in Fig. 17, a significant cross velocity c_q downwards along the cylinder was measured. This velocity was, however, small in the region of great gradients. At the centre of the wake there were four points which could be calculated only with aid of the gradient correction.

CONCLUSIONS

The influence of Reynolds number meant a difference of 2 per cent in the dynamic pressure measured by the probe. This was obtained at the Reynolds numbers 18600...63300 and the Mach numbers 0.6 and 0.8. When the probe had sensing holes with not quite sharp edges, a two-fold influence was measured. For accurate measurements these types of probe have to be also calibrated at correct Reynolds numbers.

By using the gradient correction method, the accuracy of measurement in non-uniform flow fields can be considerably improved. The method has been specially developed for measurements in turbomachines.

REFERENCES

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2. Bryer, D.W. and Pankhurst, R.C., Pressure-probe methods for determining wind speed and flow direction, HMSO, London 1971.

3. Schlichting, H., Boundary-Layer Theory, 7th ed., McGraw Hill, New York, 1979, p. 741.

4. Owen, F.K. and Johnson, D.A., Measurements of Unsteady Vortex Flowfields, AIAA Journal, vol. 18, No. 10, October 1980.

NOTATIONS

c	velocity
K	calibration coefficient. Eq. 2
Ma	Mach number
n	normal coordinate
p	pressure
q	cross coordinate
Re	Reynolds number
t	tangential coordinate
$\left.\begin{matrix} x \\ y \\ z \end{matrix}\right\}$	probe coordinates. Fig. 3
α	direction angle (yaw). Fig. 3
α_0	rotation angle of the xyz-coordinates. Fig. 12
β	direction angle (pitch). Fig. 3
δ	distance
Δ	difference
κ	half apex angle, holes 3, 4. Fig. 12
μ	preset angle of the conical body. Fig. 12
ϕ	half apex angle, holes 1, 2. Fig. 12
ψ	dimensionless pressure. Eq. 1

Subscripts

0...4	sensing holes of the probe
n	normal component
t	total condition
t	tangential component
q	cross component

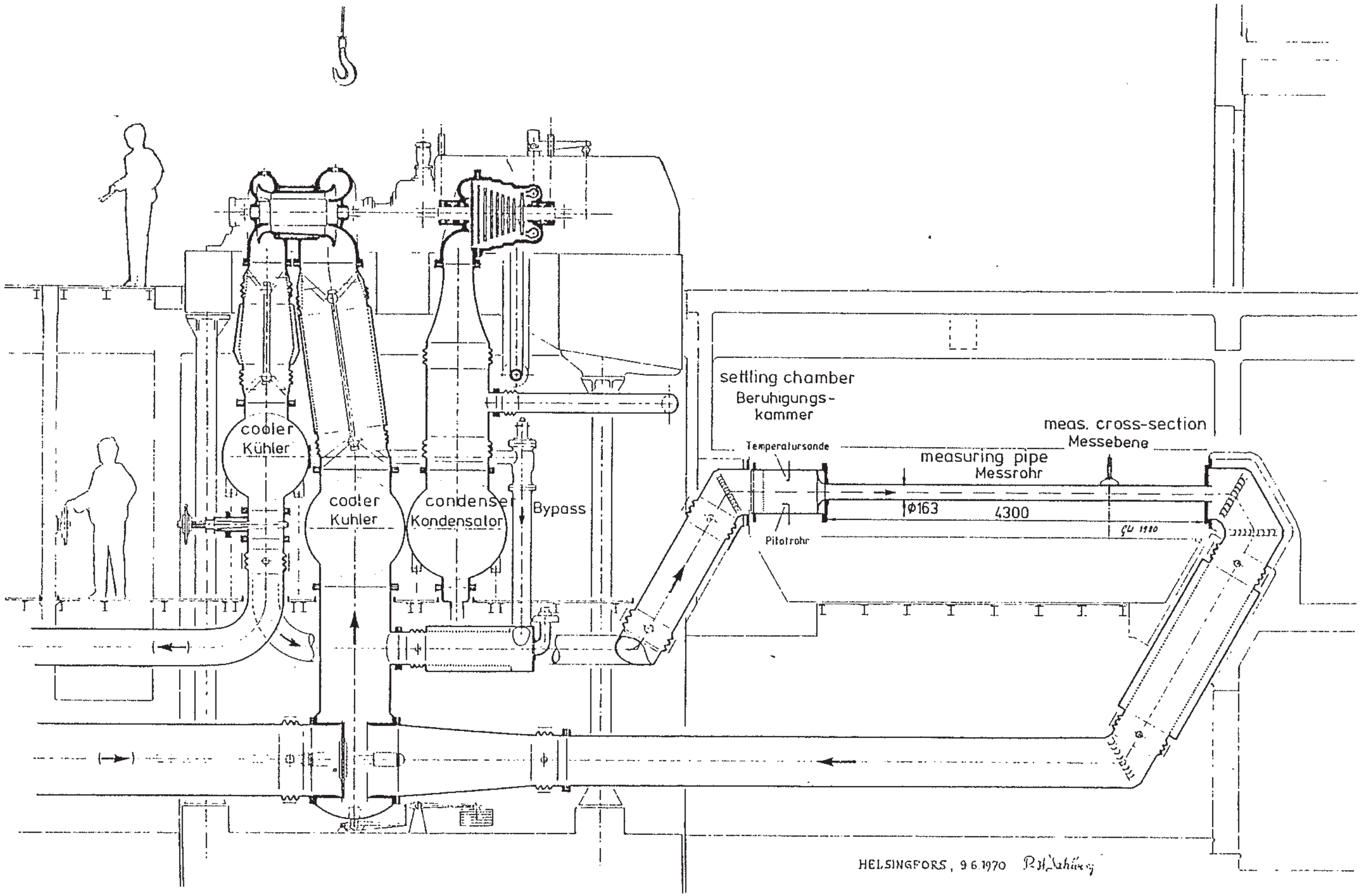

Fig. 1 Test equipment.

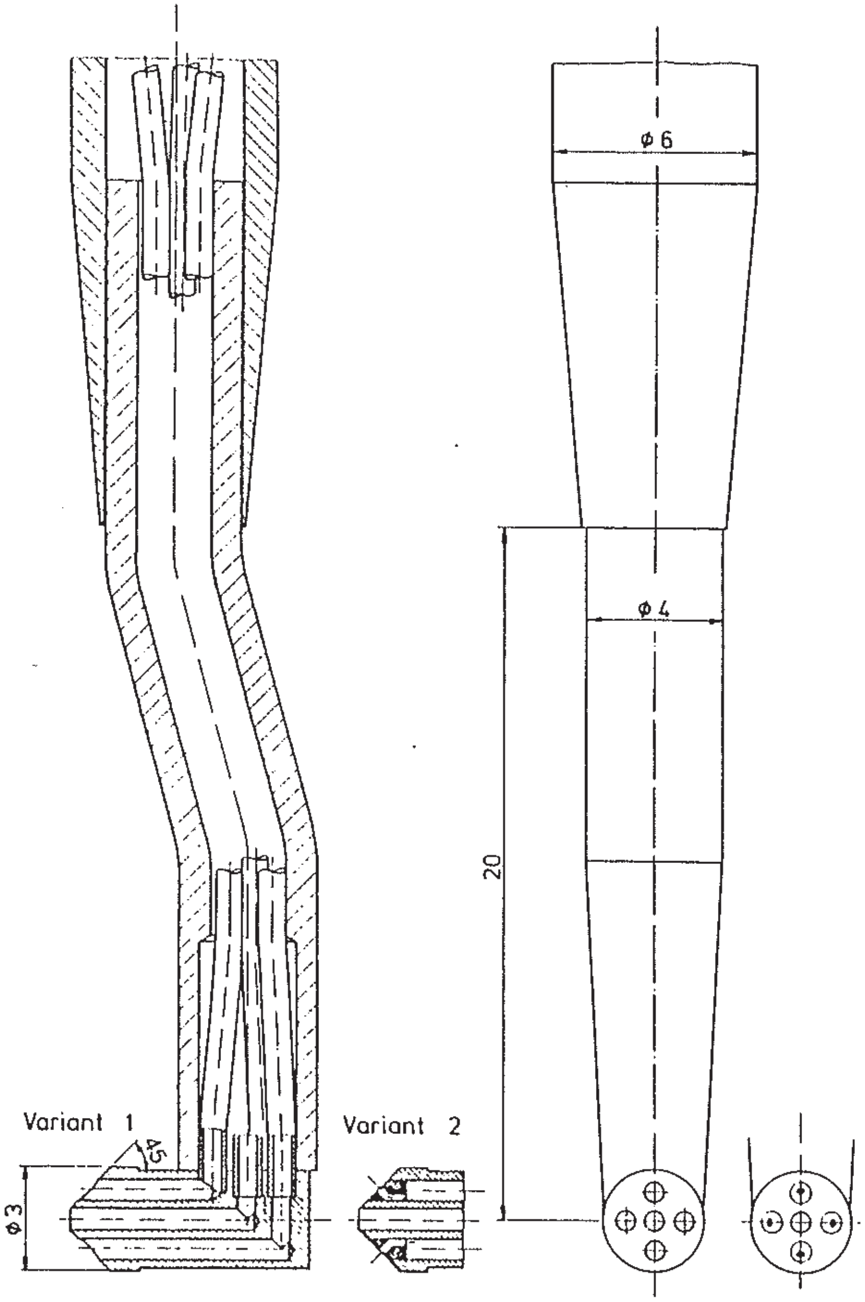

Fig. 2 Five-hole probe, variants 1 and 2.

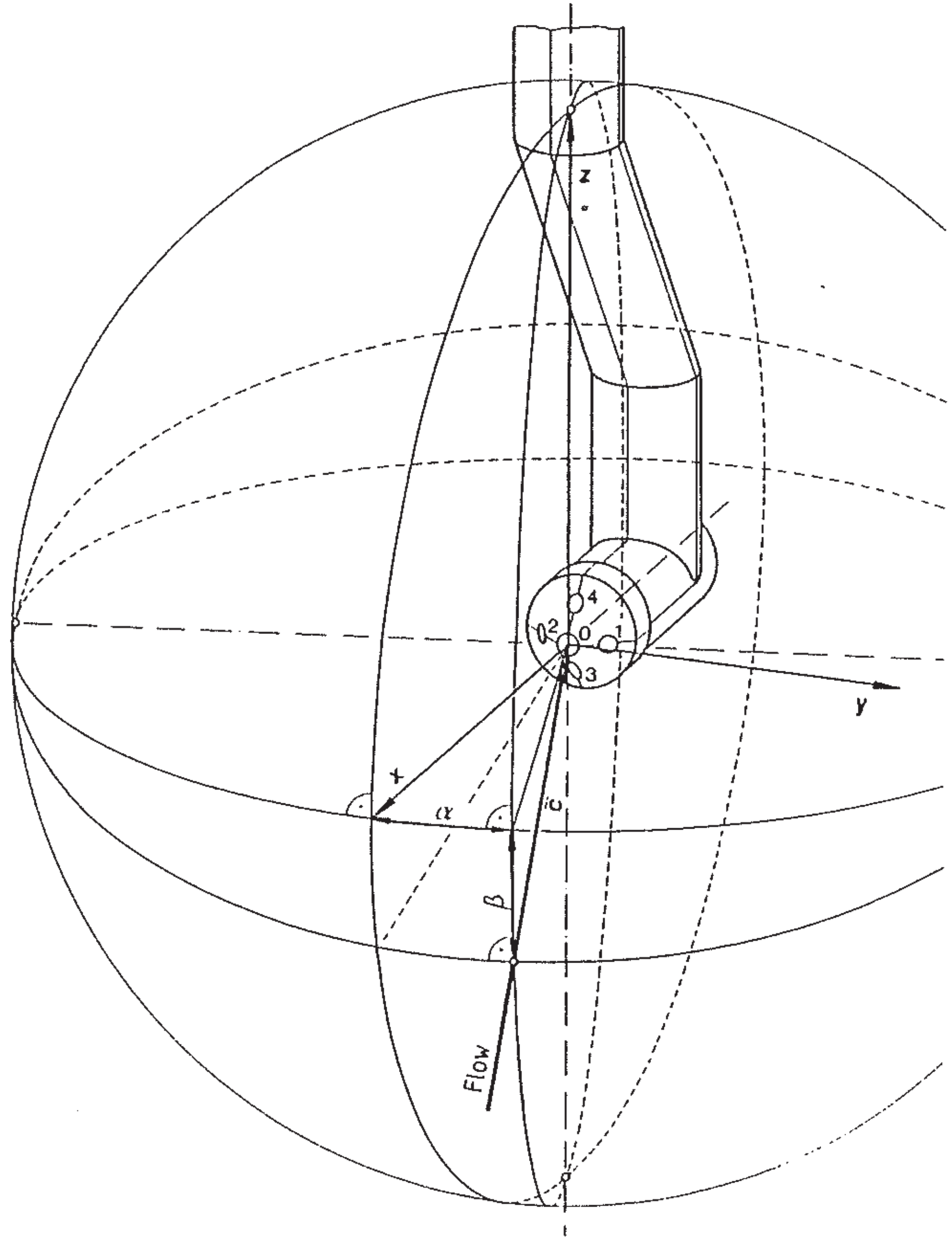

Fig. 3 Direction angles α and β in xyz-coordinates of the probe.

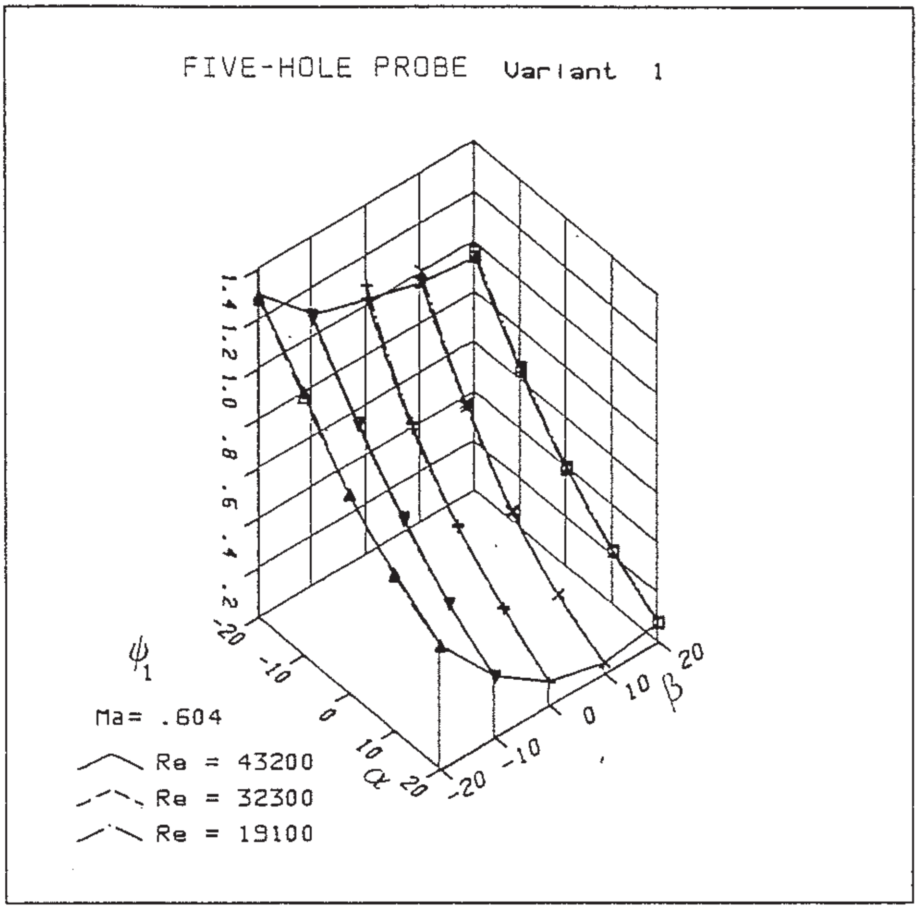

Fig. 4

Pressure ψ_1.

$$\psi_1 = \frac{p_t - p_1}{p_t - p}$$

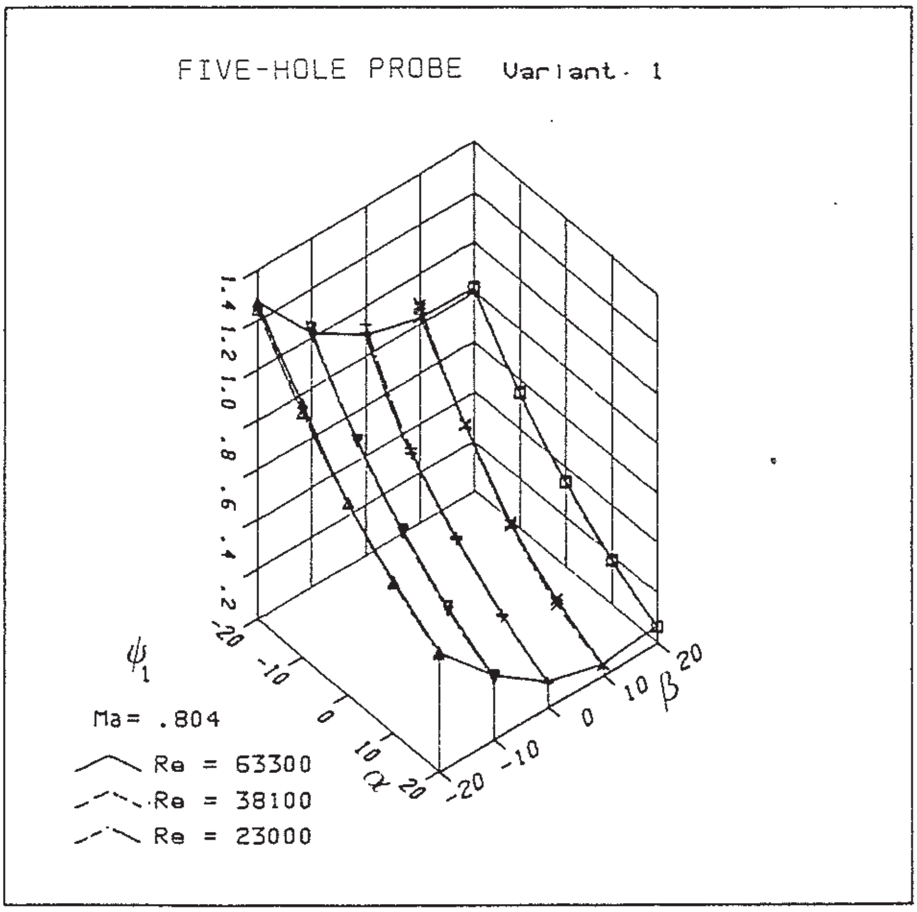

Fig. 5

Pressure ψ_1.

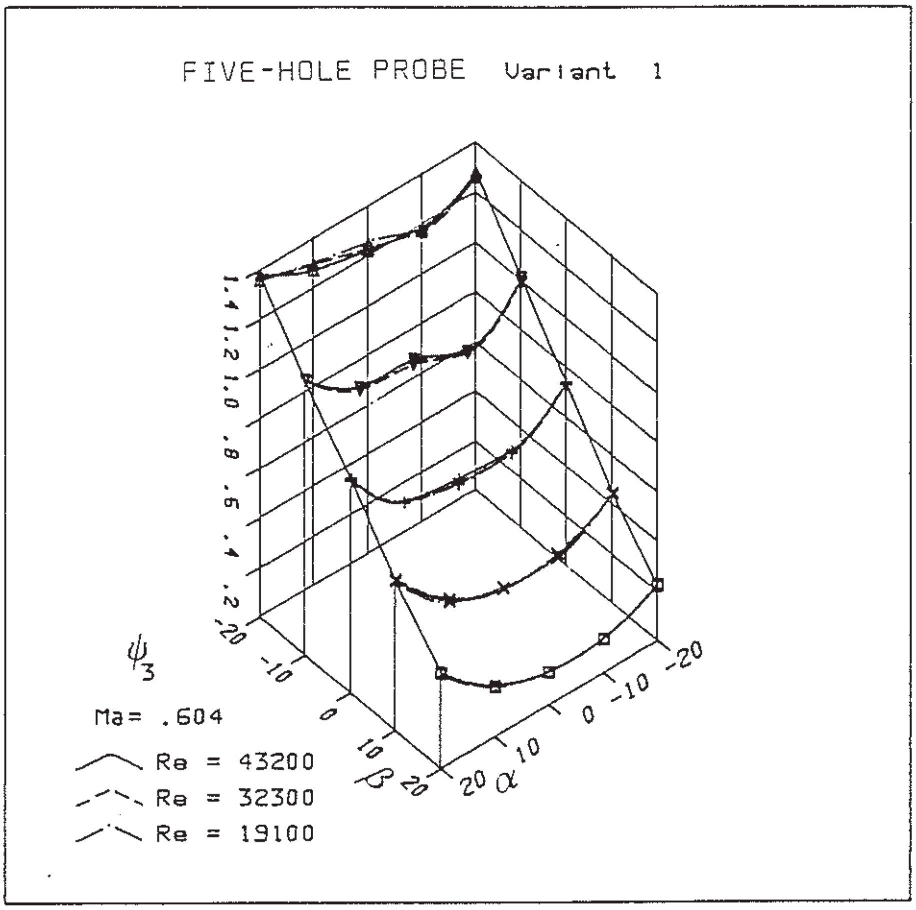

Fig. 6

Pressure ψ_3.

$$\psi_1 = \frac{p_t - p_3}{p_t - p}$$

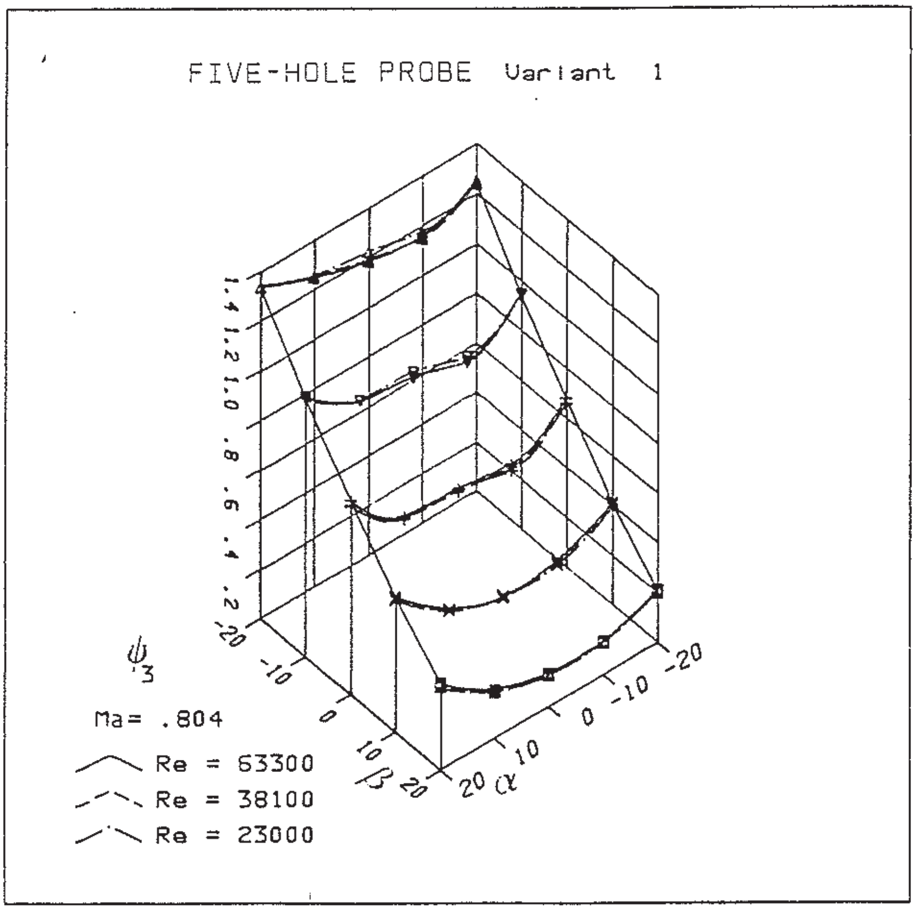

Fig. 7

Pressure ψ_3.

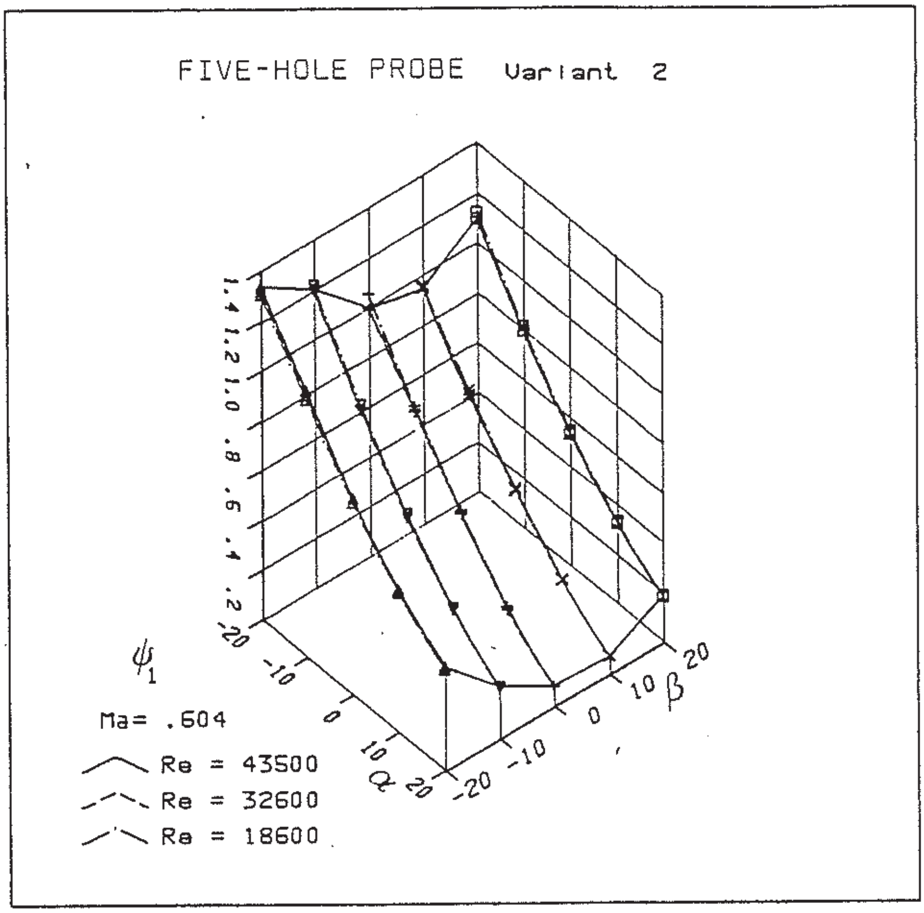

Fig. 8

Pressure ψ_1.

$$\psi_1 = \frac{p_t - p_1}{p_t - p}$$

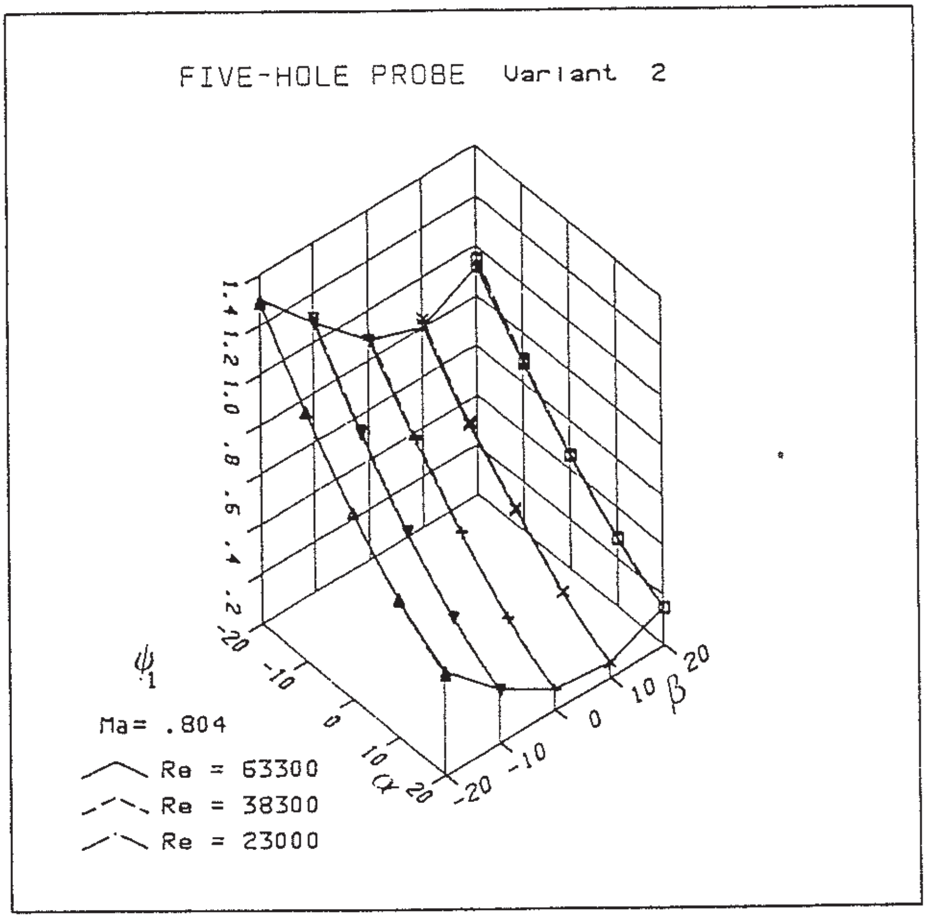

Fig. 9

Pressure ψ_1.

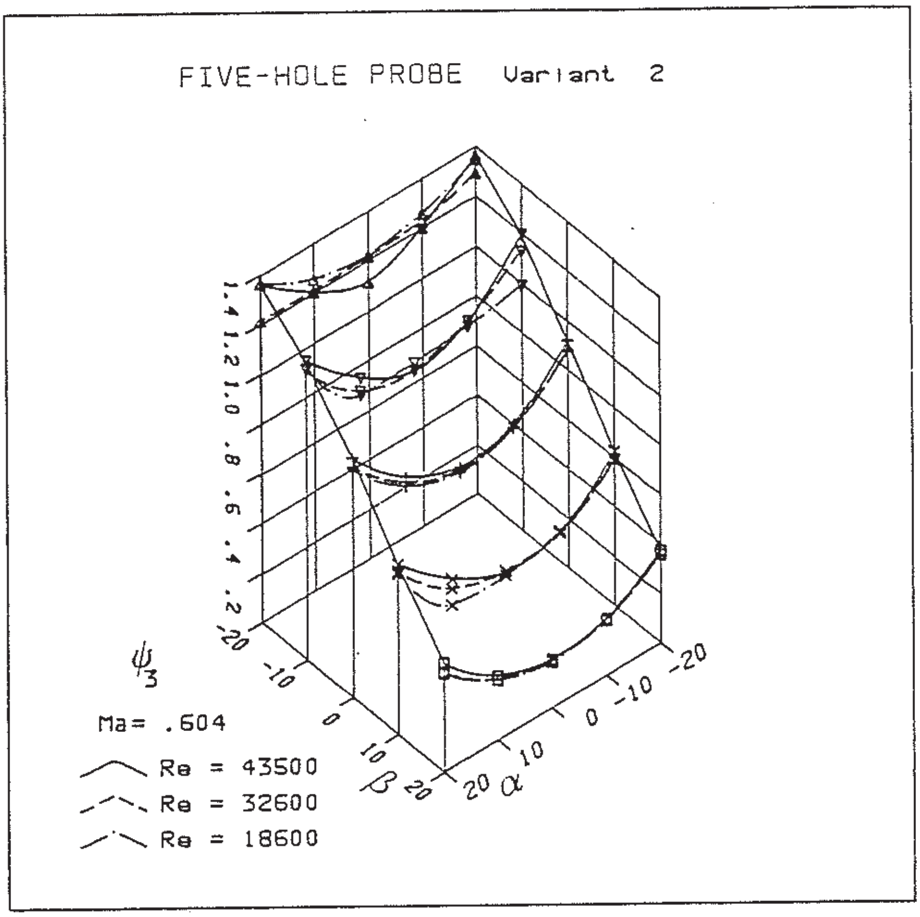

Fig. 10

Pressure ψ_3.

$$\psi_3 = \frac{p_t - p_3}{p_t - p}$$

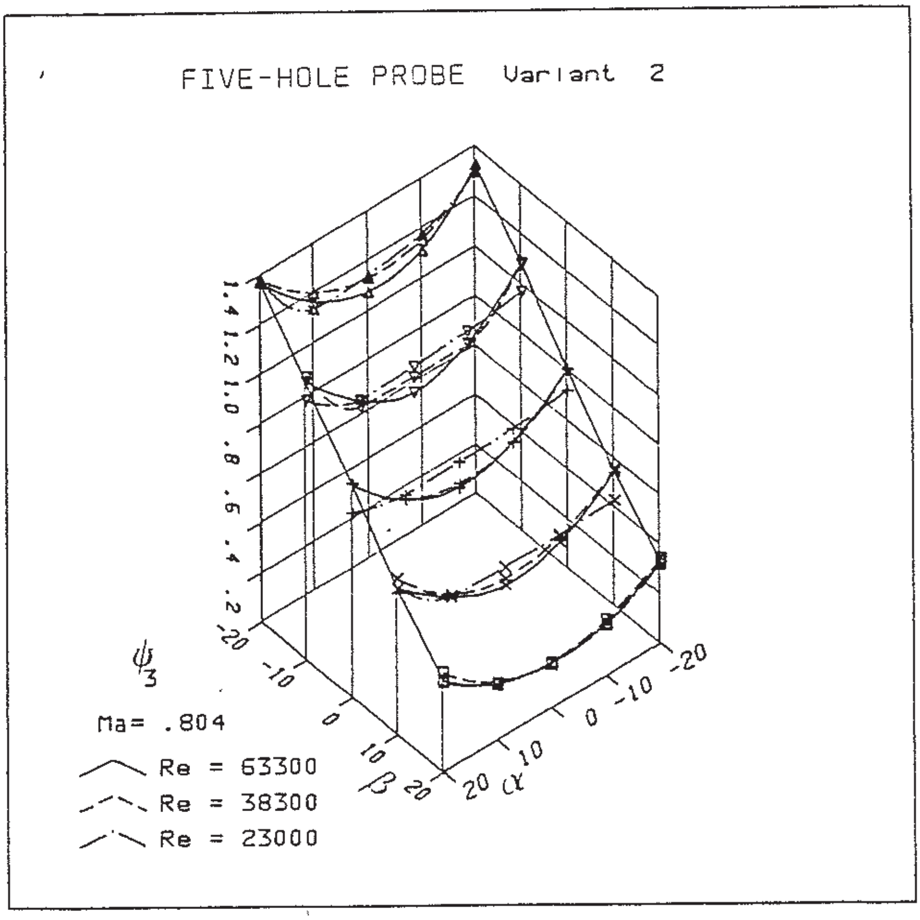

Fig. 11

Pressure ψ_3.

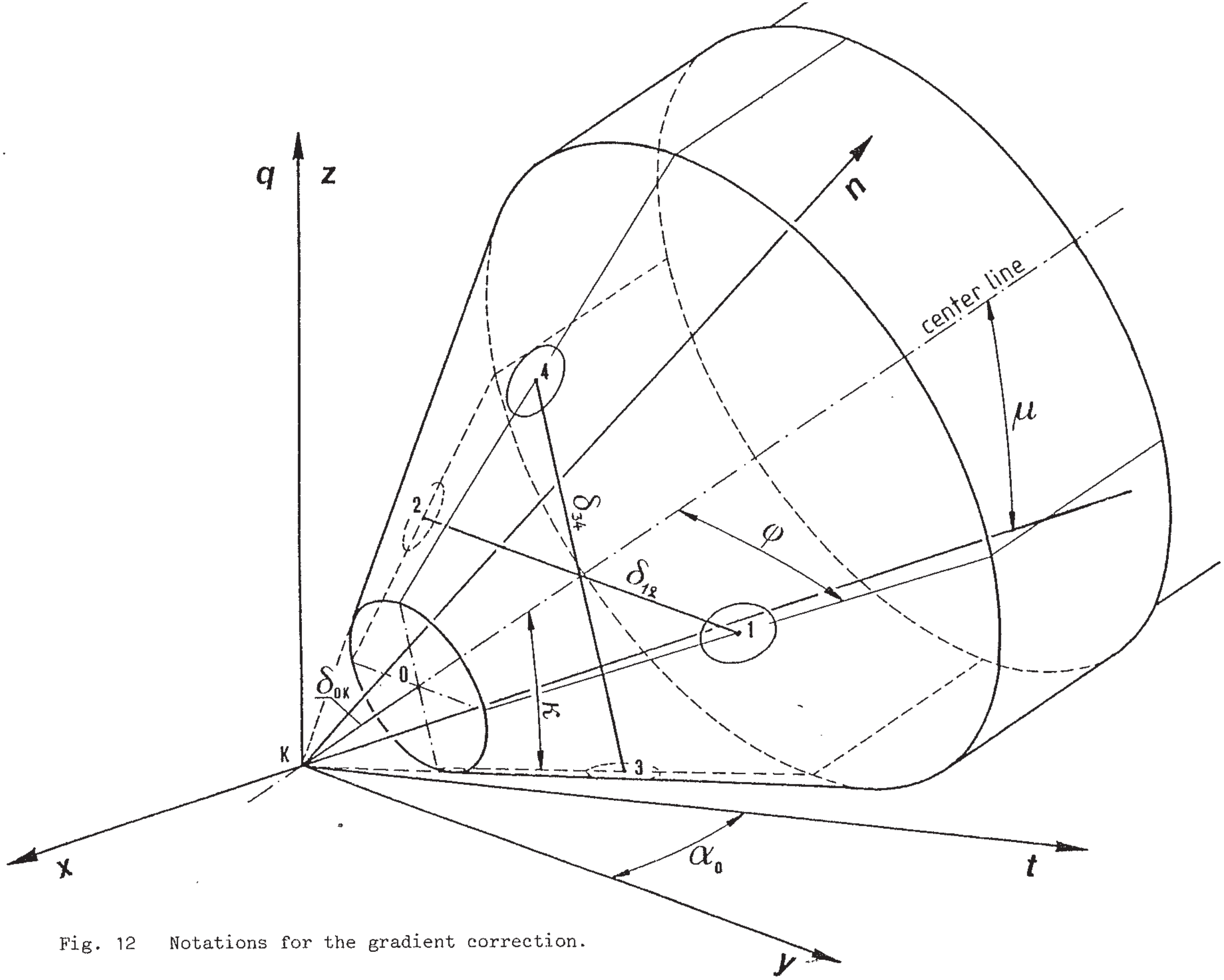

Fig. 12 Notations for the gradient correction.

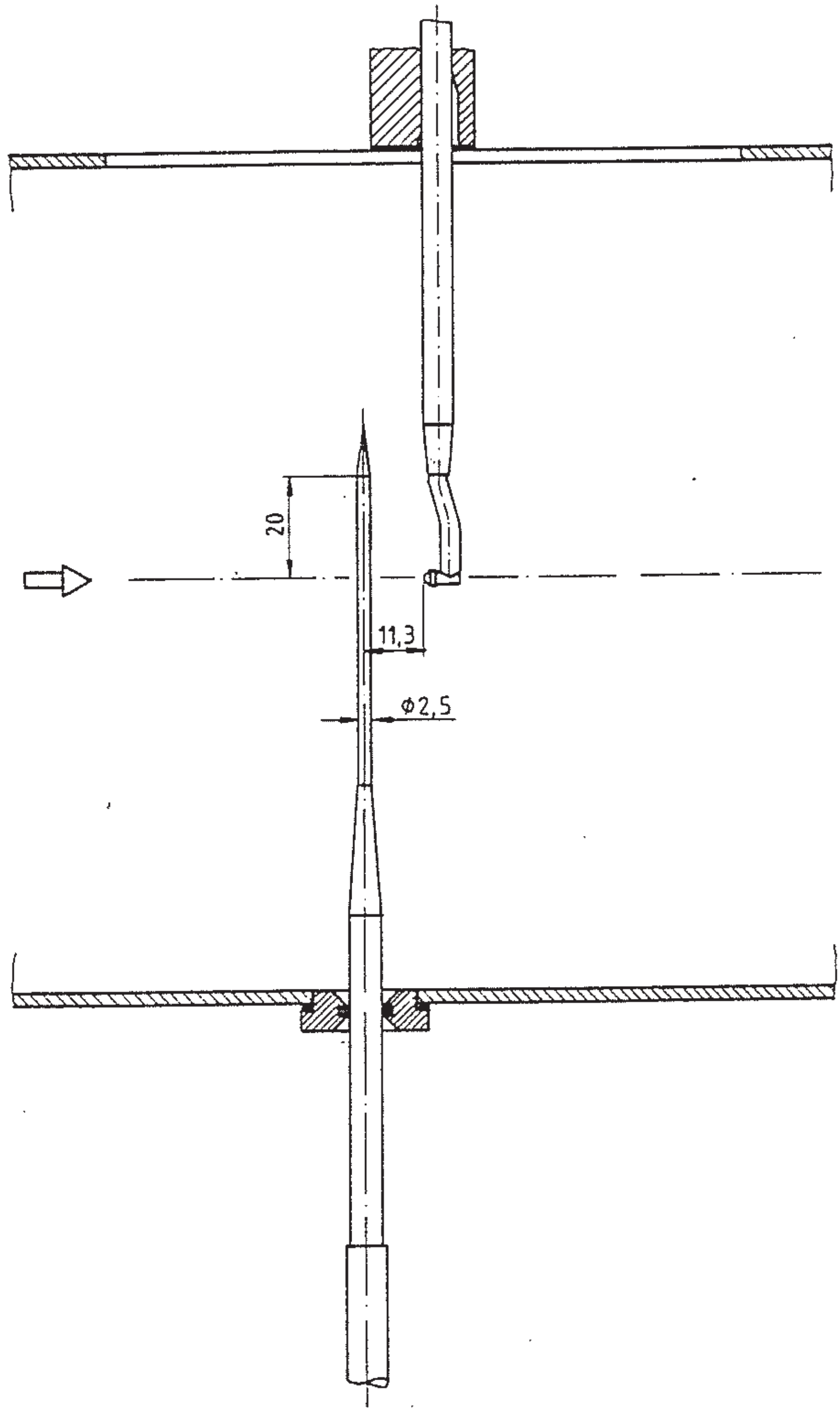

Fig. 13 Test installation for the cylinder wake measurement.

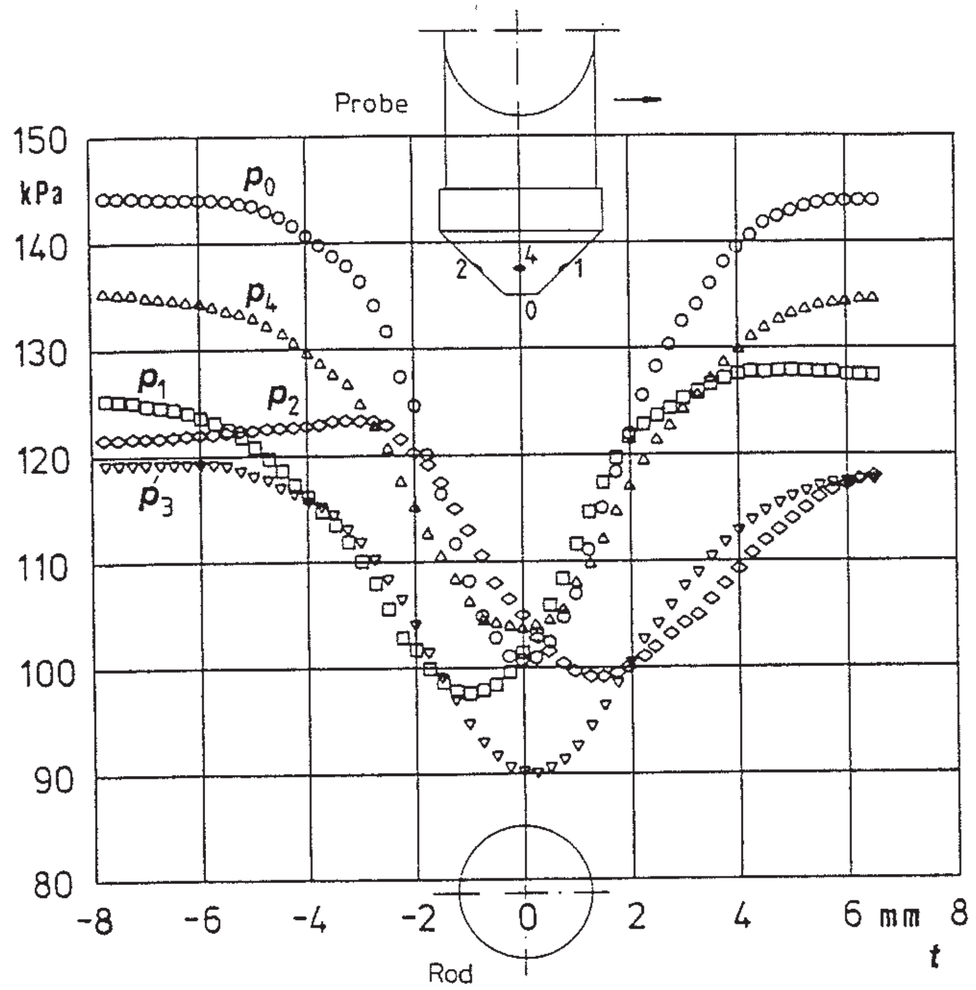

Fig. 14 Pressure distributions in the cylinder wake.

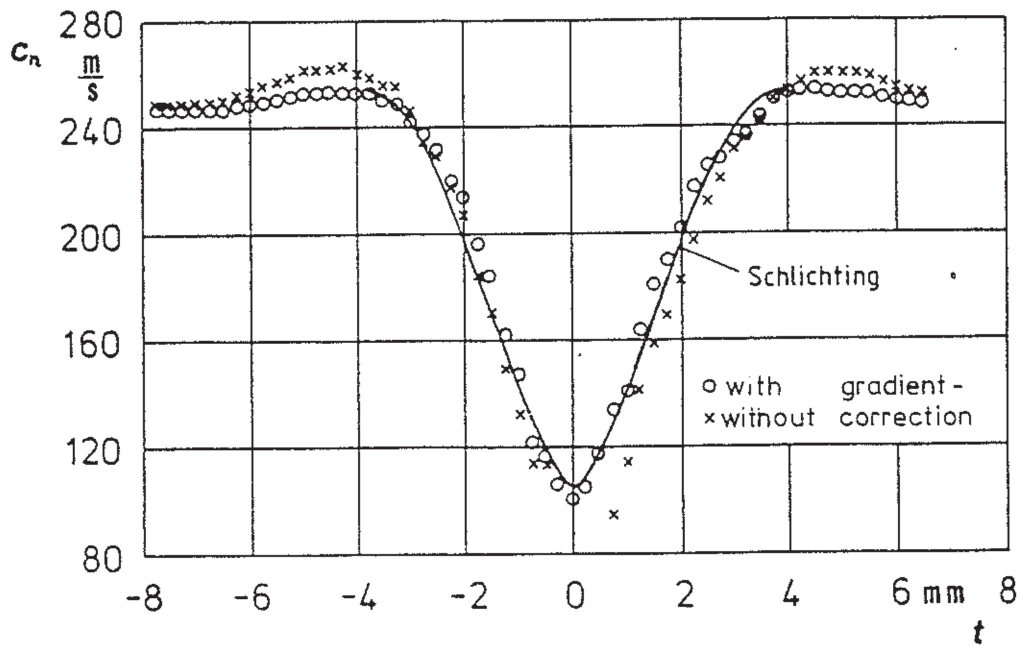

Fig. 15 Normal velocity c_n in the cylinder wake.
Axial direction in the pipe.

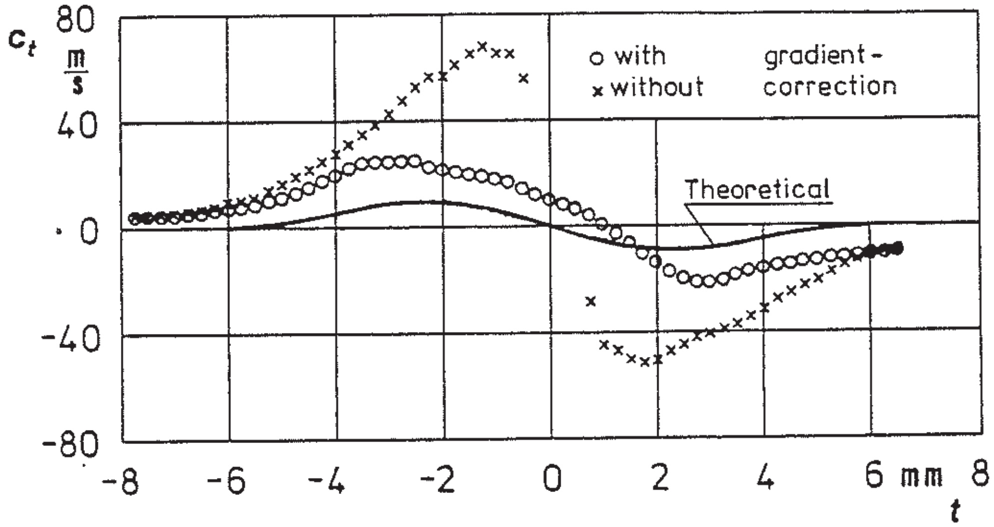

Fig. 16 Tangential velocity c_t in the cylinder wake.
Cross direction of the cylinder rod.

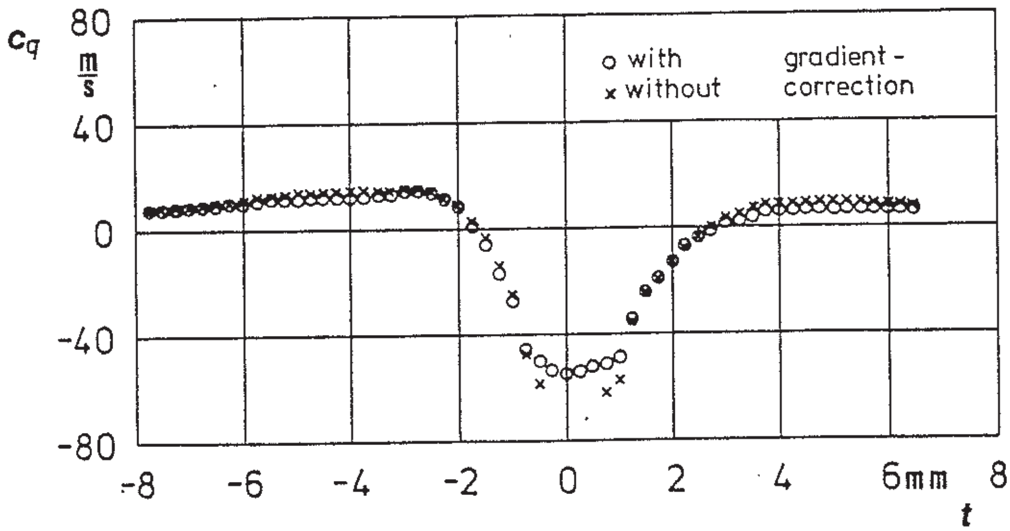

Fig. 17 Cross velocity c_q in the cylinder wake
The direction along the cylinder rod.