KERNFORSCHUNGSZENTRUM

KARLSRUHE

April 1972

KFK 1588
EUR 4728 e

Institut für Neutronenphysik und Reaktortechnik
Projekt Schneller Brüter

Friction Factors of a Cluster of 19 Rough Rods

C. Savatteri

GESELLSCHAFT FÜR KERNFORSCHUNG M. B. H.

KARLSRUHE

Als Manuskript vervielfältigt
Für diesen Bericht behalten wir uns alle Rechte vor

GESELLSCHAFT FÜR KERNFORSCHUNG M.B.H.
KARLSRUHE

KERNFORSCHUNGSZENTRUM KARLSRUHE

April 1972

KFK 1588
EUR 4728 e

Institut für Neutronenphysik und Reaktortechnik
Projekt Schneller Brüter

Friction factors of a cluster of 19 rough rods

by

C. Savatteri+)

Gesellschaft für Kernforschung mbH., Karlsruhe

+) Delegated by Euratom to the Karlsruhe Fast Breeder Project

Abstract

On the basis of the universal laws applicable to velocity distribution on smooth and roughened surfaces, as obtained for simple geometries (circular tubes, annular gap), a method of calculation is indicated which allows to determine the friction coefficients and flow distribution in artificially roughened rod bundles.

Using this method of calculation, the results of measurements found for a rod bundle of 19 roughened rods in hexagonal arrangement and with a smooth channel wall yielded a universal parameter $R(h^+)$ which is in good agreement with values applicable to simpler geometries.

Kurzfassung

Ausgehend von den universellen Gesetzen für die Geschwindigkeitsverteilung an glatten und rauhen Flächen wie sie an einfachen Geometrien (Kreisrohren, Ringspalt) gewonnen wurden, wird eine Berechnungsmethode angegeben, die es ermöglicht, die Reibungsbeiwerte und Strömungsverteilung in künstlich rauhen Stabbündeln zu bestimmen.

Die an einem Stabbündel mit 19 rauhen Stäben in hexagonaler Anordnung und glatter Kanalwand gefundenen Meßergebnisse führten mit dieser Berechnungsmethode zu einem universellen Parameter $R(h^+)$, der mit Werten aus einfacheren Geometrien gut übereinstimmt.

Contents

1. Introduction

The core of a fast reactor is characterized by a very high power density. For this reason, heat transfer gains particular significance, above all in gas-cooled fast reactors, since gas is not a good coolant, as is generally known.

To improve heat transfer in gas-cooled reactors with fuel-element rods, artificial roughnesses are used on the heat-transfer surfaces. Although improving heat transfer considerably, these roughnesses lead to an increase in pressure losses. Quite a number of experimental investigations into pressure losses and heat transfer characteristics of artifical roughnesses were carried out with simple geometries (circular tube, annular gap).

The fuel elements of nuclear reactors are assembled to rod bundles constituting the cooling channels with partly smooth and partly roughened walls of the channels at the periphery of the bundle. Here a rod bundle consisting of 19 roughened tubes in hexagonal arrangement is considered whose dimensions are given in Fig.1. In this work it is attempted to find a mean of calculating the friction coefficients and flow distribution. We refer to the universal laws applicable to the velocity distribution on smooth and roughened surfaces, as obtained for simple geometries. It is also demonstrated how in the case of rod bundles the effects can be separated from each other which are exerted by partly smooth and partly roughened walls.

Finally, the results of the calculation are compared with the results obtained by other authors, using roughnesses of similar geometries, but with different shapes of the channels (circular tubes, annular gap). This work is a continuation and an extension of the work of K. Maubach /1/. The present method of calculation is more precise of that of reference /1/ and it leads to an universal parameter $R(h^+)$ which is in better agreement with values obtained for simpler geometries.

2. Description of the Method of Calculation

In a rod bundle the flow section at the lines of symmetry is divided into channels. According to Fig.1 the 19-tube rod bundle forms the following channels:

48 central channels with roughened tubes;
24 wall channels with smooth and roughened walls;
12 corner channels with smooth and roughened walls.

Due to the symmetry of the system only one central A, wall B, and corner channel C, respectively, was considered for calculation (see Fig.2).

The central channel A was divided in three equal regions, each of these being subdivided in 1° angle subchannels by means of lines normal to the tube walls (Fig.2a). For the calculations in the channel A, it is sufficient to consider only one of these regions. In the wall channel B, the line $\tau = 0$ separates the "smooth" region from the "rough" region (Fig.2b). Two zones pertain rough walls (zones 1 and 2), the third a smooth wall. The zone 1 and 2 have been subdivided in 1° subchannels like for the channel A. The zone 3 has been subdivided in subchannels with lines normal to the wall and obtained by intersection with 1° lines of region 2. Analogously it has been proceeded in channel C (Fig.2c).

The conditions applicable to all subchannels are:

a) Isothermal flow (ρ = constant).
b) Fully developed turbulent incompressible flow.
c) The universal velocity distribution as determined by Nikuradse [2,3] for the smooth and roughened circular tubes applies to all subchannels.
Consequently, the velocity distribution on smooth surfaces is expressed by:

$$U^+ = 2.5 \ln y^+ + 5.5 \tag{1}$$

and on roughened surfaces by:

$$U^{+} = 2.5 \ln y/h + R(h^{+}) \qquad (2)$$

d) The separation of the smooth zone from the roughened zone is supposed to be the intersection of the velocity profiles determined by both walls /4/.

e) Secondary flow is not taken into account, i.e., dp/dx is constant.

If the channels considered are divided into subchannels as indicated above, these subchannels can be considered to be a section of an annular zone which is characterized by the radius r_o of the line $\tau = 0$ and the radius r_w of the wall. Thus, the shape of the annular zone is defined by the parameter

$$\varepsilon = \frac{r_o}{r_w}$$

Depending on the value of ε, the annular zone becomes a circle ($\varepsilon = 0$ for $r_o = 0$), the outer zone of an annular gap ($0 \leq \varepsilon \leq 1$), a parallel plate ($\varepsilon = 1$) and, finally, the inner zone of an annular gap ($1 \leq \varepsilon \leq \infty$).

In the present case the flow zone of the subchannels can be considered to be the inner zone of an annular gap (central channel, roughened zone of the wall and the corner channel, respectively) and as a parallel plate (smooth zone of the wall and corner channel, respectively).

These definitions and the integration of the equations 1 and 2 over the respective surfaces in the i^{th} subchannel will yield the friction coefficients.

For a roughened channel wall this will be:

$$\sqrt{\frac{8}{\lambda_i}} = 2.5 \ln \frac{D_i}{h} + R(h^+) - G_i^* \qquad (3)$$

where: $G_i^* = \frac{3.75+1.25\varepsilon_i}{1+\varepsilon_i} + 2.5 \ln(2(\varepsilon_i+1)); \varepsilon_i = \frac{\bar{r}_{oi}}{r_w}; \bar{r}_{oi} = \frac{r_{oi-1}+r_{oi}}{2}$

and for a smooth channel wall:

$$\sqrt{\frac{8}{\lambda_i}} = 2.5 \ln(Re\sqrt{\frac{\lambda}{8}} \sqrt{(\frac{D_i}{D})^3}) + 5.5 - G_i^* \qquad (4)$$

where: $G_i^* = 5.965$

Re, λ, and D being the quantities related to the entire bundle. Eqs. 3 and 4 are not sufficient to describe the bundle, because there is no link between the friction coefficient of the sub-channel and that of the bundle; likewise, the position of the line, at which the impulse transfer from one zone to the other disappears (shear stress $\tau = 0$) is not yet known.

The friction coefficient of the bundle is defined as:

$$\lambda = \frac{dP/dx}{\rho/2 \, \bar{U}^2 \, \frac{1}{D}} \qquad (5)$$

dP/dx and ρ being constant, the following relation applies to each sub-channel according to Eq.5:

$$\frac{\lambda_i \, \bar{U}_i^2}{D_i} = \frac{\lambda \, \bar{U}^2}{D} \qquad (6)$$

This yields:

$$\frac{\bar{U}_i}{\bar{U}} = \sqrt{\frac{\lambda}{\lambda_i}} \sqrt{\frac{D_i}{D}} \qquad (7)$$

We obtain from the continuity equation:

$$\sum_i \bar{U}_i F_i = \bar{U} F \qquad (8)$$

Eqs. 7 and 8 become

$$\sqrt{\frac{8}{\lambda}} = \sum_i \sqrt{\frac{8}{\lambda_i}} \sqrt{\frac{D_i}{D}} \frac{F_i}{F} \qquad (9)$$

Eq.9 establishes a relation between the friction coefficients of the sub-channels and those of the channels, and between those of the channels and of the rod bundle, respectively.

This yields:

Central channel - subscript A (see Fig.2a)

$$\sqrt{\frac{8}{\lambda_A}} = \sum_{i=1}^{N} \sqrt{\frac{8}{\lambda_{Ai}}} \sqrt{\frac{D_{Ai}}{D_A}} \frac{F_{Ai}}{F_A} \qquad (10)$$

Wall channel - subscript B (see Fig.2b)

$$\sqrt{\frac{8}{\lambda_B}} = \sum_{i=1}^{3} \sqrt{\frac{8}{\lambda_{Bi}}} \sqrt{\frac{D_{Bi}}{D_B}} \frac{F_{Bi}}{F_B} \qquad (11)$$

Corner channel - subscript C (see Fig.2c)

$$\sqrt{\frac{8}{\lambda_C}} = \sum_{i=1}^{3} \sqrt{\frac{8}{\lambda_{Ci}}} \sqrt{\frac{D_{Ci}}{D_C}} \frac{F_{Ci}}{F_C} \qquad (12)$$

Entire bundle (see Fig.2)

$$\sqrt{\frac{8}{\lambda}} = 4\sqrt{\frac{8}{\lambda_A}}\sqrt{\frac{D_A}{D}}\frac{F_A}{F} + 2\sqrt{\frac{8}{\lambda_B}}\sqrt{\frac{D_B}{D}}\frac{F_B}{F} + \sqrt{\frac{8}{\lambda_C}}\sqrt{\frac{D_C}{D}}\frac{F_C}{F} \tag{13}$$

Using again Eq.9, we obtain in the same way λ_{Bi} and λ_{Ci}.
For the values of λ_{Bi} this is expressed by:

$$\sqrt{\frac{8}{\lambda_{B1}}} = \sum_{i=1}^{M}\sqrt{\frac{8}{\lambda_{B1i}}}\sqrt{\frac{D_{B1i}}{D_{B1}}}\frac{F_{B1i}}{F_{B1}} \tag{14}$$

$$\sqrt{\frac{8}{\lambda_{B2}}} = \sum_{i=1}^{K}\sqrt{\frac{8}{\lambda_{B2i}}}\sqrt{\frac{D_{B2i}}{D_{B2}}}\frac{F_{B2i}}{F_{B1}} \tag{15}$$

$$\sqrt{\frac{8}{\lambda_{B3}}} = \sum_{i=1}^{K}\sqrt{\frac{8}{\lambda_{B3i}}}\sqrt{\frac{D_{B3i}}{D_{B3}}}\frac{F_{B3i}}{F_{B3}} \tag{16}$$

Similarly, the values for λ_{Ci} are derived for the corner channels.

The friction coefficients, λ_{B1i}, λ_{B2i}, λ_{B3i}, λ_{C1i}, λ_{C2i}, λ_{C3i} can be calculated using Eqs. 3 and 4, provided that the line $\tau = 0$ is known for the wall and corner channels, respectively.

We assume with /4/ that this line is determined by the location of the points in which the velocity distributions, starting from the respective walls, intersect. For the first sub-channel we assume that the line $\tau = 0$ is parallel to the wall (Fig.3). The distance Z_1 between this line and the wall is determined by the two conditions:

a) the pressure drops in both sub-channels are equal
b) in the intersection point the two velocity profiles starting from the respective walls give the same velocity value.

Under these conditions and with the notations of Fig.3 Z_1 is given by the relation:

$$2.5\ \ln\left(Z_1 Re \sqrt{\frac{\lambda}{8}}\sqrt{\frac{D_b}{D}}\right) + 5.5 = \sqrt{\frac{D_a}{D_b}}\left[2.5\ \ln\left(\frac{w-d/2-Z_1}{h}\right) + R(h^+)\right] \qquad (17)$$

The same for the following sub-channels.

The system of equations indicated can be solved, provided that the Re-number of the entire channel, the height of roughness h, the roughness parameter $R(h^+)$, and the geometric dimensions of the bundle are known.

In this case, we took the results measured at a 19-rod-bundle with roughened tubes as the basis and determined the roughness parameters $R(h^+)$ from the friction coefficients of the entire channel at the respective Re-numbers. In the following paragraphs this parameter is compared with the results obtained for simpler geometries.

3. Results

It has been shown that $R(h^+)$ is a function of the dimensionless roughness height h^+. It appears that for a fully developed roughness flow $R(h^+)$ leads to a constant value which is dependent on the microscopic parameters of the roughness only [4], [5].

The roughness elements of the bundle described have approximatively the shape of equal-sided triangles, as shown in Fig.4.
The calculation yielded a family of curves represented in Fig.5, from which the following equation has been derived as a curve with the least deviation from the measured values.

$$R(h^+) = 2.8 + 33/h^+ \quad \text{for } h^+ > 10 \qquad (18)$$

This equation is compared in Fig.6, with the values given by other authors measured at simpler geometries and similar forms of roughness and shows good agreement. For $h^+ = 100$, Eq.18 yields a value of $R(h^+) = 3.1$ which agrees well with the values proposed by Dalle Donne - Meerwald, Feuerstein, Koch, Puchkow (Fig.7).

With Re, h, $R(h^+)$ and the geometric quantities known, the system of equations indicated allows to determine by iteration the friction coefficient of the bundle and of the channels as well as the flow distribution. The results are given in Figs. 8 and 9. Fig.8 shows the points of the line $\tau = 0$ for two Re-numbers. Fig.9 shows the change of the friction coefficient dependent on the Re-number. The results measured by Maubach [1] are also entered and are in good agreement with our own results.

Nomenclature

b	width of the roughness at half height [cm]
D	hydraulic diameter of the bundle [cm]
d	diamter of rod in the bundle [cm]
F	Flow section area [cm^2]
h	height of the roughness [cm]
P	pitch of the rods in the bundle [cm]
p	pitch of the roughness [cm]
r_o	radius of the τ = 0-line [cm]
r_w	radius of rod in the bundle [cm]
U	local coolant velocity [cm/sec]
$U^* = \tau/\rho$	friction velocity [cm/sec]
$\bar{U}$	average coolant velocity [cm/sec]
$\varepsilon = r_o/r_w$	Annulus region parameter
y	distance from the surface [cm]
Z	distance between the wall and the τ = 0-line [cm]
ν	cinematic viscosity of the coolant gas [cm^2/sec]
ρ	coolant gas density [g/cm^3]
τ	shear stress [$dynes/cm^2$]

w	distance between the rod center and the wall [cm]
dP	pressure drop [g/cm²]
x	Coordinate in flow direction [cm]
N,M,K	Number of the Subchannels

Dimensionless parameters

$h^+ = h \cdot U^*/\nu$	dimensionless roughness height
$Re = \bar{U}D/\nu$	Reynolds number
$U^+ = U/U^*$	dimensionless velocity
$y^+ = y\ U^*/\nu$	dimensionless wall distance
λ	friction factor

Subscripts

A	refers to central channel
B	" " wall channel
C	" " corner channel
1-2	" " rough region of wall channel
3	" " smooth region of wall channel
4	" " rough region of corner channel
5-6	" " smooth region of corner channel
i	" " subchannel of the bundle

Literature

/1/ Maubach, K.: Druckverlustmessungen an einem rauhen Stabbündel
KFK 1433 - Juni 1971

/2/ Nikuradse, J.: Gesetzmäßigkeiten der turbulenten Strömung in glatten Rohren;
VDI-Forsch., 1932, 356

/3/ Nikuradse, J.: Strömungsgesetze in rauhen Rohren;
VDI-Forsch. 1933, 361

/4/ Maubach, K.: Reibungsgesetze turbulenter Strömung in geschlossenen, glatten und rauhen Kanälen von beliebigem Querschnitt;
Externer Bericht INR-4/69-22, März 1969

/5/ Dalle Donne, M. und Meerwald, E.: Heat Transfer from Surface roughned by Thread-Type Ribs at high temperatures;
Proc. of the 1970 Heat Transfer and Fluid Mechanics Institute, Stanford/California

/6/ Webb, R.L.: Turbulent Heat Tranefer in Tubes Having Two-dimensional Roughness, including the Effect of Prandtl number;
University of Minnesota, Ph.D., 1969

/7/ Sheriff, N., Gumley, P. and France, J.: Heat-transfer characteristics of roughened surfaces
TRG-Report 447(R), 1963

/8/ Nunner, W.: Druckverlust und Wärmeübergang bei verwirbelter Strömung;
VDI-Forsch.-Heft 469 (1958)

/9/ Rampf, H. und Feuerstein, G.: Wärmeübergang und Druckverlust an dreiecksförmigen Rauhigkeiten in turbulenter Ringspaltströmung
Heat Transfer 1970, Paris, Volume II, FC 5.3

/10/ Dalle Donne, M., Meerwald, E.: Experimental local Heat Transfer and Average Friction Coefficients in an Annulus at High Temperatures;
Int. J. Heat Mass Transfer, 1966, 9, 1361-1376

/11/ Puchkov, P.I.,and Vinogradov, O.S.: Heat Transfer and Hydraulic Resistance in Annular Channels with Smooth and Rough Heat Transfer Surfaces;
Teplo-i massoperenos, Volume I, Nauka i Tekhnika Minsk, 1965

/12/ Feurstein, G. and Rampf: Der Einfluß rechteckiger Rauhigkeiten auf den Wärmeübergang und den Druckabfall in turbulenter Ringspaltströmung;
Wärme- und Stoffübertragung, Bd.2, Nr.1, 1969

/13/ Koch, R.: Druckverlust und Wärmeübergang bei verwirbelter Strömung;
VDI-Forsch.-Heft 469 (1958)

/14/ Meerwald, E.: Druckverlust und Wärmeübergang an glatten und rauhen Flächen bei hohen Temperaturen und turbulenter Strömung und deren Darstellung durch universelle Gesetze;
Externer Bericht INR-4/71-29, Kernforschungszentrum Karlsruhe, Mai 1971

/15/ Schlichting, H.: Boundary Layer Theory
New York, Mc Graw-Hill, 1954, ch.XIX

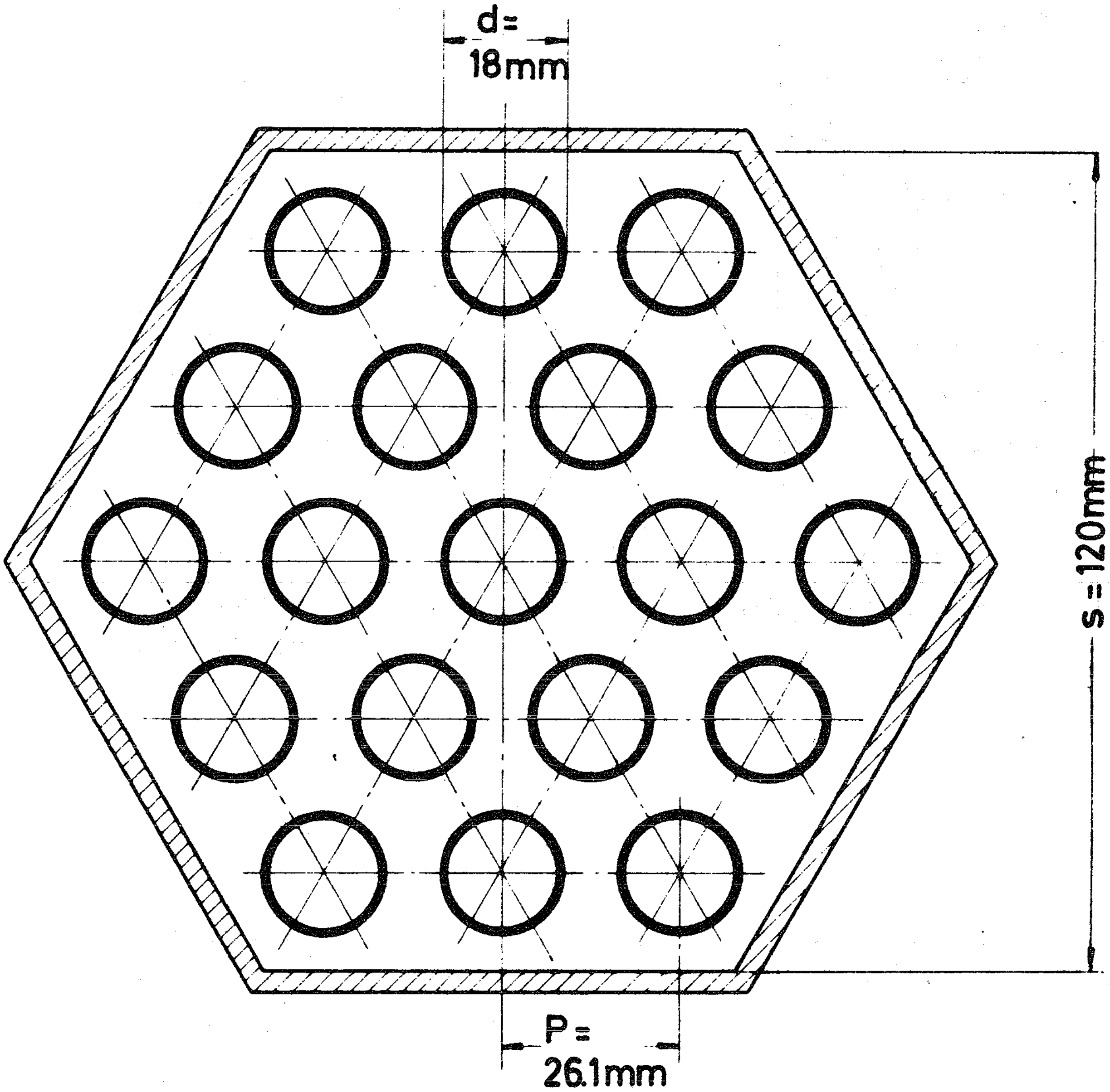


Fig. 1 Bundle with 19 rough rods in hexagonal array

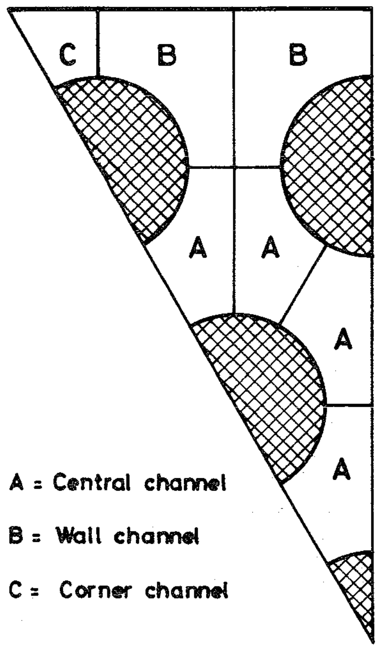


Fig. 2 Channels of the cluster

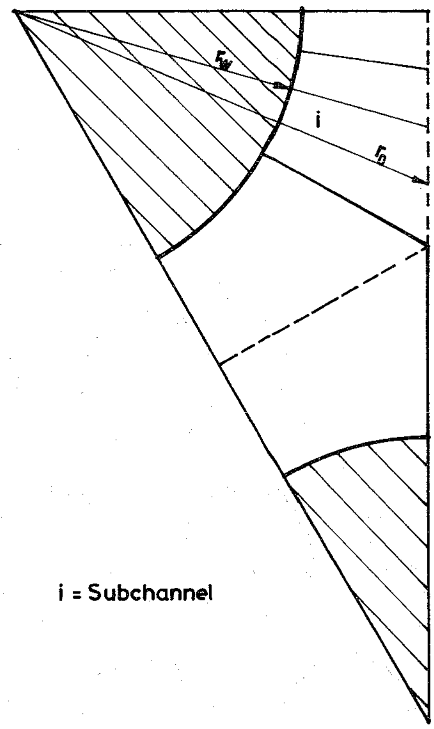


Fig. 2a Subdivision of the central channel A

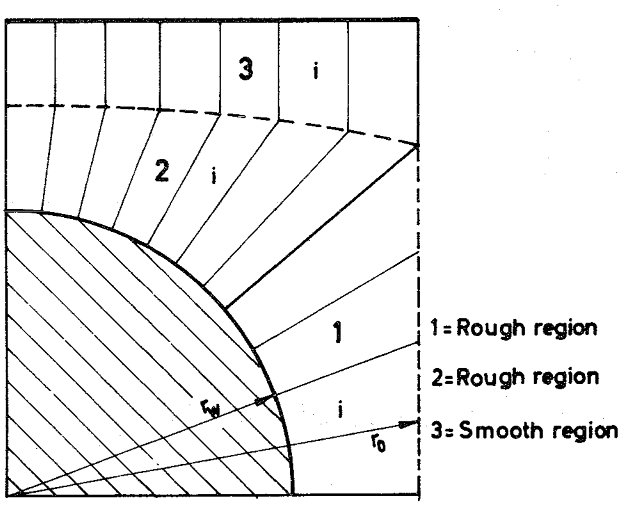


Fig. 2b Subdivision of the wall channel B

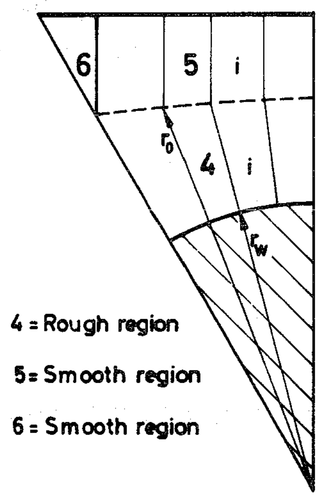


Fig. 2c Subdivision of the corner channel C

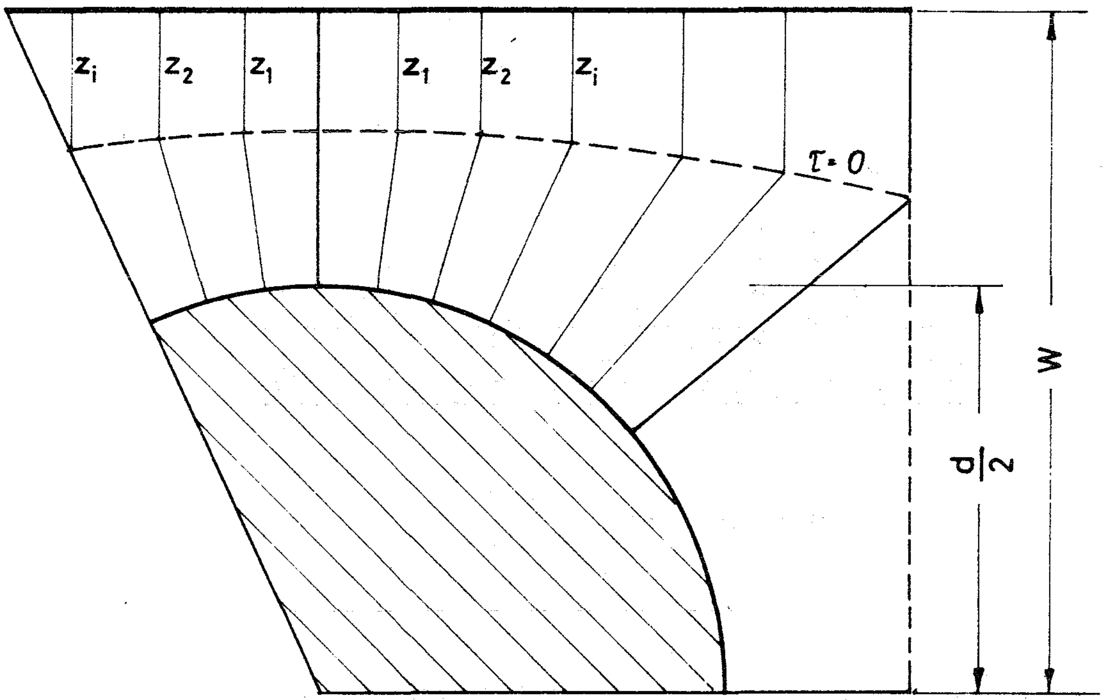
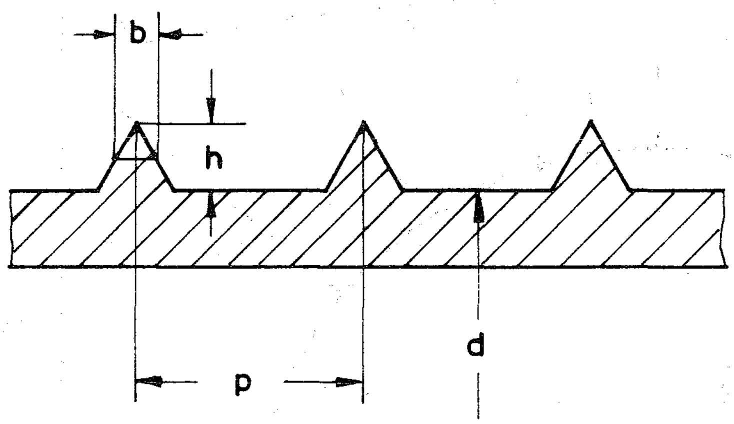


Fig. 3 Determination of the line $\tau = 0$ in the wall and corner channel



h = 0.111 mm   p/h = 8.25   h/b = 1.73

p = 0.916 mm   h/d = 0.00617

Fig. 4 Geometry of the roughness

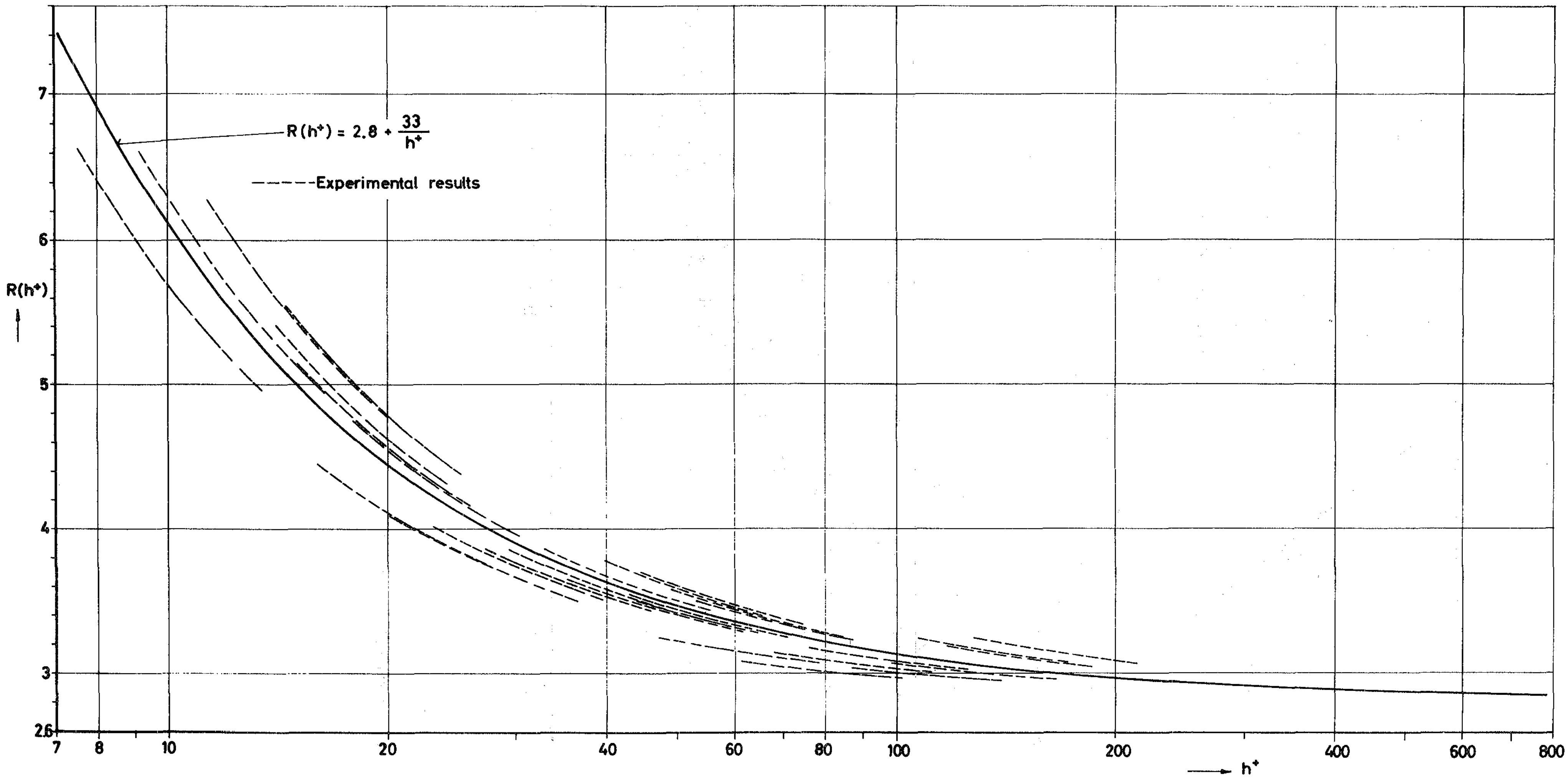


Fig. 5 Roughness function R (h⁺)

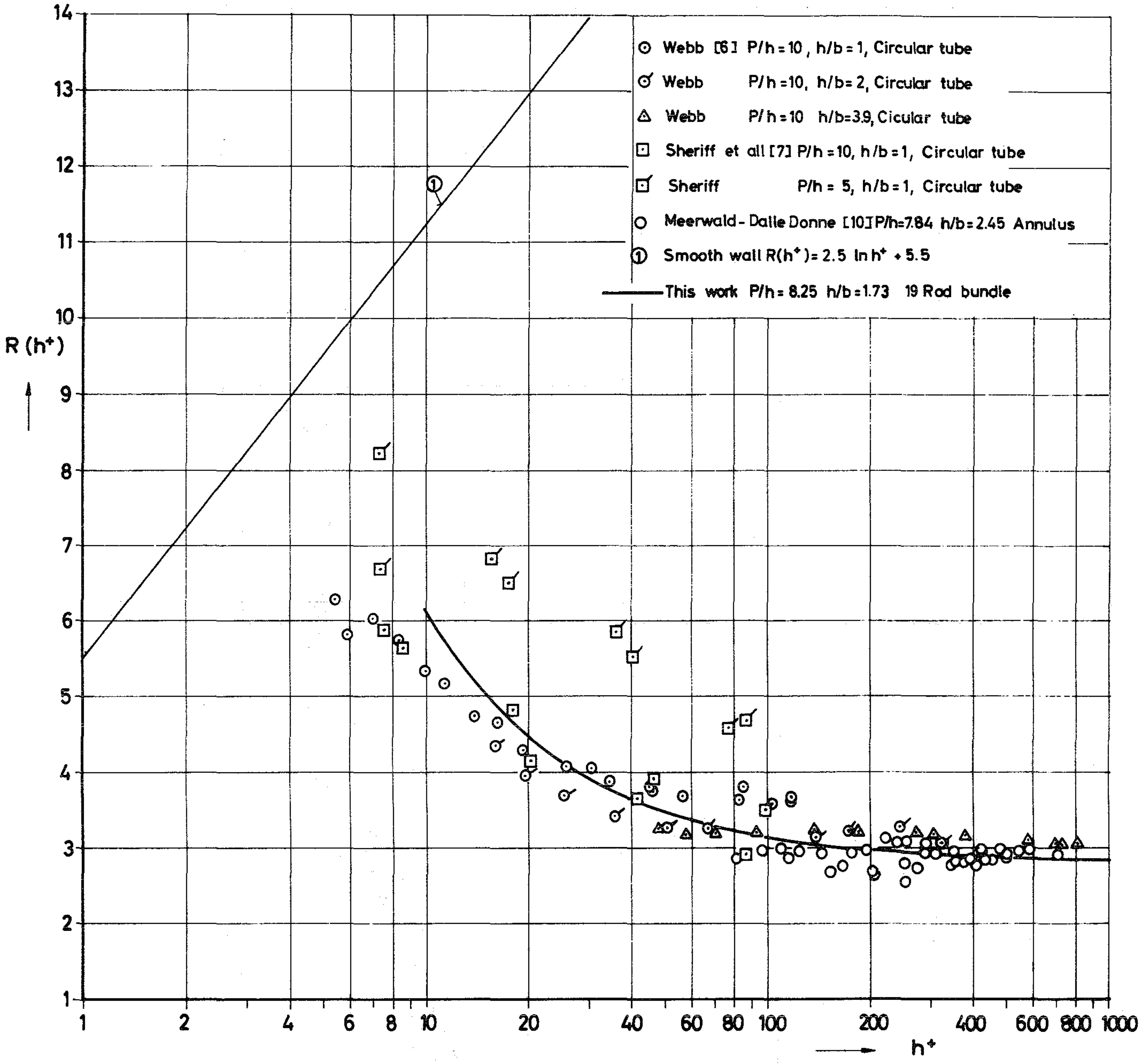
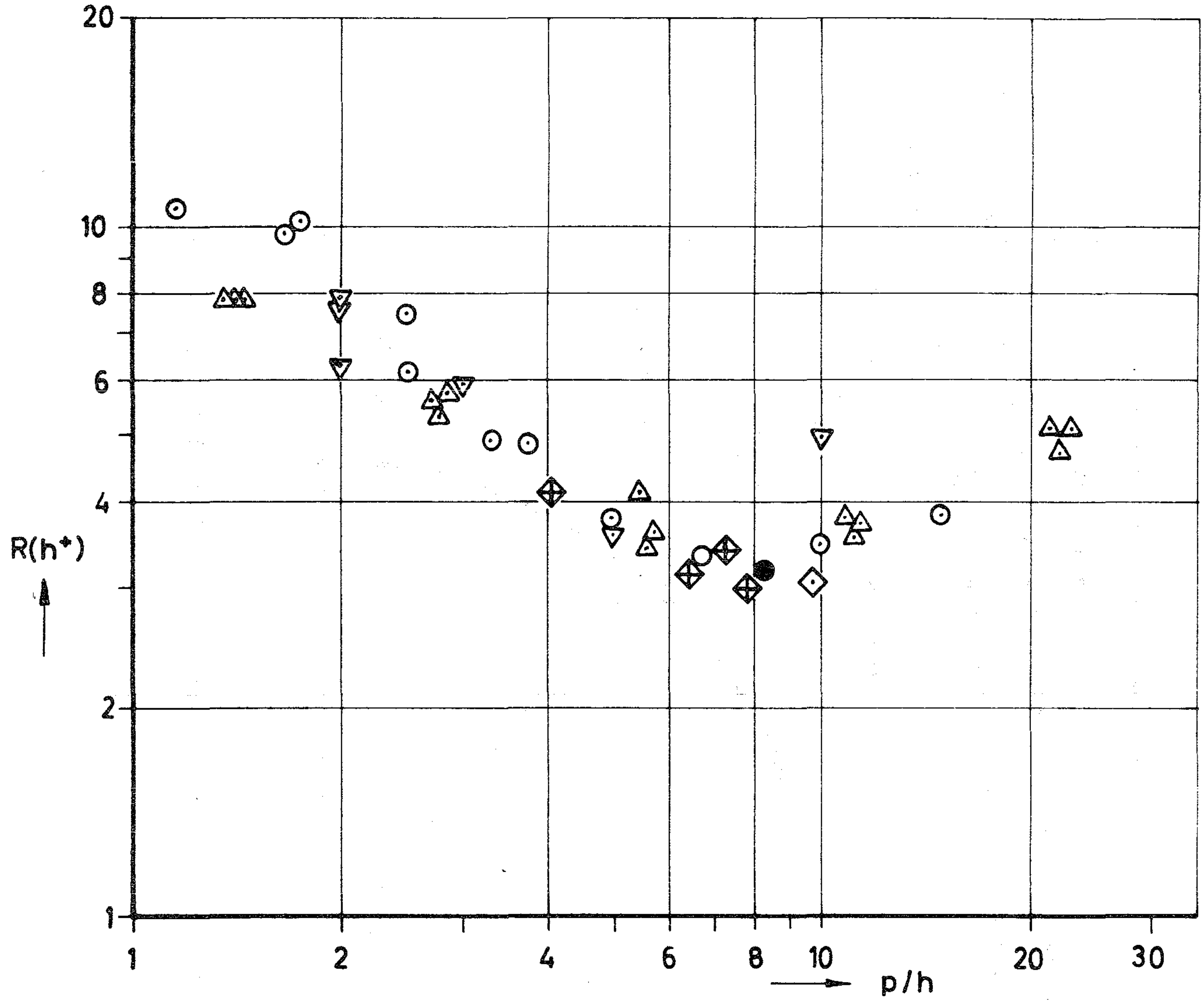


Fig. 6 Roughness funktion $R(h^{+})$



Δ Rampf-Feuerstein [9]

∇ Puchkov [11]

⊙ Feuerstein [12]

◇ Koch [13]

◈ Meerwald [14]

● This work

Fig. 7 $R(h^+)$ - values for $h^+ \geq 100$

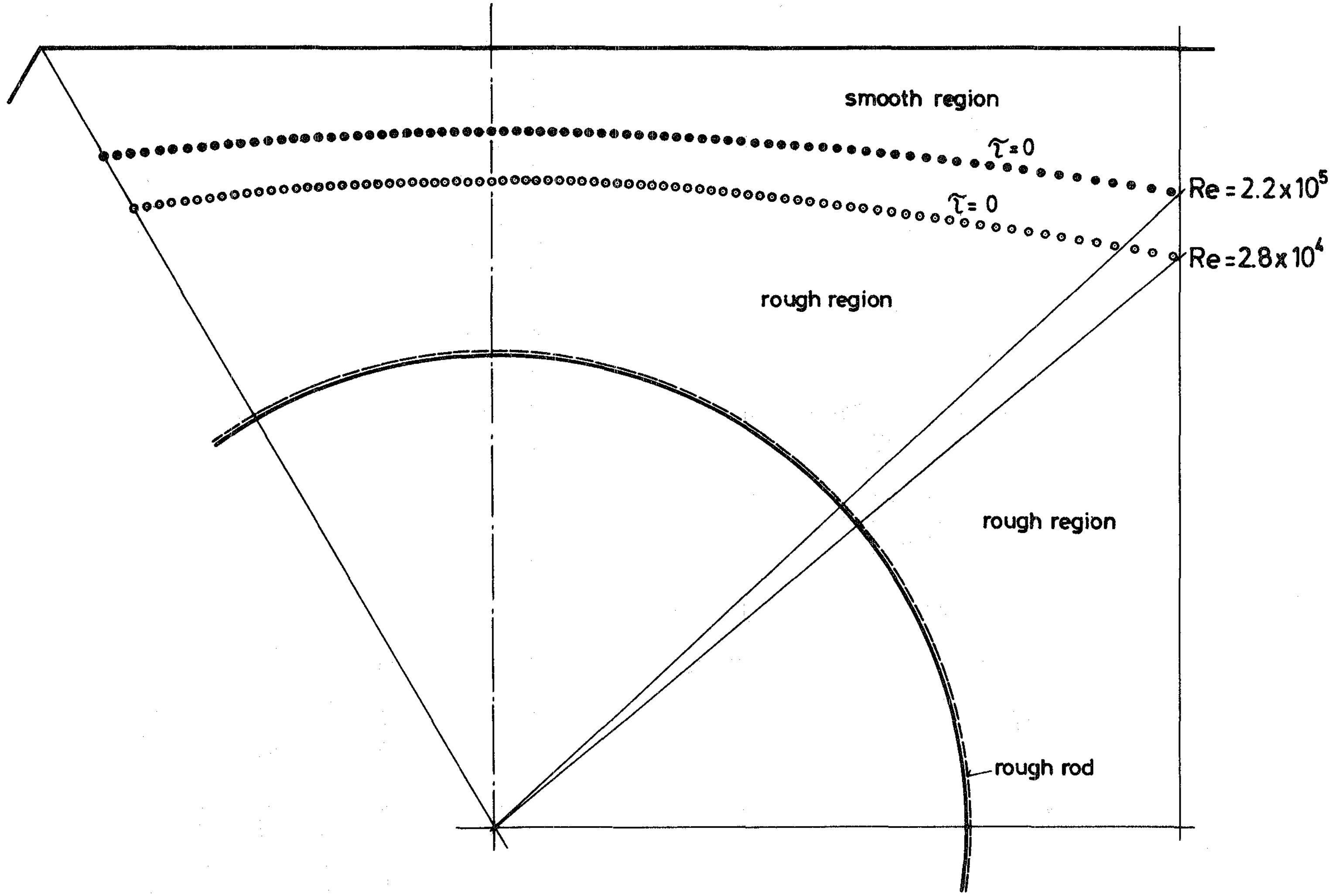


Fig. 8 Partition of the smooth and rough region in wall and corner channel

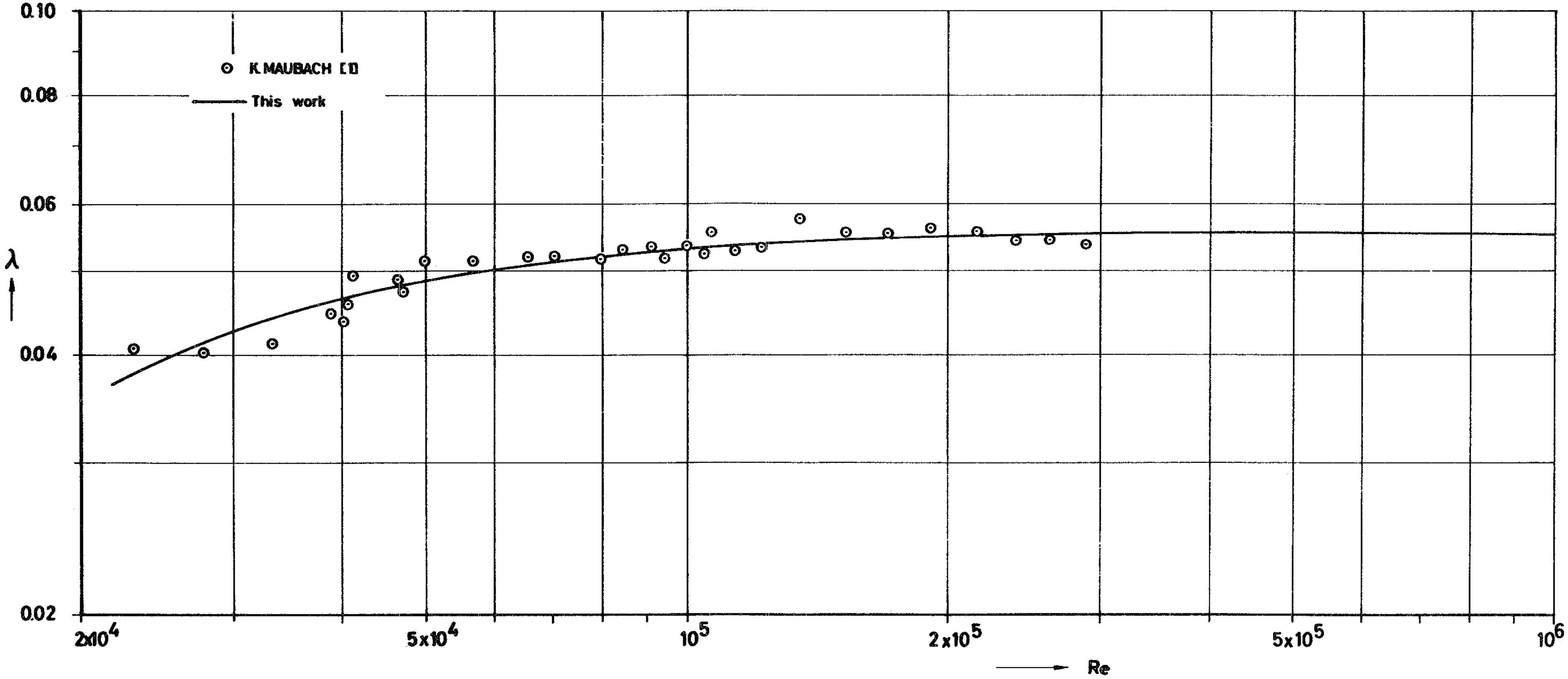


Fig. 9 Friction factor of the rough rod bundle