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Abstract

The roughness parameters $R(h^+)$ calculated on the basis of the theoretical method of Kobzar' have been compared with those experimental values correlated by Baumann and Rehme, and Dalle Donne and Meyer. It is observed that in case of Kobzar's method the h/L-effect on $R(h^+)$ is opposite to the experimentally determined increasing tendency of $R(h^+)$ with increasing h/L. Moreover the $R(h^+)$- values in case of Kobzar' lie always higher than the experimental values.

However, as Kobzar' has considered less experimental data to determine the correlation between the friction factor ζ and the roughness variable $K\omega$, it is shown that this method can be improved by taking more experimental data from the literature. It is also found that the re-attachment length defined in terms of rib heights has a remarkable influence on the roughness parameter $R(h^+)$. By varying the re-attachment length a better agreement is found between the predicted and the experimental values of the roughness parameter.

Vergleich der theoretischen Methode von Kobzar' zur Berechnung von Rauhigkeitsparametern mit experimentellen Ergebnissen

Zusammenfassung

Die nach der theoretischen Methode von Kobzar' berechneten Rauhigkeitsparameter $R(h^+)$ wurden mit Beziehungen verglichen, die Baumann und Rehme sowie Dalle Donne und Meyer aus experimentellen Werten ermittelt haben. Es ist zu beobachten, daß die Rauhigkeitsparameter $R(h^+)$ nach der Methode von Kobzar' mit steigendem h/L absinken, was im Gegensatz zu den Auswertungen der experimentellen Ergebnisse steht. Darüberhinaus liegen die $R(h^+)$-Werte nach Kobzar' durchweg über den experimentell bestimmten Werten.
Kobzar' benutzte jedoch nur wenige Versuchsdaten, um die Beziehung zwischen dem Reibungsbeiwert ζ und der Rauhigkeitsvariablen K_ω zu bestimmen. Im Rahmen der Arbeit wird daher gezeigt, daß diese Methode durch Verwendung weiterer Versuchsergebnisse aus der Literatur verbessert werden kann. Ebenso wird gefunden, daß die in Vielfachen der Rippenhöhe definierte sog. "re-attachment"-Länge einen bemerkenswerten Einfluß auf den Rauhigkeitsparameter $R(h^+)$ aufweist. Durch Änderung der "re-attachment"-Länge ergibt sich eine bessere Übereinstimmung zwischen den berechneten und den experimentell gefundenen Werten des Rauhigkeitsparameters.

CONTENTS

1. Introduction

Due importance is given to the efficient core heat transfer in the development of fast reactors because of their high power density (i.e. small core size and high operating temperature). Liquid metals are undoubtedly good heat transfer media because of their high specific heat and thermal conductivity. But due to their induced radioactivity, change in phase during operation and possibility of fire due to any leakage in the secondary flow system (i.e. water reacts with liquid sodium and leads to fire), gases (e.g. Helium) have been given an alternate choice as coolant. The major advantages of gases as coolants are as follows:

a) low chemical activity;
b) low neutron absorption and
c) one phase flow, which makes the operation very simple.

But because of their low density and thermal conductivity heat transfer from the fuel elements is not good.

So various workers have tried to improve heat transfer in case of gas cooling by extending the heat-transfer surfaces i.e. by putting fins of different types on the fuel elements (Magnox reactors). Another possibility to improve the heat transfer from the fuel elements is to roughen the heat-transfer surfaces artificially.

Generally the artificial roughness is cut on a heat-transfer surface in a definite geometrical shape, and therefore it is possible to combine the various geometrical parameters of a roughness element (e.g. rib spacing, rib height and rib width) according to the technical needs. The advantage of artificial roughness in case of gas cooling can be described as follows:

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> During the convective heat transfer, very near to the wall a viscous sublayer is formed, where the heat transfer is done by conduction. Since the thermal conductivity of gases is very low, this viscous sublayer acts as an insulator. Now by putting artificial roughness in such a case, we are breaking up this viscous sublayer by producing turbulence. As a result heat transfer is improved.

But due to turbulence an additional loss of pressure is caused. So it has become important to optimise the artificial roughness to produce turbulence necessary to reduce the wall temperature efficiently without causing an unnecessary loss of pressure.

Accordingly to assess the thermal performance of the artificial roughness a dimensionless parameter St^3/λ has been introduced, where the Stanton number (St) is directly proportional to the convective heat-transfer coefficient (α_c) and the total friction factor (λ) is directly proportional to the pressure drop (Δp). We can experimentally determine the friction factor from the isothermal pressure drop measurements or from the measurements of the velocity distribution. But it is too expensive and time consuming to determine the friction factors for all possible artificial roughnesses.

So Baumann and Rehme /2/ and Dalle Donne and Meyer /3/ have given some correlations on the basis of the experimental results to compute friction factors as a function of various geometrical parameters of the roughness elements (p/h, h/b, h/L), where,

p/h = pitch/rib height
h/b = rib height/rib width
h/L = rib height/ the length of the velocity profile.

Moreover, a theoretical method to determine friction factors on the basis of the universal velocity profile and the roughness geometry has been developed by Kobzar /1/. So it has become a technical interest for us to have a comparative study of all the possible ways of computing friction factors.

Therefore, the present work is aimed to develop a computer program according to the method of Kobzar for two-dimensional roughness (rectangular transverse ribs) in a circular tube. Moreover, the results have to be compared with the experimental values correlated by Baumann and Rehme /2/ and Dalle Donne and Meyer /3/ in the following range of the geometrical parameters:

$$2 \leq p/h \leq 25$$
$$0.3 \leq h/b \leq 5$$
$$0.01 \leq h/L \leq 0.20$$

by using the following relation /4/:

$$\sqrt{\frac{8}{\lambda_{vol}}} = 2.5 \ln \left(\frac{L}{h}\right) + R(h^+) - G \qquad (1)$$

where, $R(h^+)$ = roughness parameter (characteristic value of the roughness geometry)

G = geometry parameter (characteristic value of the channel geometry)

λ_{vol} = total friction factor evaluated at the volumetric diameter D_{vol} of the tube.

For a circular tube it is given in /4/

$$G = 3.75$$
$$L = 0.5\, D_{vol}$$

2. Description of the different ways of computing roughness parameters

2.1 Method of Kobzar

The method of Kobzar is based on an equivalent diameter known as effective diameter (D_{eff}), and is defined as follows:

$$D_{eff} = \sqrt{\frac{4\, V_{eff}}{\pi\, l}} \qquad (2)$$

where, V_{eff} = effective volume of the tube
= inner volume - the volume of the eddy vortex
l = length of the tube

The angle of penetration α and the angle β, (see Fig.1) which determine the volume of the eddy vortices are defined as follows:

$$\alpha = \text{arc tan } (h/RAL) \tag{3}$$

where, RAL = re-attachment length (defined as the length at which the free stream again touches the wall behind the end of a rib).

In his method, Kobzar has assumed the re-attachment length (RAL) to be 8 times the rib height (h) and the angle β is 45° for all cases. The effective height of the roughness element (h_{eff}) is defined as:

$$h_{eff} = \frac{(p-b) \sin \alpha \ \sin \beta}{\sin(\alpha+\beta)} \tag{4}$$

At $h_{eff} > h$, h_{eff} is assumed to be h.
According to him the flow resistance of a rough tube can be represented as the sum of the skin drag of an equivalent smooth tube (i.e. if the rough tube is replaced by a smooth tube of an equivalent diameter D_{eff}) and the form drag of the individual roughness element.
So, by making a force balance over a unit length Δl (see Fig.1a) in fully rough flow we get,

$$\Delta p \cdot \frac{\pi D_{eff}^2}{4} = \tau_s \pi D_{eff} \Delta l + \sum_{i=1}^{n} P_{\phi_i} \tag{5}$$

where, Δp = pressure drop over a unit length Δl
τ_s = wall shear stress of a smooth tube of diameter D_{eff}
n = No. of roughness elements in Δl
P_ϕ = form drag of a roughness element

The form drag p_ϕ is expressed as follows:

$$p_\phi = c_\phi \; F_h \; \frac{\rho \bar{u}_F^{\;2}}{2} \tag{6}$$

where,
c_ϕ = drag coefficient
F_h = projected cross-section of the roughness element in the flow direction
$\bar{u}_F$ = average velocity over the area F_h along the rib height

From the definition of the friction factor we get,

$$\Delta p = \lambda_{eff} \; \frac{\Delta l}{D_{eff}} \; \frac{\rho \bar{u}_{eff}^{\;2}}{2} \tag{7}$$

and the wall shear stress is expressed as :

$$\tau_s = \lambda_s \; \frac{\rho \bar{u}_{eff}^{\;2}}{8} \tag{8}$$

where,
λ_{eff} = total friction factor evaluated at D_{eff}
λ_s = smooth friction factor evaluated at D_{eff}
$\bar{u}_{eff}$ = average velocity over the effective flow cross-section (F_{eff})
F_{eff} = $\frac{\pi}{4} D_{eff}^{\;2}$
ρ = fluid density

Putting Equs.(6) to (8) in Equ.(5) we get,

$$\lambda_{eff} = \lambda_s + \frac{D_{eff}}{\Delta l} \; n \; c_\phi \; \frac{F_h}{F_{eff}} \left[\frac{\bar{u}_F}{\bar{u}_{eff}} \right]^2 \tag{9}$$

considering Δl = pitch = p (i.e. n=1), Equ.(9) can be written as:

$$\lambda_{eff} = \lambda_s + \frac{D_{eff}}{p} \; c_\phi \; \frac{F_h}{F_{eff}} \left[\frac{\bar{u}_F}{\bar{u}_{eff}} \right]^2 \tag{10}$$

Now we define a term ζ as the difference between the total friction factor (λ_{eff}) and the smooth friction factor (λ_s), and consider this as the rough friction factor. ζ can be represented by the following expression:

$$\zeta = \frac{D_{eff}}{p} \quad c_\phi \frac{F_h}{F_{eff}} \left[\frac{\bar{u}_F}{\bar{u}_{eff}} \right]^2 \qquad (11)$$

After proper analysis of the experimental results Kobzar has found that the drag coefficient c_ϕ depends on the form of the roughness elements and therefore he expresses c_ϕ as a function of the angle of attack γ (see fig.1).

So the form drag p_ϕ can be written in the following general form with u as the undisturbed flow velocity over the cross-sectional area F:

$$p_\phi = c\ f(\gamma)\ F \frac{\rho u^2}{2} \qquad (12)$$

where, c is the drag coefficient at $\gamma = 90^\circ$, and the function $f(\gamma)$ varies within $0 \leq f(\gamma) \leq 1$.

For our particular case, as the flow velocity in front of the roughness element is inhomogeneous it is logical to integrate the local velocity component $u(y_h)$ over the area F_h along the effective height of the roughness element (h_{eff}) to obtain the form drag p_ϕ of the roughness element.
i.e.

$$p_\phi = c \int_{F_h} f(\gamma)\ \frac{\rho}{2} \left[u(y_h) \right]^2\ dF \qquad (13)$$

where, $u(y_h)$ = local velocity at a distance y_h

y_h = distance from the effective root of the roughness element in the direction of the centre of the tube (see Fig.2)

dF = unit element of area

Taking into consideration this integral form of the form drag p_ϕ, we can rewrite Equ. (11) as:

$$\xi = \frac{D_{eff}}{p} \quad c \int_{F_h} f(\gamma) \left[\frac{u(y_h)}{\bar{u}_{eff}} \right]^2 \frac{dF}{F_{eff}} \qquad (14)$$

To compute ζ according to Equ. (14) the velocity distribution in front of the roughness element should be known. No doubt the velocity distribution is very much affected by the geometry of the roughness element near to the wall, but since no experimental results are available the dimensionless velocity distribution is assumed also to be valid in front of a roughness element. And the average dimensionless velocity profile in a rough tube is considered hypothetically to be the same as the velocity distribution in a smooth tube of diameter D_{eff} and is represented by the following equation with a very good approximation:

$$u^+_r = f(\eta + \Delta\eta) - f(\Delta\eta) \qquad (15)$$

where, $\Delta\eta$ = displacement/shifting of the dimensionless rough velocity profile from the dimensionless smooth velocity profile

η = dimensionless distance from the wall

For the function 'f' the following dimensionless smooth velocity profile from Millionshchikov /5/ is used:

$$u^+_s = \frac{1}{0.39} \ln \left[1+0.39(\eta-7.8)\right] +7.8 \qquad (16)$$

To take into account the deformation of the velocity profile near to the wall a transformation of the velocity profile given by Equ.(15) i.e. the shifting of the origin of the profile from D_{eff} to the effective root diameter is done under the following assumptions:

1) there is a geometrical similarity between the two profiles and

2) the mass flow rate remains constant.

Under the above assumptions from Fig.2 we get,

a) $$\frac{y_h}{R_h} = \frac{y_{eff}}{R_{eff}} \quad \text{and} \quad \frac{u(y_h)}{u_{maxh}} = \frac{u(y_{eff})}{u_{maxeff}}$$

or $$\frac{\bar{u}_h}{u_{maxh}} = \frac{\bar{u}_{eff}}{u_{maxeff}} \qquad (17)$$

b) $$\frac{\bar{u}_h}{\bar{u}_{eff}} = \left(\frac{R_{eff}}{R_h}\right)^2$$

From experiments it is found that the function $f(\gamma)$ can be good approximated as follows:

$$f(\gamma) = \sin^2 2\gamma \qquad \text{for } \gamma = 0 - 45^\circ \qquad (18)$$
$$f(\gamma) = 1 \qquad \text{for } \gamma = 45^\circ - 90^\circ$$

Moreover, Kobzar has found that the drag coefficient $[c_\phi = cf(\gamma)]$ depends on the friction factor. Therefore he has assumed that the right hand side in Equ. (14) should not be equal to ζ, but is proportional to ζ. Accordingly a new parameter known as roughness variable (K_ω) is defined in such a way that the constant 'c' drops automatically and the Equ. (14) reduces to:

$$\zeta = f(K_\omega) \qquad (19)$$

where,

$$K_\omega = \frac{D_{eff}}{p} \int_{F_h} f(\gamma) \left[\frac{u(y_h)}{\bar{u}_{eff}}\right]^2 \frac{dF}{F_{eff}} \qquad (20)$$

By using Equs. (15) to (18) in Equ. (20) the roughness variable K_ω is determined by a numerical integration over the effective height (h_{eff}) of the roughness element.

On the basis of the experimental results from the literature /5,6,7,8,9,10/ Kobzar has recommended the following correlation to represent Equ. (19):

$$\zeta = 30\, K_\omega^{1.8} \qquad (21)$$

with the following range of validity:

$$1 \leq p/h \leq 20$$
$$0 \leq h/L \leq 0.20$$

The total friction factor is the summation of the smooth friction factor (λ_s) and the rough friction factor (ζ).

i.e. $$\lambda_{eff} = \lambda_s + \zeta \tag{22}$$

The smooth friction factor (λ_s) is calculated as follows:

i) $$\lambda_s = \frac{0.3164}{Re_{eff}^{0.25}} \tag{23}$$

according to Blasius for $Re_{eff} \leqslant 10^5$

ii) $$\lambda_s = 0.0032 + \frac{0.221}{Re_{eff}^{0.237}} \tag{24}$$

according to Nikuradse for $Re_{eff} > 10^5$

where, $$Re_{eff} = \frac{D_{vol}}{D_{eff}} \quad Re_{vol} \tag{25}$$

The total friction factor evaluated at D_{eff} is transformed to D_{vol} as follows:

$$\lambda_{vol} = \lambda_{eff} \left(\frac{D_{vol}}{D_{eff}} \right)^5 \tag{26}$$

Using the value of λ_{vol} in Equ.(1) the roughness parameter (R) is calculated as follows:

$$R(h^+) = \sqrt{\frac{8}{\lambda_{vol}}} - 2.5 \ln \left(\frac{0.5\ D_{vol}}{h} \right) + 3.75 \tag{27}$$

2.2 Correlation of Baumann and Rehme /2/

The roughness parameter R can be written as a function of geometrical parameters of the roughness elements in dimensionless quantities as follows:

$$R = f(p/h,\ h/b,\ h/L) \tag{28}$$

The dependence of the roughness parameter on h/L is determined by a polynomial setup and expressed by the following relation at a given reference:

$$R_{k1,k2} - R_{0\,k1,k2} = \sum_{k=2}^{n} Z_k (h/L)^{k-1} \tag{29}$$

where, k_1 = a reference h/b

k_2 = a reference p/h

R_0 = roughness parameter at $h/L \rightarrow 0$

Now for random values of h/b and p/h Equ.(29) can be written as:

$$R - R_o = \frac{R_o}{R_{o\,k1,k2}} \sum_{k=2}^{n} z_k \ (h/L)^{k-1} \qquad (30)$$

Substituting Equ.(29) in Equ.(30) and re-arranging we can write:

$$R = R_o + \frac{R_o}{R_{o\,k1,k2}} \ (R_{k1,k2} - R_{o\,k1,k2}) \qquad (31)$$

For the simplification of the Equ.(31) R_o was defined as a function of h/b & p/h only and approximated by the following relation:

$$R_o = a_1 (p/h)^{a_2} + a_3 (p/h)^{a_4} \qquad (32)$$

in the following range of validity:

$$1 \leq p/h \leq 40$$
$$0.3 \leq h/b \leq 8$$
$$R_o \leq 10$$

where,
$$a_1 = 18.5 (h/b)^{-0.9475}$$
$$a_2 = -1.143 (h/b)^{-0.147}$$
$$a_3 = 0.33 \ (h/b)^{0.1483}$$
$$a_4 = 0.758 (h/b)^{-0.11}$$

Now by normalizing all the experimental data to a reference $h/b=k_1=1.4622$ and to a reference $p/h=k_2=10$, the dependence of roughness parameter on h/L is approximated by a Least Squares Fit as follows:

$$R_{k1,k2} = 2.900 + 1.490 \ h/L - 1.972 \ (h/L)^2 \qquad (33)$$

When $h/L \rightarrow 0$, $R_{k1,k2} \rightarrow 2.900$, which is by definition $R_{o\,k1,k2}$.

2.3 Correlations of Dalle Donne and Meyer /3/

The experimental results have been correlated as follows:

$$R(\infty)01 = 9.3 \left(\frac{p-b}{h}\right)^{-0.73} - \left[2 + \frac{7}{(p-b)/h}\right] \log_{10} \frac{h}{b} \pm 1 \qquad (34)$$

$$\text{for} \quad 1 \leq \frac{p-b}{h} \leq 6.3$$

$$R(\infty)_{01} = 1.04 \left(\frac{p-b}{h}\right)^{0.46} - \left[2 + \frac{7}{(p-b)/h}\right] \log_{10} \frac{h}{b} \pm 1 \qquad (35)$$

$$\text{for } 6.3 \leq \frac{p-b}{h} \leq 160$$

$$R(h^+) = R(h^+)_{01} + 0.4 \ln\left(\frac{h/L}{0.01}\right) \qquad (36)$$

It is assumed at $h^+ \geq 150$, $R(h^+)_{01} = R(\infty)_{01}$

The above equations are restricted to the following range:

$$2 \leq \frac{p-b}{h} \leq 20$$
$$0.25 \leq \frac{h}{b} \leq 2$$
$$0.008 \leq \frac{h}{L} \leq 0.235$$

3. Results and Discussion

On the basis of the method of Kobzar a FORTRAN program has been written to compute the roughness parameter R as a function of the geometrical parameters of the roughness element (p/h, h/b, h/L) for the following requirements:

a) for fully rough flow, $Re_{vol} \geq 10^5$
b) for flow through a circular tube
c) for rectangular transverse ribs in the following range

$$2 \leq p/h \leq 25$$
$$0.3 \leq h/b \leq 5$$
$$0.01 \; h/L \leq 0.20$$

The correlations of Baumann and Rehme and of Dalle Donne and Meyer to compute the roughness parameter have also been incorporated in this program. For the documentation, the program has been listed in the Appendix.
Using this program the values of the roughness parameters according to Kobzar (RK), Baumann and Rehme (RR) and Dalle Donne and Meyer (RD) have been listed in Tables 1 and 2.

To study the influence of p/h and h/b on the roughness parameter the values RK, RR and RD have been plotted against p/h ($4 \leq p/h \leq 20$) in log-log co-ordinates for h/L = 0.01 and for different values of h/b($0.3 \leq h/b \leq 4$). From the figures 3,4,5 it is observed that the R-values have a minimum in the vicinity of p/h = 10. From there with increasing p/h and also with decreasing p/h the R-values increase, that means the friction factor decreases. Now, on the basis of the Figs.1b and 1c we can explain this phenomenon as follows:

When the spacing between two ribs (p-b) is just equal to ($h/\tan \alpha + h/\tan \beta$) the eddy produced is optimum and the utilization of the roughness height is maximum ($h_{eff} = h$). Now with increasing p/h for a given h/b, (p-b) increases. As a result the main stream comes in contact with a smooth surface inbetween and therefore the total friction factor decreases. Similarly for decreasing p/h for a given h/b, (p-b) decreases. As a result h_{eff} becomes smaller than the rib height that means the surface appears to be smoother to the flow and therefore the friction factor decreases.

From the same figures it is observed that with increasing h/b the R-values decrease, that means the friction factor increases.
The reason is that for the same p/h at the smaller values of h/b (e.g. 0.3, 0.5) the surface appears to be smoother to the flow, on the other hand at the heigher values of h/b (e.g. 3,4), the roughness elements are very sharp and the main stream experiences high turbulence. Therefore the friction factor increases and consequently the R-values decrease.

For the comparison of the three R-values (RK,RR,RD) from the figure 3 it is seen that for smaller h/b values (0.3 and 0.5) the three curves lie close to each other. Especially RR and RD lie very close to each other i.e.within $\pm$ 10% (the difference was built up with RR as reference) and remarkably RK lies always higher and varies within +4% to +40%. At $p/h \approx 10$ the difference is minimum. For $p/h < 7$ roughness parameters were not computed according to the method of Kobzar, because according to his definition the flow remains no more in the fully rough region. With increasing h/b (Figs.4,5) the difference between RR and RK increases to about +150%. The reason is that the effect of h/b in case of Kobzar's method is very low compared to the other two curves. But in principle RK also decreases with increasing h/b as explained earlier. It can also be mentioned here that although h/b=2 is the higher limit of the correlations of Dalle Donne and Meyer, it appears from the Fig.4 that the difference between RR and RD comes to about -44% and at p/h=7 the minimum value of RD is approximately 1.5, which seems to be a relative low value for the roughness parameter.

In figures 6 and 7 the three values of the roughness parameter (RK,RR,RD) have been plotted against h/L ($0.01 \leq h/L \leq 0.20$) for h/b = 1.0 and 0.3, for p/h = 10 and 8. It is very remarkable that while the experimental values of roughness parameter (RR and RD) increase with increasing h/L, the theoretical values of the roughness parameter computed according to the method of Kobzar (RK) tend to decrease.
But it is interesting that for higher h/b values at $p/h \geq 8$ there is also a tendency of the roughness parameter to increase for $h/L \geq 0.16$.

For values of $h/b \leq 1$ RR-and RD-values are in very good agreement to each other (i.e. within ± 10%) and the RK-values are always higher. But as RK has an opposite tendency, at $h/L \geq 0.10$ it comes closer to the other two curves. It is also observed from the figures that the RR-values increase very slowly with increasing h/L whereas the RD-values increase considerably faster.

Now, from the above discussion it can be concluded that the method of Kobzar can be applied satisfactorily for a very small range of our interest only (namely for $7 \leq p/h \leq 20$, $h/b \leq 0.5$, and h/L = 0.01). Outside this range the RK-values are too high compared to the experimental data from the literature (RR and RD). Moreover the method of Kobzar contradicts the experimentally measured h/L effect on the roughness parameter.

However, since the method of Kobzar is based on a logical system, it is believed that an improvement of this method may be possible.

4. Proposed improvements of the method of Kobzar

4.1 Additional experimental data

It is seen from the computation of the roughness parameters according to Kobzar that the roughness variable K_ω for the given roughness geometry $2 \leq p/h \leq 20$, $0.3 \leq h/b \leq 5.0$, $h/L=0.01$ lies within 0.01 and 0.03. But in the determination of $\zeta = f(K_\omega)$ Kobzar has considered a few experimental data in the said region (see Fig.8). Moreover our present interest is only for the rectangular transverse ribs. Therefore, we have discarded all data for non-rectangular ribs. However we have taken into account additional experimental data of friction factors measured in tubes with rectangular transverse ribs available from the literature /6,7,8,9,10,11,12/ in the following range ($1 \leq p/h \leq 40$, $0.1 \leq h/b \leq 11$, $0.67 \leq (p-b)/h \leq 40$, $0.01 \leq h/L \leq 0.34$). All of them are listed in Table 3. Now, the K_ω-values have been computed according to the method of Kobzar for the known values of ζ and have been plotted in Fig. 9a, where ζ is represented by 'ZETR' and K_ω is represented by 'XKW', respectively. By using a Least Squares Fit(LSF) the following correlation (No.1) is obtained:

$$ZETR = 5.728 \quad XKW^{1.134} \tag{37}$$

Which can be a replacement of the correlation of Kobzar given in Equ.(27). For the documentation the values of ζ and K_ω have been listed under ZETR1 and XKW1 in Table 3.

It is seen from Fig.9a that for smaller values of XKW there is a considerable scattering of the experimental data. However no definite reason for this scattering is known to us. But from the discussions in the 4th Specialist Meeting on GCFR Heat Transfer at Karlsruhe in October 1977 we came to know that the re-attachment length was measured from 4 to 13 rib heights depending on different roughness geometries. So we thought that the assumption of the re-attachment length equal to 8h may have some influence on this scattering of the experimental data.

4.2 Changing the re-attachment length

Since Kobzar has developed his method on the basis of the effective diameter (see Fig.1) the re-attachment length of the free stream on the wall (which determines the angle α and subsequently the effective diameter) has a very important role. Dalle Donne and Meyer /3/ have shown that there is a minimum of R-values at about $(p-b)/h = 6.3$. That means the optimum spacing between ribs is

$$\frac{h}{\tan\alpha} + \frac{h}{\tan\beta} = 6.3h. \tag{38}$$

Assuming as before $\beta=45^{\circ}$, the re-attachment length becomes $RAL = \frac{h}{\tan\alpha} = 5.3h$, i.e. $\alpha = \arctan(1/5.3)$.

On the basis of this assumption the XKW-values have been calculated and plotted in Fig.9b. By using a Least Squares Fit (LSF) the following correlation (No.2) is obtained:

$$ZETR = 6.632 \quad XKW^{1.257} \tag{39}$$

From the figure it is very interesting to mark that there is a definite influence of the re-attachment length.

For example in Fig.9a for smaller values of XKW the deviation in ZETR is higher, on the other hand in Fig.9b all the experimental data in this region have come close to each other, but for higher values of XKW the deviation is higher than in Fig.9a. Moreover in Fig.9b the whole set of the experimental data has been shifted towards the right hand side that means towards higher values of XKW as compared with Fig.9a. This shifting confirms the influence of the re-attachment length on the computation of the roughness parameter (R).

Now by varying the re-attachment length from 5.3h to 8h we tried to find out the best fit of the experimental data. In Fig. 10 we have plotted the standard deviation (σ) for different values of re-attachment length/rib height (RAL/h). It is found that the error becomes a minimum (i.e. the scattering of the points becomes the smallest) at RAL/h=6.6 (σ=0.13648). Therefore we recommend the optimum spacing between two ribs as 7.6 times the rib height and the corresponding correlation (No.3) which is shown in Fig. 11 as the best fit.

$$ZETR = 7.633\ XKW^{1.263} \tag{40}$$

In this case the values of ζ and K_{ω} have been listed as ZETR3 and XKW3 in Table 3.
For a comparison, we have plotted all the three modified correlations [Equs.(37),(38) and (40)] and the correlation of Kobzar [Equ.(21)] in Fig. 12.

4.3 Results of the improved method

To visualize the improvement of the method of Kobzar, the values of the roughness parameters according to the modified correlation No.1 with RAL = 8h(RK*) and according to the modified correlation No.3 with RAL=6.6h(RK**) have been calculated using the same FORTRAN program and have been listed in Tables 1 and 2.
For comparison the R-values according to Kobzar's method and its two modifications (RK*, RK**) have been plotted with RR and RD as a function of h/L in figures 13,14,15,16,17 for different values of p/h (10,8,6,4) and h/b (0.3,1,4) respectively.
The important achievement is that the h/L effect on the roughness parameter in case of both the modified correlations (in figures indicated as Kobzar *, Kobzar **) shows an increasing tendency which is in agreement with the experimental values (RR and RD). From the figures it is observed that for small h/b (=0.3) RK**

lies below RR and RD (the maximum deviation is -23% at p/h=10), but for higher h/b (≥ 4) RK ** lies above RR for p/h ≥ 8 (the maximum deviation is +27%). It can be also seen that for p/h ≤ 6 there is a downward tendency in RK* and RK**-values with increasing h/L.
Moreover for the same h/b (=1,4) at p/h = 10,8 the positions of the curves corresponding to RK* and RK** have been interchanged. From these phenomenon it seems to us that the re-attachment length should be different for different roughness geometries. That means it should be a function of p/h and h/b, rather than a constant value applied to all roughness geometries.

From figures 18,19 and 20 the improvement in the calculation of the roughness parameter as a function of p/h can be clearly seen. Remarkable is that according to the modified correlations(No.1 and 3) computations of the roughness parameters are possible for p/h < 7 even at h/b < 0.5, which is not possible according to the method of Kobzar. Moreover in general RK*-and RK**-values have come nearer to the experimental values (RR and RD) compared to the RK-values. For h/b ≤ 1 and p/h ≤ 8 the agreement between the modified R-values (RK*, RK**) and the experimental R-values (RR, RD) is very good (deviation is within +5% and -10% compared to RR; and compared to RD there is almost no deviation).

5. Conclusion

From the above discussions the following conclusions may be drawn:

a) The method of Kobzar may be a useful tool to predict the roughness parameter R and thereby the friction factors of different roughnesses.

b) Since the method of Kobzar is based on a few experimental data, it is shown in this work that this method can be improved by taking into account more experimental data from the literature to obtain the correlation between the rough friction factor and the roughness variable.

c) It is found that the re-attachment length (defined in terms of rib heights) has a remarkable influence on the roughness parameter R. By changing the re-attachment length from 8h to 6.6h, a better agreement has been found between the predicted and the experimental values of roughness parameters.

d) A further improvement of this method may be achieved by applying a variable re-attachment length. But up-to-now no experimental data are available to represent the re-attachment length as a function of the geometrical parameters of the roughness element.

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Nomenclature

b	= width of the roughness element
c_ϕ	= drag coefficient
D_{eff}	= effective diameter of the tube
D_{root}	= root diameter of the tube
D_{vol}	= volumetric diameter
F_{eff}	= effective cross-sectional area of the tube
F_h	= projected cross-sectional area of the roughness element with effective height
dF	= unit element of area
G	= geometry parameter
h	= height of the roughness element
h_{eff}	= effective height of the roughness element
h^+	= dimensionless height of the roughness element
K_ω	= roughness variable
l	= length of the tube
Δl	= unit length
L	= the length of the velocity profile from the wall to the line of the zero-shear stress
p	= pitch of the roughness element
Δp	= pressure drop over a unit length Δl
p_ϕ	= form drag of a roughness element
R	= roughness parameter
R_o	= roughness parameter at $h/L \rightarrow 0$
$R(h^+)$	= roughness parameter evaluated at h^+
$R(\infty)$	= roughness parameter for the fully rough flow
$R(\infty)_{01}$	= $R(\infty)$ evaluated at $h/L = 0.01$
$R_h = R_{in} + h_{eff}$	= effective root radius
R_{eff}	= effective radius
R_{in}	= inner radius of the tube
RAL	= re-attachment length
Re_{eff}	= Reynolds number calculated with D_{eff}
Re_{vol}	= Reynolds number calculated with D_{vol}
$u(y_h)$	= local velocity at y_h
$u(y_{eff})$	= local velocity at y_{eff}
u^*	= friction velocity
$\bar{u}_{eff}$	= average velocity over the area F_{eff}
$\bar{u}_F$	= average velocity over the area F_h

$\bar{u}_h$	= average velocity over the area πR_h^2
u_s^+	= dimensionless velocity in a smooth tube
u_r^+	= dimensionless velocity in a rough tube
$u_{max_{eff}}$	= maximum velocity over F_{eff}
u_{max_h}	= maximum velocity over πR_h^2
V_{eff}	= effective volume of the tube
	= inner volume - volume of the eddy vortex
XKW	= roughness variable
y_h	= distance from the effective root of the roughness element
y_{eff}	= distance from the effective diameter towards the tube centre
ZETR	= rough friction factor
α	= the angle of penetration
α_c	= convective heat-transfer coefficient
β	= an angle shown in fig.2
γ	= the angle of attack
η	= dimensionless distance from the wall
ζ	= rough friction factor
λ_{eff}	= total friction factor evaluated at D_{eff}
λ_s	= smooth friction factor evaluated at D_{eff}
λ_{vol}	= total friction factor evaluated at D_{vol}
τ_s	= wall shear stress of a smooth tube
ν	= kinematic viscosity
ρ	= fluid density

<u>Notations used in Tables</u>

B	= width of the roughness element
DREF	= reference diameter
DROOT	= root diameter
H	= height of the roughness element
L	= length of the velocity profile
.LE.	= less than and equals to
P	= pitch of the roughness element
REVOL	= volumetric Reynolds number
RD	= roughness parameter according to the correlation of Dalle Donne and Meyer

RK = roughness parameter according to the method of Kobzar

RK* = roughness parameter according to Equ.(37) with RAL=8h and represented in the figures as 'KOBZAR*'

RK** = roughness parameter according to Equ.(40) with RAL=6.6h and represented in the figures as 'KOBZAR**'

RR = roughness parameter according to the correlation of Baumann and Rehme

XLAMREF = total friction factor evaluated at the reference diameter

XKW = roughness variable (K_ω)

ZETR = rough friction factor (ζ)

1 refers to RAL = 8.0 h

2 refers to RAL = 5.3 h

3 refers to RAL = 6.6 h

Table 1. ROUGHNESS PARAMETER AS A FUNCTION OF P/H

VALUES OF ROUGHNESS PARAMETERS FOR H/L=.01,H/B=.3,4.LE.P/H.LE.20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	0.30	20.00	4.6836	5.0592	5.8320	3.9607	4.4512
0.01	0.30	15.00	4.3362	4.5793	5.0074	3.3718	3.8168
0.01	0.30	13.00	4.3114	4.3774	4.6232	3.0869	3.5108
0.01	0.30	12.00	4.3434	4.2764	4.5413	3.0335	3.3424
0.01	0.30	11.00	4.4178	4.1775	4.9392	3.3701	3.1614
0.01	0.30	10.00	4.5495	4.0838	5.4065	3.7619	3.4796
0.01	0.30	9.00	4.7609	4.3132	5.9846	4.2274	3.9669
0.01	0.30	8.00	5.0871	4.8508	0.0	4.7977	4.5637
0.01	0.30	7.00	5.5854	5.6462	0.0	5.5344	5.3316
0.01	0.30	6.00	6.3563	6.9632	0.0	6.6386	6.4565
0.01	0.30	5.00	7.5912	9.6471	0.0	0.0	0.0
0.01	0.30	4.00	9.6990	0.0	0.0	0.0	0.0

VALUES OF ROUGHNESS PARAMETERS FOR H/L=.01,H/B=.5,4.LE.P/H.LE.20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	0.50	20.00	4.2795	4.6497	5.8244	3.9550	4.4452
0.01	0.50	15.00	3.9071	4.1483	4.9982	3.3645	3.8091
0.01	0.50	13.00	3.8354	3.9274	4.6129	3.0786	3.5020
0.01	0.50	12.00	3.8295	3.8122	4.4024	2.9210	3.3329
0.01	0.50	11.00	3.8523	3.6937	4.1773	2.7514	3.1512
0.01	0.50	10.00	3.9138	3.5723	4.4638	2.9987	2.9548
0.01	0.50	9.00	4.0287	3.4486	4.8674	3.3440	3.0410
0.01	0.50	8.00	4.2201	3.4677	5.3459	3.7505	3.4654
0.01	0.50	7.00	4.5255	3.8958	5.9471	4.2415	3.9787
0.01	0.50	6.00	5.0094	4.5094	0.0	4.8586	4.6232
0.01	0.50	5.00	5.7936	5.4749	0.0	5.6939	5.4899
0.01	0.50	4.00	7.1336	7.2627	0.0	0.0	0.0

VALUES OF ROUGHNESS PARAMETERS FOR H/L=.01,H/B=1.,4.LE.P/H.LE.20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	1.00	20.00	3.8186	4.0296	5.8188	3.9508	4.4407
0.01	1.00	15.00	3.4250	3.5015	4.9913	3.3590	3.8033
0.01	1.00	13.00	3.3089	3.2618	4.6051	3.0723	3.4954
0.01	1.00	12.00	3.2675	3.1338	4.3941	2.9143	3.3258
0.01	1.00	11.00	3.2418	2.9994	4.1683	2.7442	3.1437
0.01	1.00	10.00	3.2375	2.8575	3.9251	2.5602	2.9466
0.01	1.00	9.00	3.2629	2.7068	4.1858	2.7870	2.7317
0.01	1.00	8.00	3.3306	2.5455	4.5563	3.1072	2.7930
0.01	1.00	7.00	3.4608	2.5144	4.9898	3.4823	3.1839
0.01	1.00	6.00	3.6884	2.8723	5.5182	3.9332	3.6544
0.01	1.00	5.00	4.0776	3.3805	6.2248	4.4953	4.2411
0.01	1.00	4.00	4.7611	4.1705	0.0	5.2428	5.0184

contd.

VALUES OF ROUGHNESS PARAMETERS FOR H/L=.01,H/B=2.,4.LE.P/H.LE.20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	2.00	20.00	3.4516	3.3679	5.8159	3.9487	4.4384
0.01	2.00	15.00	3.0515	2.8111	4.9879	3.3562	3.8003
0.01	2.00	13.00	2.9098	2.5530	4.6012	3.0692	3.4922
0.01	2.00	12.00	2.8469	2.4133	4.3900	2.9109	3.3224
0.01	2.00	11.00	2.7917	2.2647	4.1639	2.7406	3.1399
0.01	2.00	10.00	2.7474	2.1056	3.9202	2.5562	2.9425
0.01	2.00	9.00	2.7181	1.9334	3.8775	2.5354	2.7272
0.01	2.00	8.00	2.7105	1.7446	4.2064	2.8200	2.4941
0.01	2.00	7.00	2.7353	1.5340	4.5840	3.1489	2.8360
0.01	2.00	6.00	2.8105	1.6941	5.0288	3.5368	3.2400
0.01	2.00	5.00	2.9690	2.0316	5.5780	4.0077	3.7312
0.01	2.00	4.00	3.2781	2.5225	6.3400	4.6052	4.3540

VALUES OF ROUGHNESS PARAMETERS FOR H/L=.01,H/B=3.,4.LE.P/H.LE.20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	3.00	20.00	3.2765	2.9699	5.8150	3.9480	4.4377
0.01	3.00	15.00	2.8785	2.3953	4.9867	3.3553	3.7993
0.01	3.00	13.00	2.7283	2.1260	4.5999	3.0682	3.4911
0.01	3.00	12.00	2.6577	1.9793	4.3886	2.9098	3.3212
0.01	3.00	11.00	2.5918	1.8224	4.1625	2.7395	3.1386
0.01	3.00	10.00	2.5325	1.6532	3.9186	2.5549	2.9411
0.01	3.00	9.00	2.4828	1.4687	3.7788	2.4551	2.7257
0.01	3.00	8.00	2.4469	1.2644	4.0951	2.7287	2.4886
0.01	3.00	7.00	2.4320	1.0338	4.4562	3.0436	2.7262
0.01	3.00	6.00	2.4502	1.0779	4.8777	3.4126	3.1104
0.01	3.00	5.00	2.5233	1.3508	5.3896	3.8569	3.5735
0.01	3.00	4.00	2.6957	1.7371	6.0664	4.4132	4.1535

VALUES OF ROUGHNESS PARAMETERS FOR H/L=.01,H/B=4.,4.LE.P/H.LE.20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	4.00	20.00	3.1684	2.6845	5.8145	3.9476	4.4373
0.01	4.00	15.00	2.7739	2.0967	4.9861	3.3549	3.7989
0.01	4.00	13.00	2.6200	1.8194	4.5992	3.0676	3.4905
0.01	4.00	12.00	2.5456	1.6676	4.3879	2.9093	3.3206
0.01	4.00	11.00	2.4743	1.5047	4.1617	2.7388	3.1379
0.01	4.00	10.00	2.4073	1.3283	3.9178	2.5543	2.9404
0.01	4.00	9.00	2.3468	1.1349	3.7302	2.4156	2.7249
0.01	4.00	8.00	2.2960	0.9196	4.0404	2.6839	2.4877
0.01	4.00	7.00	2.2602	0.6748	4.3935	2.9919	2.6725
0.01	4.00	6.00	2.2481	0.6567	4.8040	3.3518	3.0471
0.01	4.00	5.00	2.2762	0.8906	5.2989	3.7834	3.4968
0.01	4.00	4.00	2.3771	1.2156	5.9412	4.3204	4.0566

Table 2. ROUGHNESS PARAMETER AS A FUNCTION OF H/L

VALUES OF ROUGHNESS PARAMETERS FOR H/B=.3,P/H=10,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	0.30	10.00	4.5495	4.0838	5.4065	3.7619	3.4796
0.02	0.30	10.00	4.5718	4.3611	5.2227	3.8300	3.4938
0.04	0.30	10.00	4.6146	4.6383	4.9374	3.8838	3.5237
0.06	0.30	10.00	4.6550	4.8005	4.7626	3.9304	3.5735
0.08	0.30	10.00	4.6929	4.9156	4.6519	3.9736	3.6265
0.10	0.30	10.00	4.7283	5.0048	4.5771	4.0132	3.6779
0.12	0.30	10.00	4.7613	5.0778	4.5243	4.0495	3.7266
0.14	0.30	10.00	4.7918	5.1394	4.4859	4.0833	3.7730
0.16	0.30	10.00	4.8199	5.1929	4.4578	4.1153	3.8175
0.18	0.30	10.00	4.8454	5.2400	4.4376	4.1461	3.8608
0.20	0.30	10.00	4.8686	5.2821	4.4237	4.1763	3.8980

VALUES OF ROUGHNESS PARAMETERS FOR H/B=.3,P/H= 8,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.20	0.30	8.00	5.4439	6.0491	5.1884	4.7977	4.5637
0.18	0.30	8.00	5.4180	6.0069	5.2506	4.8721	4.5774
0.16	0.30	8.00	5.3894	5.9598	5.3221	4.8678	4.5309
0.14	0.30	8.00	5.3580	5.9064	5.4050	4.8469	4.5032
0.12	0.30	8.00	5.3239	5.8447	5.5028	4.8288	4.4901
0.10	0.30	8.00	5.2871	5.7718	5.6203	4.8132	4.4844
0.08	0.30	8.00	5.2474	5.6826	5.7654	4.7993	4.4827
0.06	0.30	8.00	5.2051	5.5675	5.9496	4.7863	4.4833
0.04	0.30	8.00	5.1599	5.4053	6.1881	4.7741	4.4855
0.02	0.30	8.00	5.1121	5.1280	6.4811	4.7626	4.4889
0.01	0.30	8.00	5.0871	4.8508	0.0	4.7517	4.4935

VALUES OF ROUGHNESS PARAMETERS FOR H/B=1.,P/H=10,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	1.00	10.00	3.2375	2.8575	3.9251	2.5602	2.9466
0.02	1.00	10.00	3.2534	3.1347	3.6935	2.6307	2.9509
0.04	1.00	10.00	3.2839	3.4120	3.4449	2.7384	2.9861
0.06	1.00	10.00	3.3126	3.5742	3.3294	2.8261	3.0344
0.08	1.00	10.00	3.3396	3.6893	3.2608	2.8962	3.0779
0.10	1.00	10.00	3.3648	3.7785	3.2093	2.9526	3.1128
0.12	1.00	10.00	3.3883	3.8514	3.1609	2.9978	3.1381
0.14	1.00	10.00	3.4100	3.9131	3.0907	3.0386	3.1545
0.16	1.00	10.00	3.4299	3.9665	3.1242	3.1232	3.2297
0.18	1.00	10.00	3.4481	4.0136	3.1641	3.2048	3.3037
0.20	1.00	10.00	3.4646	4.0558	3.2093	3.2841	3.3770

contd.

VALUES OF ROUGHNESS PARAMETERS FOR H/B=1.,P/H= 8,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	1.00	8.00	3.3306	2.5455	4.5563	3.1072	2.7930
0.02	1.00	8.00	3.3469	2.8228	4.3148	3.1396	2.7814
0.04	1.00	8.00	3.3783	3.1000	3.9901	3.1689	2.7970
0.06	1.00	8.00	3.4078	3.2622	3.8046	3.1959	2.8277
0.08	1.00	8.00	3.4355	3.3773	3.6818	3.2176	2.8542
0.10	1.00	8.00	3.4615	3.4666	3.5896	3.2340	2.8722
0.12	1.00	8.00	3.4856	3.5395	3.5134	3.2456	2.8799
0.14	1.00	8.00	3.5080	3.6012	3.4449	3.2532	2.9148
0.16	1.00	8.00	3.5285	3.6546	3.3781	3.2574	2.9817
0.18	1.00	8.00	3.5472	3.7017	3.3192	3.2795	3.0481
0.20	1.00	8.00	3.5641	3.7438	3.3247	3.3226	3.1144

VALUES OF ROUGHNESS PARAMETERS FOR H/B=1.,P/H= 6,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	1.00	6.00	3.6884	2.8723	5.5182	3.9332	3.6544
0.02	1.00	6.00	3.7065	3.1496	5.2731	3.9384	3.6054
0.04	1.00	6.00	3.7412	3.4269	4.8813	3.8781	3.5195
0.06	1.00	6.00	3.7739	3.5890	4.6081	3.8272	3.4701
0.08	1.00	6.00	3.8047	3.7041	4.4082	3.7845	3.4350
0.10	1.00	6.00	3.8334	3.7934	4.2522	3.7463	3.4053
0.12	1.00	6.00	3.8601	3.8663	4.1238	3.7108	3.3776
0.14	1.00	6.00	3.8848	3.9280	4.0142	3.6774	3.3500
0.16	1.00	6.00	3.9076	3.9814	3.9177	3.6457	3.3215
0.18	1.00	6.00	3.9283	4.0285	3.8307	3.6156	3.2940
0.20	1.00	6.00	3.9471	4.0706	3.7503	3.5868	3.3119

VALUES OF ROUGHNESS PARAMETERS FOR H/B=1.,P/H= 4,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.20	1.00	4.00	5.0950	5.3688	4.6561	5.2428	5.0184
0.18	1.00	4.00	5.0708	5.3266	4.7901	5.2500	4.9692
0.16	1.00	4.00	5.0440	5.2795	4.9385	5.1164	4.7896
0.14	1.00	4.00	5.0147	5.2261	5.1039	4.9740	4.6369
0.12	1.00	4.00	4.9828	5.1644	5.2907	4.8464	4.5118
0.10	1.00	4.00	4.9483	5.0915	5.5045	4.7319	4.4048
0.08	1.00	4.00	4.9112	5.0022	5.7536	4.6278	4.3105
0.06	1.00	4.00	4.8715	4.8872	6.0489	4.5320	4.2255
0.04	1.00	4.00	4.8293	4.7250	6.4017	4.4433	4.1477
0.02	1.00	4.00	4.7845	4.4477	6.8119	4.3607	4.0759
0.01	1.00	4.00	4.7611	4.1705	0.0	4.2836	4.0091

contd.

VALUES OF ROUGHNESS PARAMETERS FOR H/B=4.,P/H=10,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	4.00	10.00	2.4073	1.3283	3.9178	2.5543	2.9404
0.02	4.00	10.00	2.4191	1.6055	3.6791	2.6193	2.9388
0.04	4.00	10.00	2.4418	1.8828	3.4178	2.7169	2.9631
0.06	4.00	10.00	2.4631	2.0450	3.2906	2.7949	3.0009
0.08	4.00	10.00	2.4832	2.1601	3.2101	2.8555	3.0339
0.10	4.00	10.00	2.5019	2.2493	3.1452	2.9016	3.0574
0.12	4.00	10.00	2.5194	2.3223	3.0805	2.9356	3.0699
0.14	4.00	10.00	2.5355	2.3839	3.0148	2.9787	3.0887
0.16	4.00	10.00	2.5504	2.4373	3.0394	3.0568	3.1564
0.18	4.00	10.00	2.5639	2.4844	3.0708	3.1324	3.2234
0.20	4.00	10.00	2.5761	2.5266	3.1079	3.2061	3.2900

VALUES OF ROUGHNESS PARAMETERS FOR H/B=4.,P/H= 8,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	4.00	8.00	2.2960	0.9196	4.0404	2.6839	2.4877
0.02	4.00	8.00	2.3073	1.1969	3.7823	2.7198	2.4804
0.04	4.00	8.00	2.3289	1.4741	3.4765	2.7689	2.5087
0.06	4.00	8.00	2.3493	1.6363	3.3120	2.8091	2.5437
0.08	4.00	8.00	2.3684	1.7514	3.2014	2.8382	2.5673
0.10	4.00	8.00	2.3863	1.8407	3.1124	2.8575	2.5750
0.12	4.00	8.00	2.4029	1.9136	3.0293	2.8680	2.6032
0.14	4.00	8.00	2.4183	1.9753	2.9266	2.8757	2.6768
0.16	4.00	8.00	2.4325	2.0287	2.9299	2.9311	2.7496
0.18	4.00	8.00	2.4454	2.0758	2.9414	2.9855	2.8220
0.20	4.00	8.00	2.4571	2.1179	2.9599	3.0394	2.8939

VALUES OF ROUGHNESS PARAMETERS FOR H/B=4.,P/H= 6,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	4.00	6.00	2.2481	0.6567	4.8040	3.3518	3.0471
0.02	4.00	6.00	2.2592	0.9339	4.5354	3.3446	2.9932
0.04	4.00	6.00	2.2803	1.2112	4.1413	3.2985	2.9310
0.06	4.00	6.00	2.3003	1.3734	3.8913	3.2637	2.9001
0.08	4.00	6.00	2.3190	1.4885	3.7134	3.2334	2.8753
0.10	4.00	6.00	2.3365	1.5777	3.5739	3.2044	2.8491
0.12	4.00	6.00	2.3528	1.6506	3.4565	3.1755	2.8180
0.14	4.00	6.00	2.3679	1.7123	3.3517	3.1463	2.7915
0.16	4.00	6.00	2.3817	1.7657	3.2527	3.1162	2.8203
0.18	4.00	6.00	2.3944	1.8128	3.1445	3.0941	2.8515
0.20	4.00	6.00	2.4058	1.8550	3.1183	3.1070	2.8848

contd.

VALUES OF ROUGHNESS PARAMETERS FOR H/B=4.,P/H= 4,.01.LE.H/L.LE..20

H/L	H/B	P/H	RR	RD	RK	RK*	RK**
0.01	4.00	4.00	2.3771	1.2156	5.9412	4.3204	4.0566
0.02	4.00	4.00	2.3887	1.4929	5.6350	4.2840	3.9648
0.04	4.00	4.00	2.4111	1.7701	5.1686	4.1306	3.7814
0.06	4.00	4.00	2.4322	1.9323	4.8142	3.9980	3.6488
0.08	4.00	4.00	2.4520	2.0474	4.5407	3.8855	3.5439
0.10	4.00	4.00	2.4705	2.1366	4.3199	3.7869	3.4545
0.12	4.00	4.00	2.4877	2.2096	4.1351	3.6985	3.3749
0.14	4.00	4.00	2.5037	2.2712	3.9760	3.6180	3.3018
0.16	4.00	4.00	2.5183	2.3246	3.8360	3.5442	3.2330
0.18	4.00	4.00	2.5317	2.3718	3.7106	3.4760	3.1666
0.20	4.00	4.00	2.5438	2.4139	3.5964	3.4127	3.1155

Table 3. ROUGHNESS GEOMETRY AND THE VALUES OF K_W AND ζ

KOCH

P	H	B	DROOT	DREF	REVOL	XLAMREF
19.600	5.000	1.000	50.000	50.000	0.1500E+05	0.52000
49.000	5.000	1.000	50.000	50.000	0.1900E+05	0.60000

XKW1	ZETR1	XKW2	ZETR2	XKW3	ZETR3
0.066005	0.189636	0.117688	0.212677	0.087488	0.199290
0.096788	0.340901	0.102097	0.400680	0.099458	0.371215

WEBB

P	H	B	DROOT	DREF	REVOL	XLAMREF
3.680	0.368	0.380	36.830	36.830	0.1143E+06	0.08600
7.360	0.736	0.380	36.830	36.830	0.1185E+06	0.14800
14.720	1.472	0.380	36.830	36.830	0.1144E+06	0.24230
14.720	0.736	0.380	36.830	36.830	0.1402E+06	0.11120
29.540	0.736	0.380	36.830	36.830	0.1420E+06	0.07200

XKW1	ZETR1	XKW2	ZETR2	XKW3	ZETR3
0.032460	0.064256	0.032175	0.065349	0.032311	0.064822
0.039551	0.116980	0.039116	0.120641	0.039325	0.118871
0.058906	0.183430	0.058749	0.194749	0.058817	0.189251
0.025700	0.089373	0.025576	0.090779	0.025636	0.090100
0.018755	0.053798	0.018727	0.054256	0.018740	0.054035

NUNNER

P	H	B	DROOT	DREF	REVOL	XLAMREF
40.900	2.000	2.500	50.000	50.000	0.4350E+05	0.15370

XKW1	ZETR1	XKW2	ZETR2	XKW3	ZETR3
0.038318	0.115727	0.038262	0.119399	0.038289	0.117624

contd.

MOEBIUS

P	H	B	DROOT	DREF	REVOL	XLAMREF
25.000	2.501	2.500	50.000	49.520	0.1000E+06	0.25800
50.000	4.985	5.000	99.990	99.040	0.1000E+06	0.25900
47.500	2.501	2.500	50.000	49.750	0.1000E+06	0.20400
95.000	4.985	5.000	99.990	99.480	0.1000E+06	0.20500
92.500	2.501	2.500	50.000	49.870	0.1000E+06	0.14100
47.500	1.489	2.500	50.000	49.790	0.1000E+06	0.07970
47.500	5.491	2.500	50.000	49.480	0.1000E+06	0.92500
102.500	3.475	3.500	49.990	49.770	0.1000E+06	0.24000
28.500	1.499	1.500	49.980	49.830	0.1000E+06	0.13100
14.250	0.727	0.750	49.980	49.900	0.1000E+06	0.07870
19.000	0.982	10.000	49.970	49.860	0.1000E+06	0.09730

XKW1	ZETR1	XKW2	ZETR2	XKW3	ZETR3
0.070142	0.187731	0.070343	0.202748	0.070236	0.195437
0.069534	0.188782	0.069732	0.203764	0.069626	0.196470
0.042989	0.163919	0.043010	0.170470	0.043000	0.167299
0.042568	0.165059	0.042588	0.171606	0.042577	0.168436
0.027639	0.115336	0.027653	0.117716	0.027647	0.116567
0.029692	0.059318	0.029668	0.060271	0.029680	0.059811
0.094460	0.492986	0.109623	0.599999	0.106749	0.545822
0.035125	0.198956	0.035318	0.205805	0.035224	0.202491
0.035261	0.104507	0.035123	0.107108	0.035190	0.105851
0.026489	0.058571	0.026380	0.059323	0.026432	0.058960
0.030203	0.067041	0.030080	0.068236	0.030139	0.067659

GARGAUD

P	H	B	DROOT	DREF	REVOL	XLAMREF
5.000	0.500	0.500	50.000	49.500	0.2010E+07	0.08700
8.000	0.800	0.800	50.000	49.200	0.2030E+07	0.11150
1.400	0.200	0.200	50.000	49.800	0.4850E+07	0.06200
2.000	0.200	0.200	50.000	49.800	0.1500E+07	0.05120
3.000	0.200	0.200	50.000	49.800	0.2050E+07	0.04840
1.500	0.300	0.300	50.000	49.700	0.1500E+07	0.06400
2.100	0.300	0.300	50.000	49.700	0.2460E+07	0.06800
4.500	0.300	0.300	50.000	49.700	0.2050E+07	0.05240
1.800	0.500	0.300	50.000	49.500	0.5000E+06	0.07250
2.300	0.500	0.300	50.000	49.500	0.2900E+06	0.08120

XKW1	ZETR1	XKW2	ZETR2	XKW3	ZETR3
0.028609	0.076701	0.028371	0.077753	0.028485	0.077246
0.036695	0.101217	0.036482	0.103398	0.036582	0.102344
0.012308	0.052614	0.023065	0.052944	0.017864	0.052758
0.023846	0.040393	0.023717	0.040640	0.023779	0.040521
0.017235	0.038469	0.017174	0.038624	0.017203	0.038549
0.011008	0.052051	0.024027	0.052364	0.016028	0.052185
0.017519	0.057320	0.032621	0.057861	0.025076	0.057555
0.022751	0.042674	0.022655	0.042927	0.022701	0.042805
0.011613	0.056922	0.025507	0.057363	0.016958	0.057112
0.013691	0.064390	0.029900	0.065070	0.019940	0.064682

contd.

SKUPINSKI

P	H	B	DROOT	DREF	REVOL	XLAMREF
22.200	2.000	1.000	20.000	20.000	0.9960E+05	0.61040
44.400	2.000	1.000	20.000	20.000	0.8090E+05	0.41350

XKW1	ZETR1	XKW2	ZETR2	XKW3	ZETR3
0.090875	0.370906	0.093808	0.424906	0.092395	0.398372
0.054823	0.314406	0.056627	0.335082	0.055674	0.325032

SAVAGE

P	H	B	DROOT	DREF	REVOL	XLAMREF
1.088	1.000	0.088	6.065	4.065	0.1000E+06	0.14440
2.088	1.000	0.088	6.065	4.065	0.1000E+06	0.18880
3.088	1.000	0.088	6.065	4.065	0.1195E+06	0.24160
5.088	1.000	0.088	6.065	4.065	0.1122E+06	0.31160
8.088	1.000	0.088	6.065	4.065	0.1105E+06	0.34600
0.588	0.750	0.088	6.065	4.565	0.1026E+06	0.11680
3.088	0.750	0.088	6.065	4.565	0.6920E+05	0.24440
5.088	0.750	0.088	6.065	4.565	0.8088E+05	0.29680
8.088	0.750	0.088	6.065	4.565	0.6452E+05	0.27040
0.588	0.500	0.088	6.065	5.065	0.1058E+06	0.12480
1.088	0.500	0.088	6.065	5.065	0.4025E+05	0.15720
3.088	0.500	0.088	6.065	5.065	0.8089E+05	0.24520
8.088	0.500	0.088	6.065	5.065	0.7549E+05	0.20520
0.588	0.250	0.088	6.065	5.565	0.1087E+06	0.11880
1.088	0.250	0.088	6.065	5.565	0.1143E+06	0.15520
2.088	0.250	0.088	6.065	5.565	0.1061E+06	0.17360
3.088	0.250	0.088	6.065	5.565	0.1117E+06	0.16400

XKW1	ZETR1	XKW2	ZETR2	XKW3	ZETR3
0.045589	0.147461	0.087587	0.156461	0.062565	0.151279
0.070160	0.228823	0.126594	0.257054	0.093418	0.240639
0.084038	0.342899	0.141792	0.406107	0.108572	0.369012
0.097888	0.582682	0.154477	0.760913	0.122497	0.654551
0.108963	0.944725	0.134381	1.308554	0.125817	1.118258
0.022969	0.106338	0.048036	0.109104	0.032795	0.107520
0.078301	0.328452	0.134985	0.382384	0.102199	0.350820
0.094808	0.512969	0.141920	0.650533	0.119600	0.569747
0.094177	0.636766	0.099484	0.756764	0.096924	0.697462
0.018619	0.113885	0.040001	0.116533	0.026924	0.115018
0.032739	0.152352	0.066250	0.159913	0.046049	0.155567
0.072272	0.318340	0.128323	0.365458	0.096151	0.337950
0.058116	0.381150	0.058801	0.409909	0.058470	0.395911
0.017706	0.106883	0.038208	0.109164	0.025656	0.107859
0.031011	0.153286	0.063315	0.160085	0.043799	0.156181
0.056911	0.192980	0.068593	0.207485	0.068638	0.200186
0.048059	0.197658	0.048023	0.207635	0.048036	0.202797

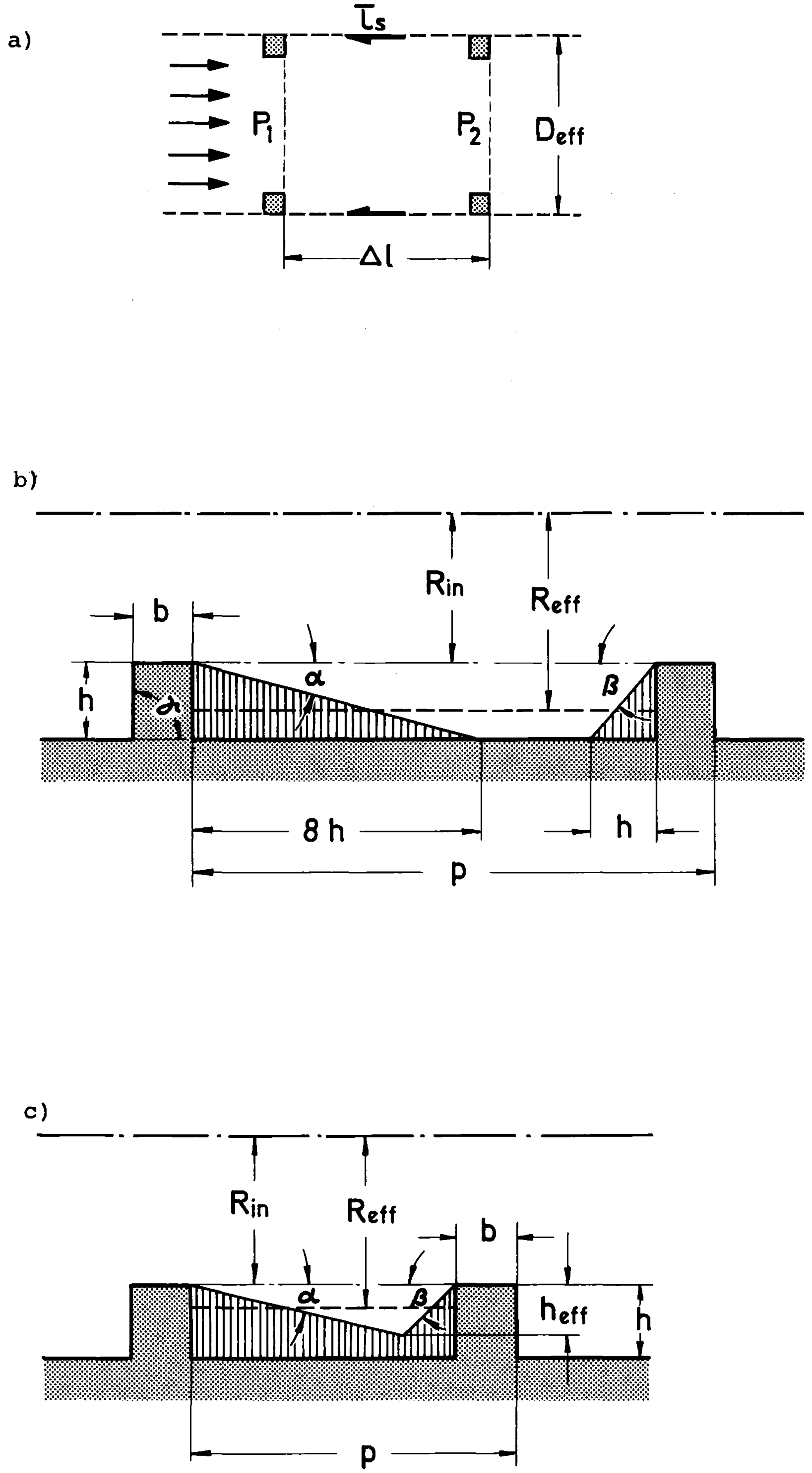


Fig.1 FLOW PATTERN IN A CIRCULAR TUBE WITH RECTANGULAR TRANSVERSE RIBS

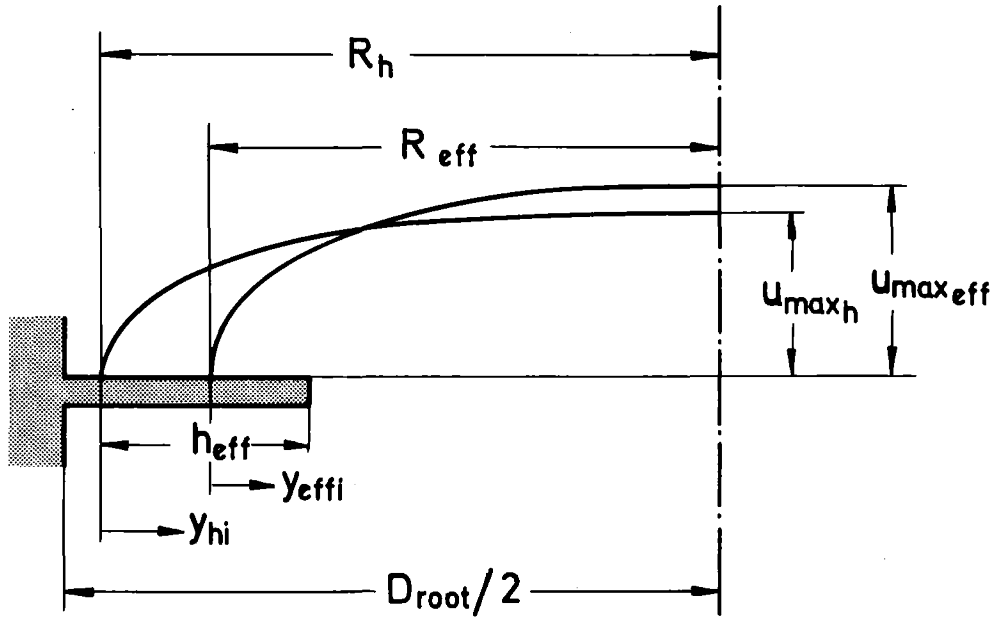
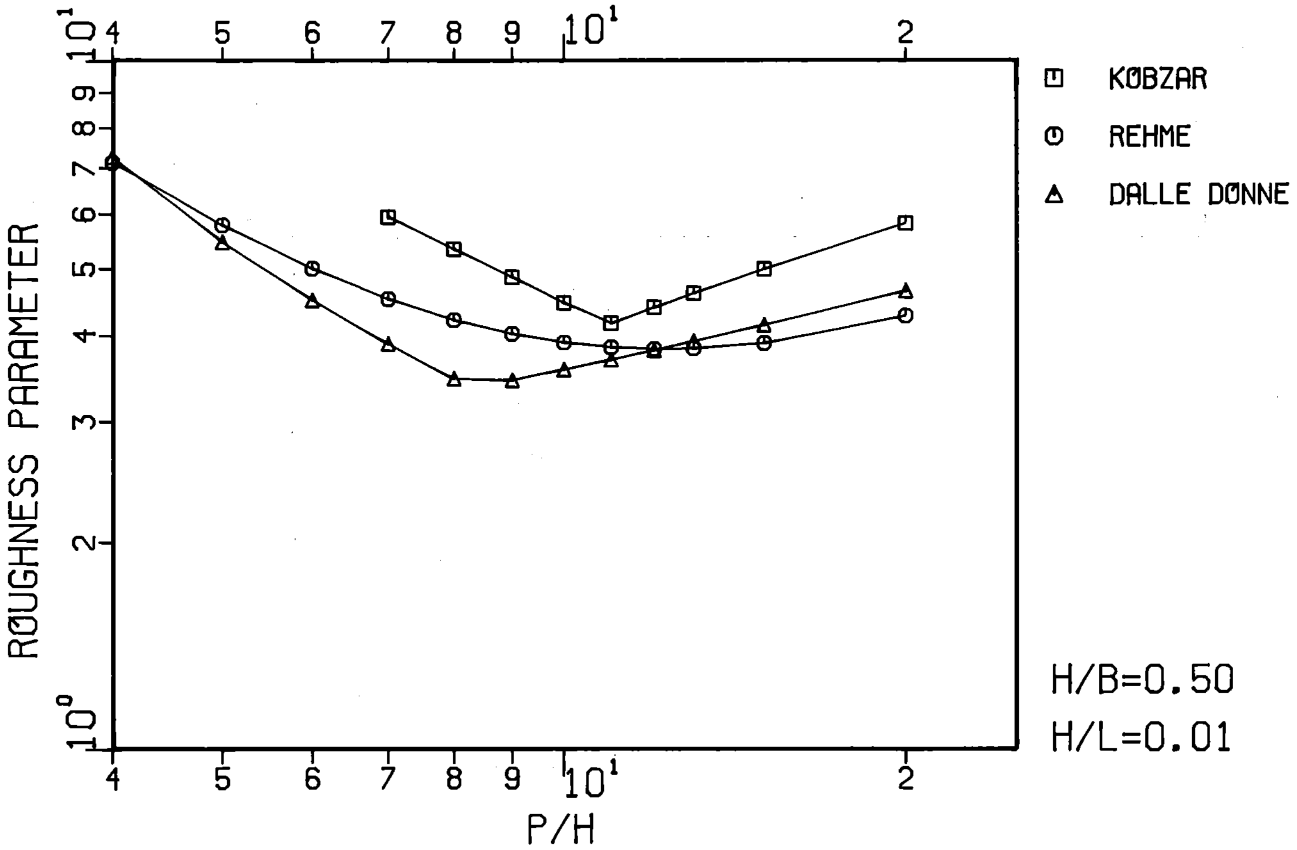


Fig.2 SCHEMATIC DIAGRAM OF THE VELOCITY TRANSFORMATION



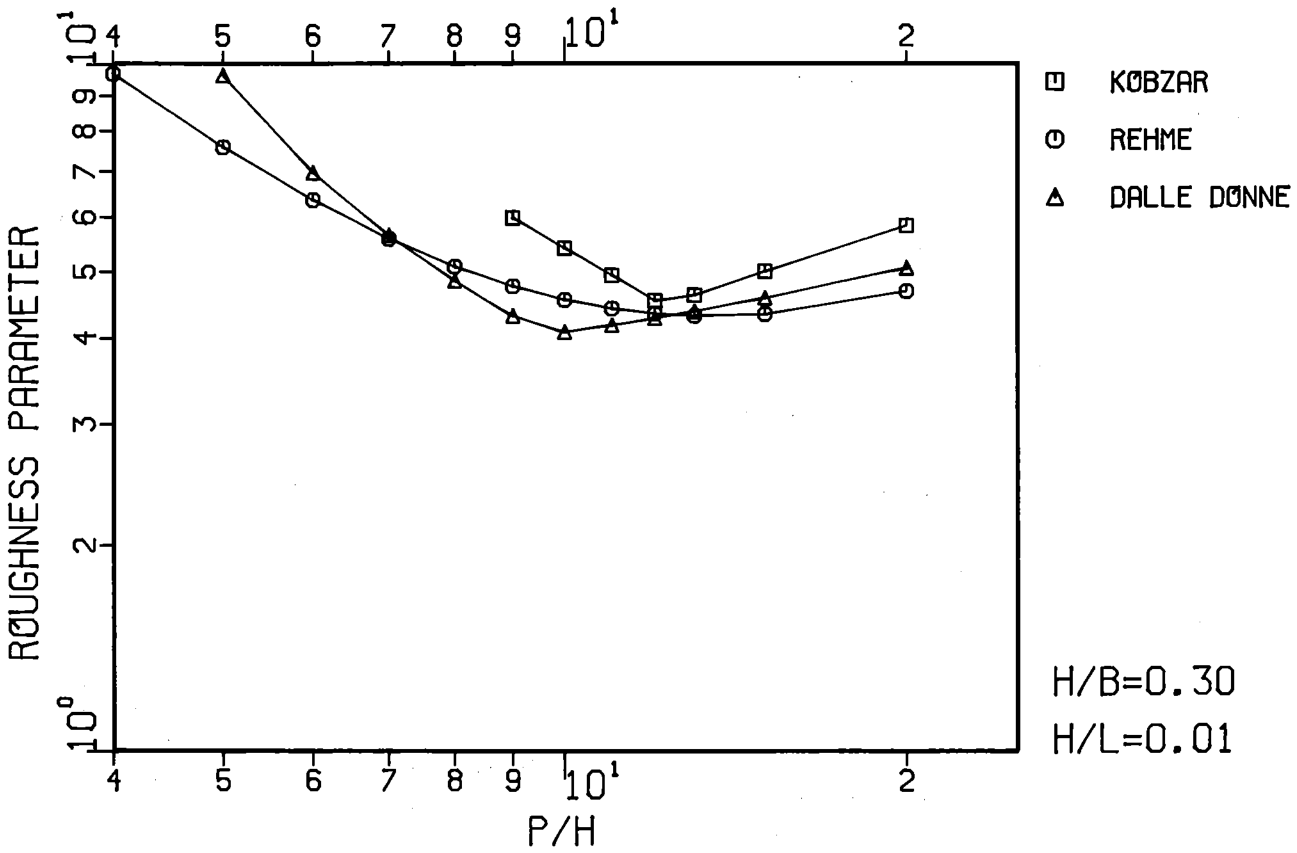
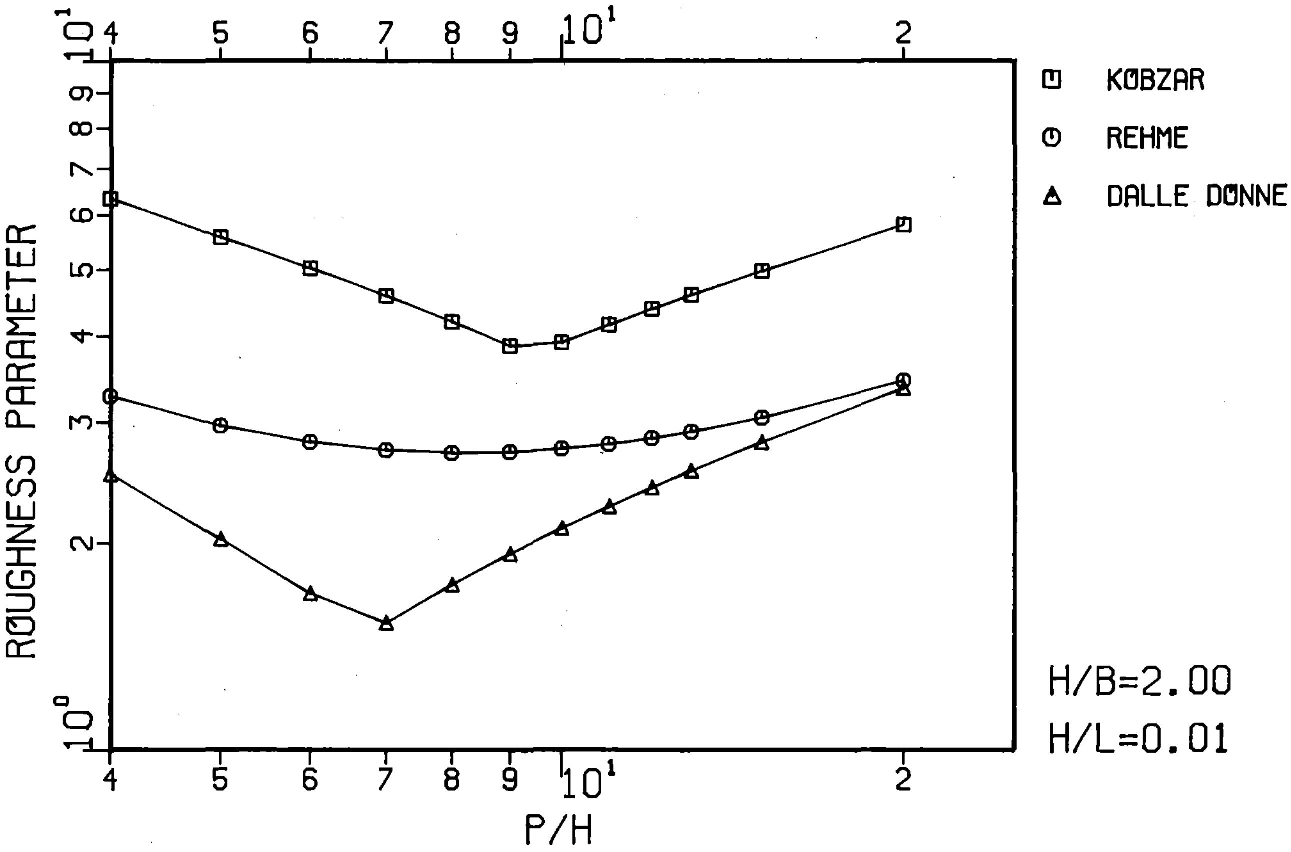


Fig.3 ROUGHNESS PARAMETER ACCORDING TO KOBZAR, REHME AND DALLE DONNE AS A FUNCTION OF P/H



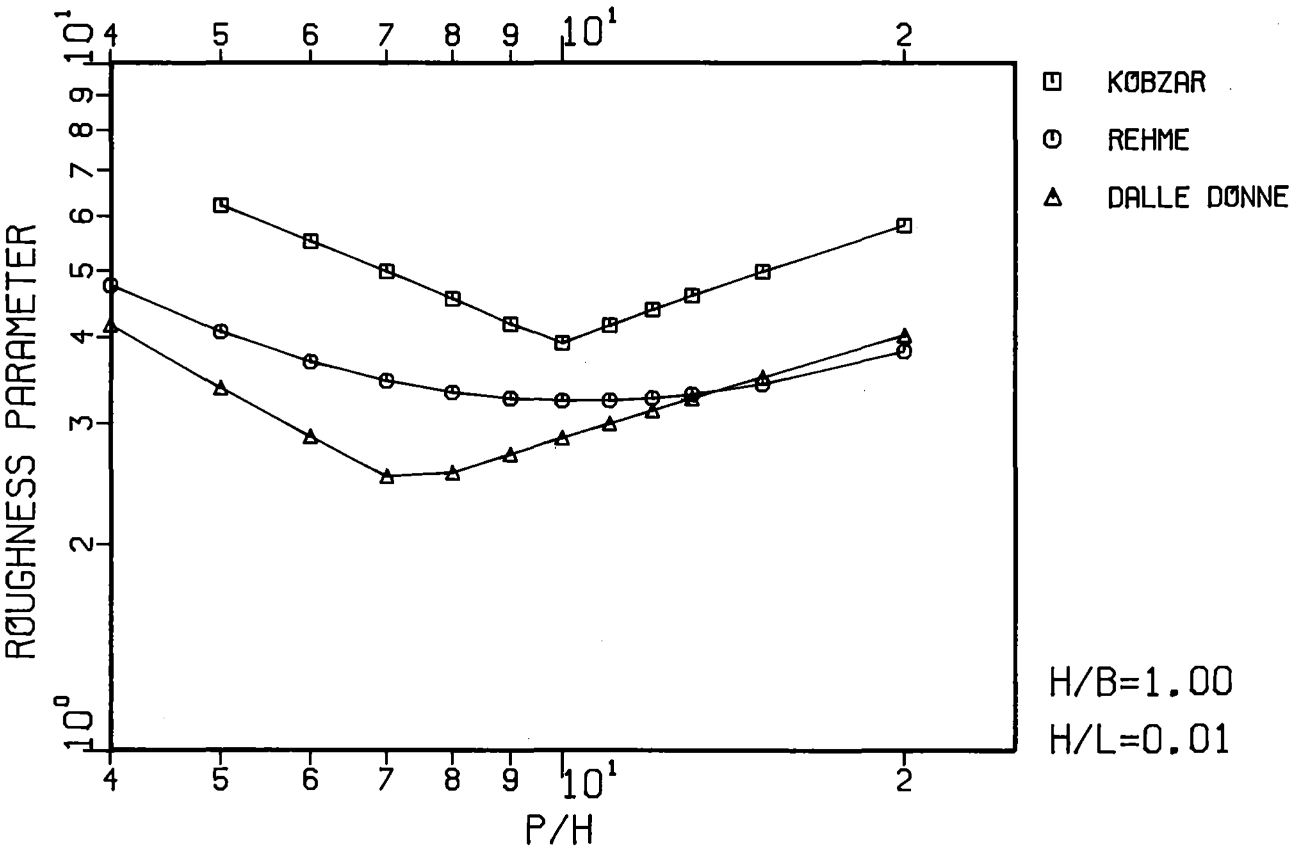
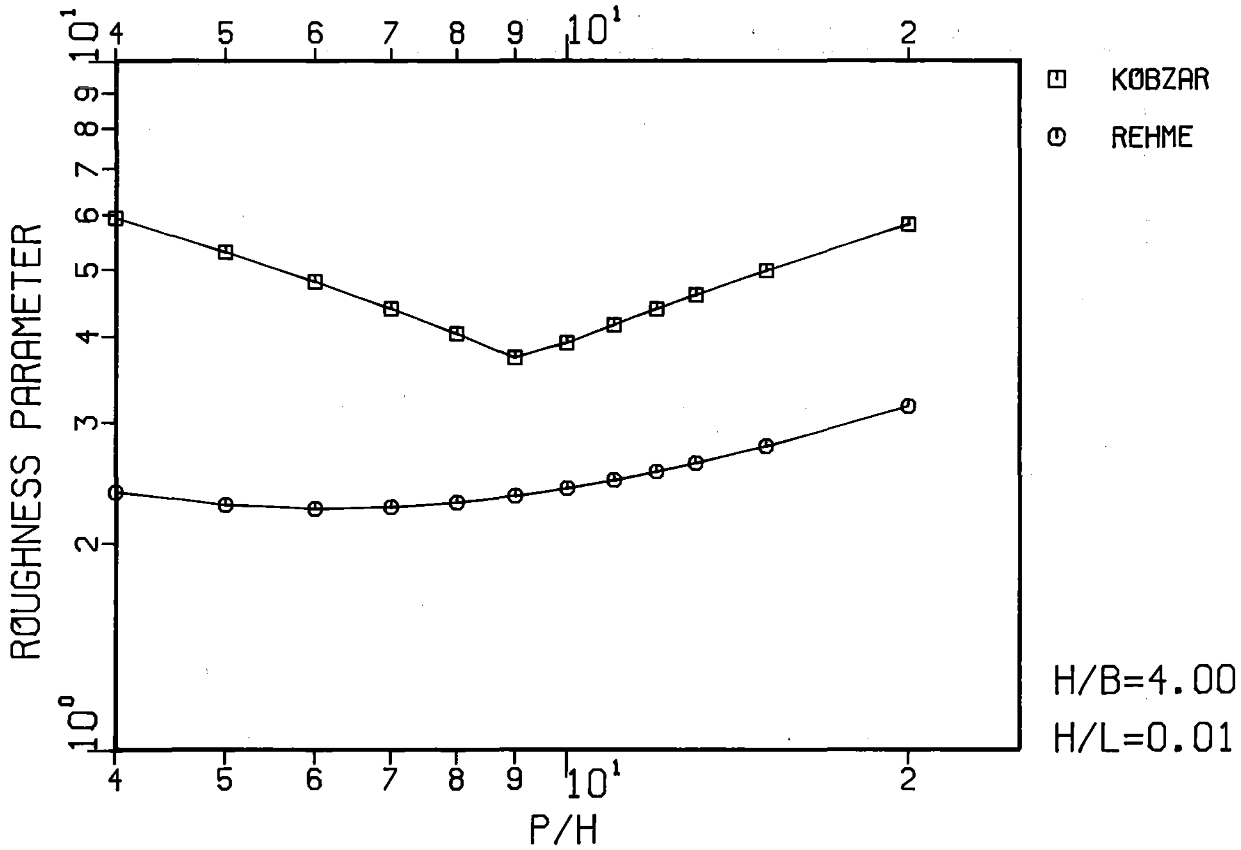


Fig.4 ROUGHNESS PARAMETER ACCORDING TO KOBZAR, REHME AND DALLE DONNE AS A FUNCTION OF P/H



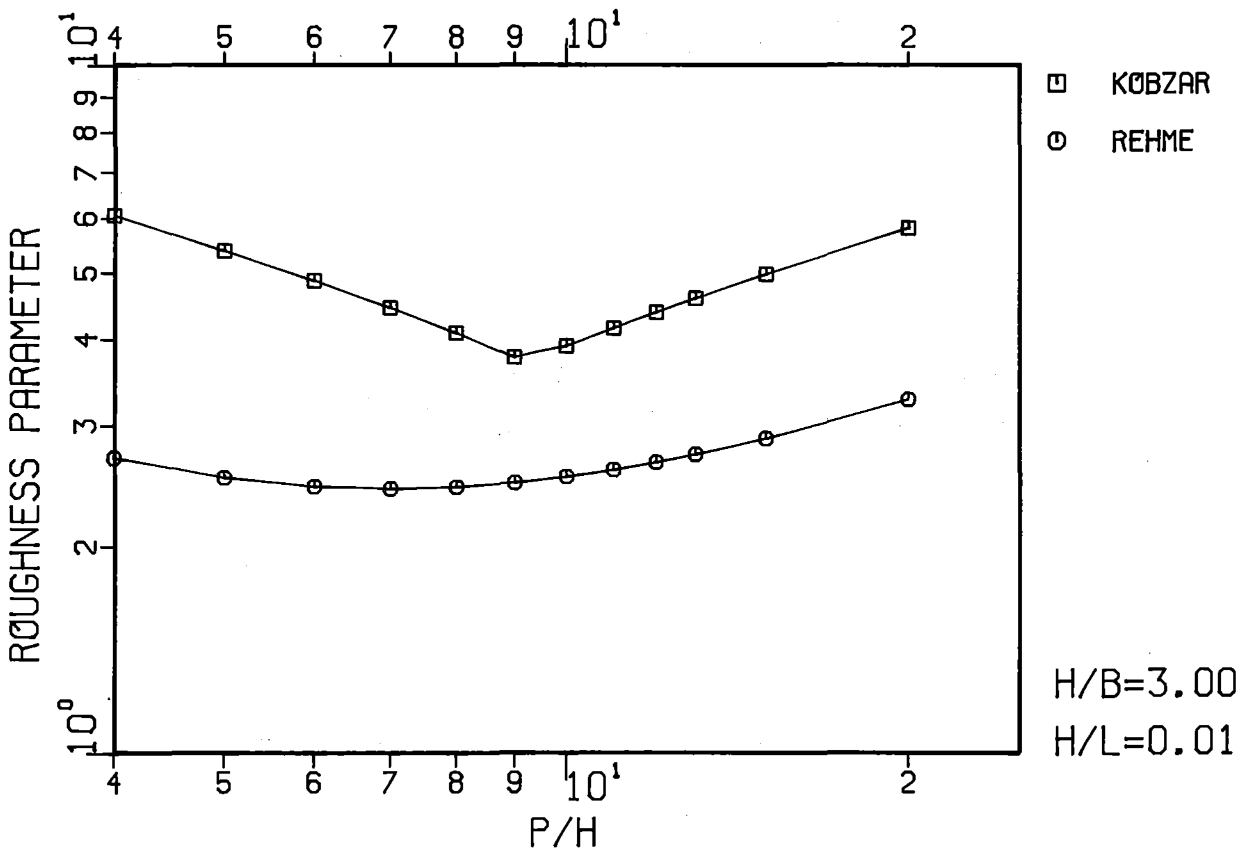
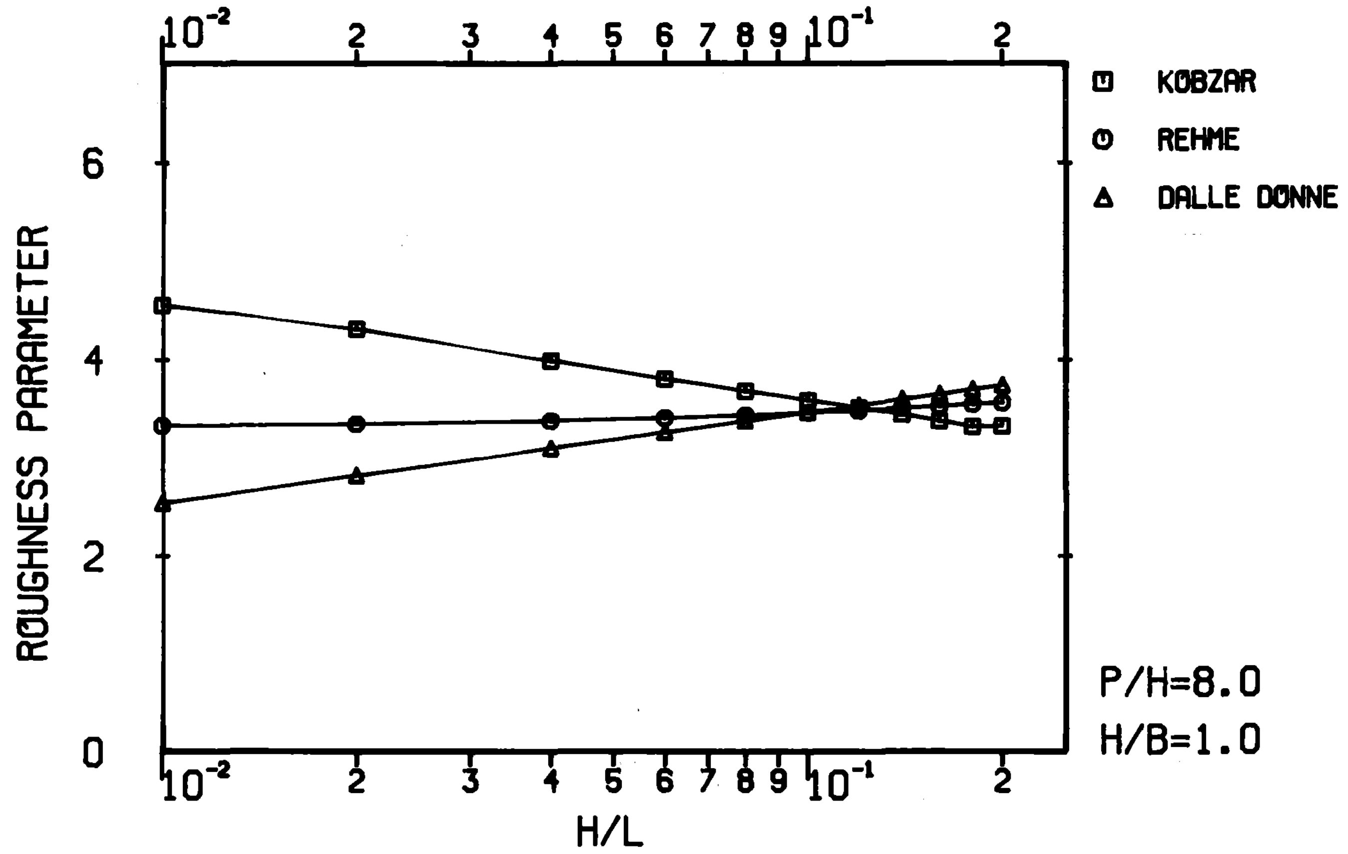


Fig.5 ROUGHNESS PARAMETER ACCORDING TO KOBZAR, REHME AND DALLE DONNE AS A FUNCTION OF P/H



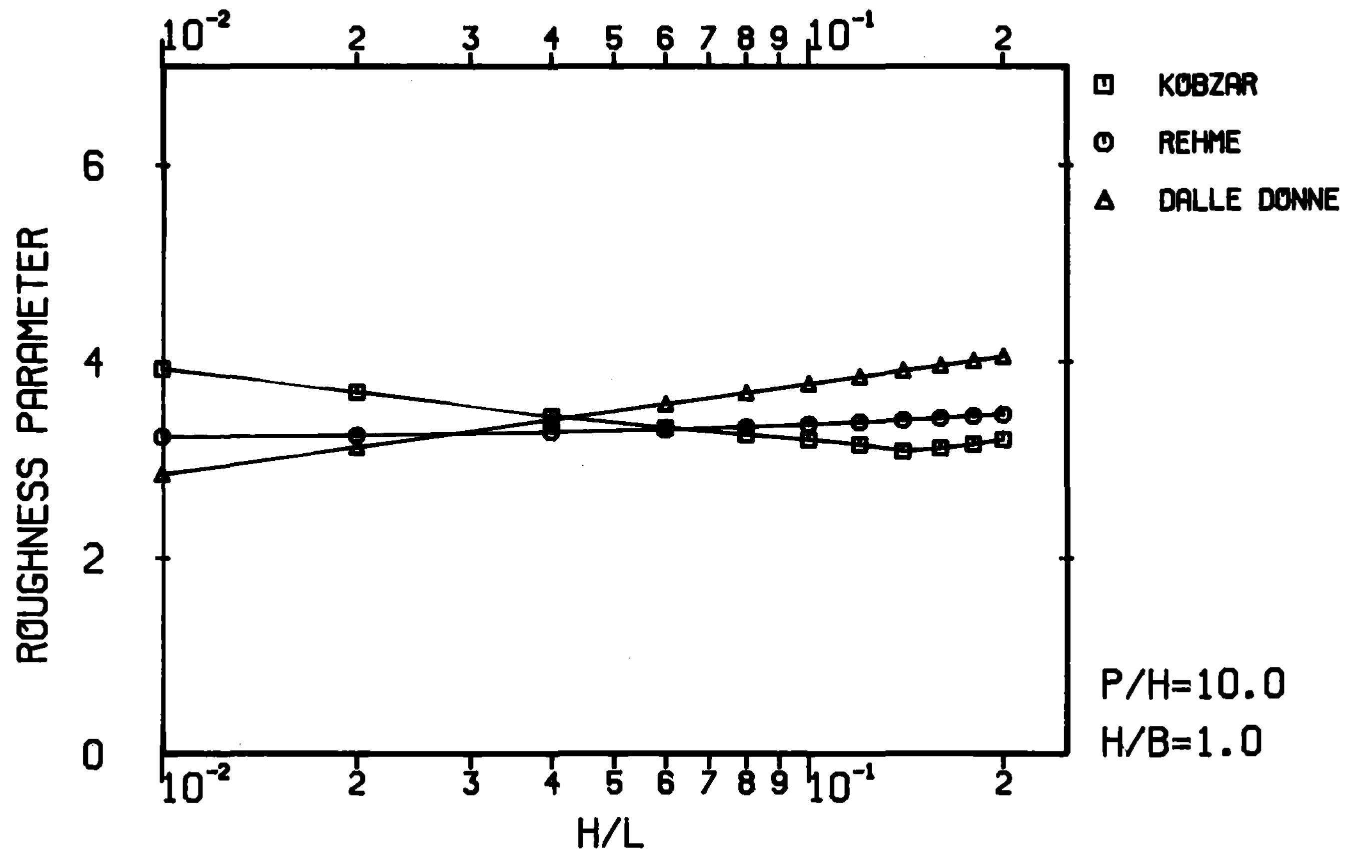
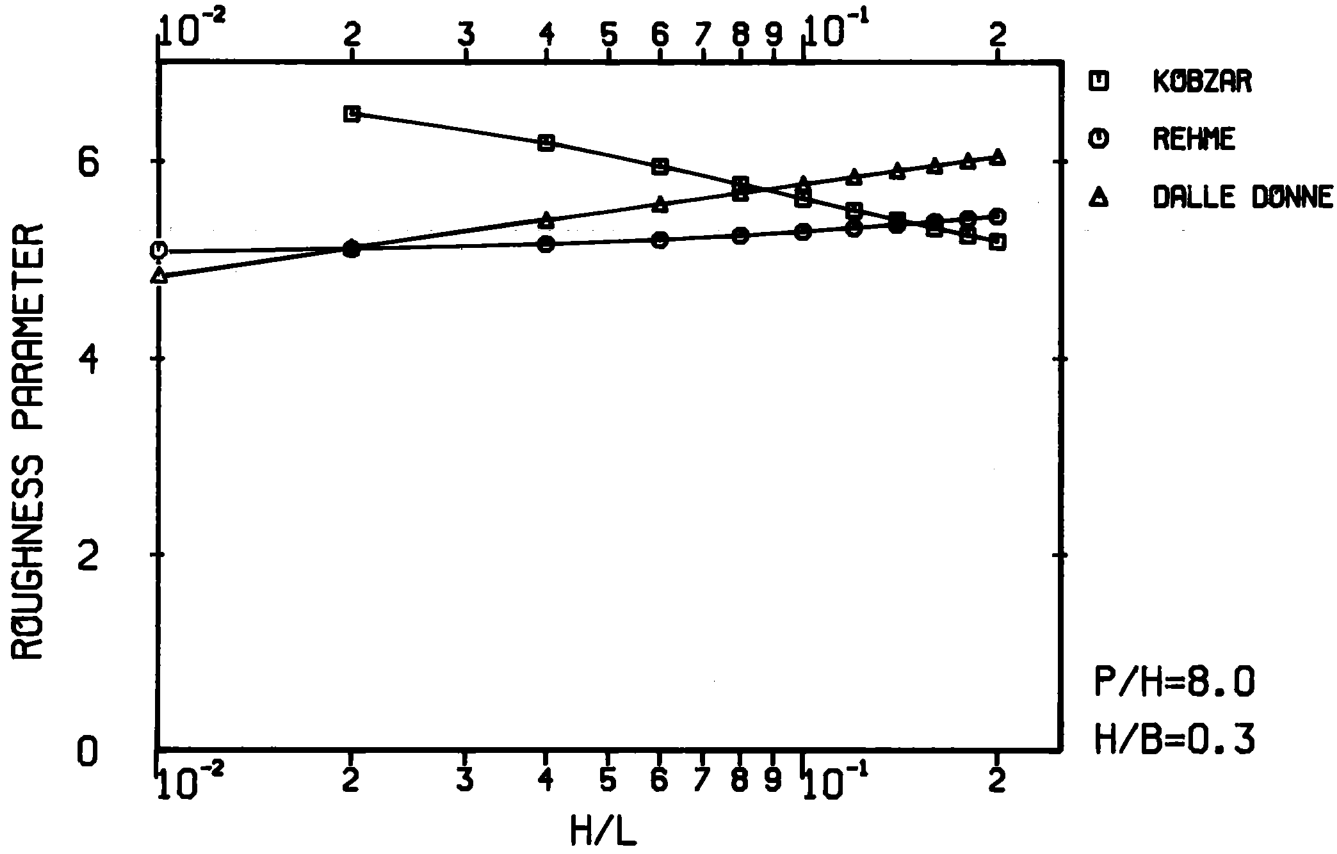


Fig.6 ROUGHNESS PARAMETER ACCORDING TO KOBZAR, REHME AND DALLE DONNE AS A FUNCTION OF H/L



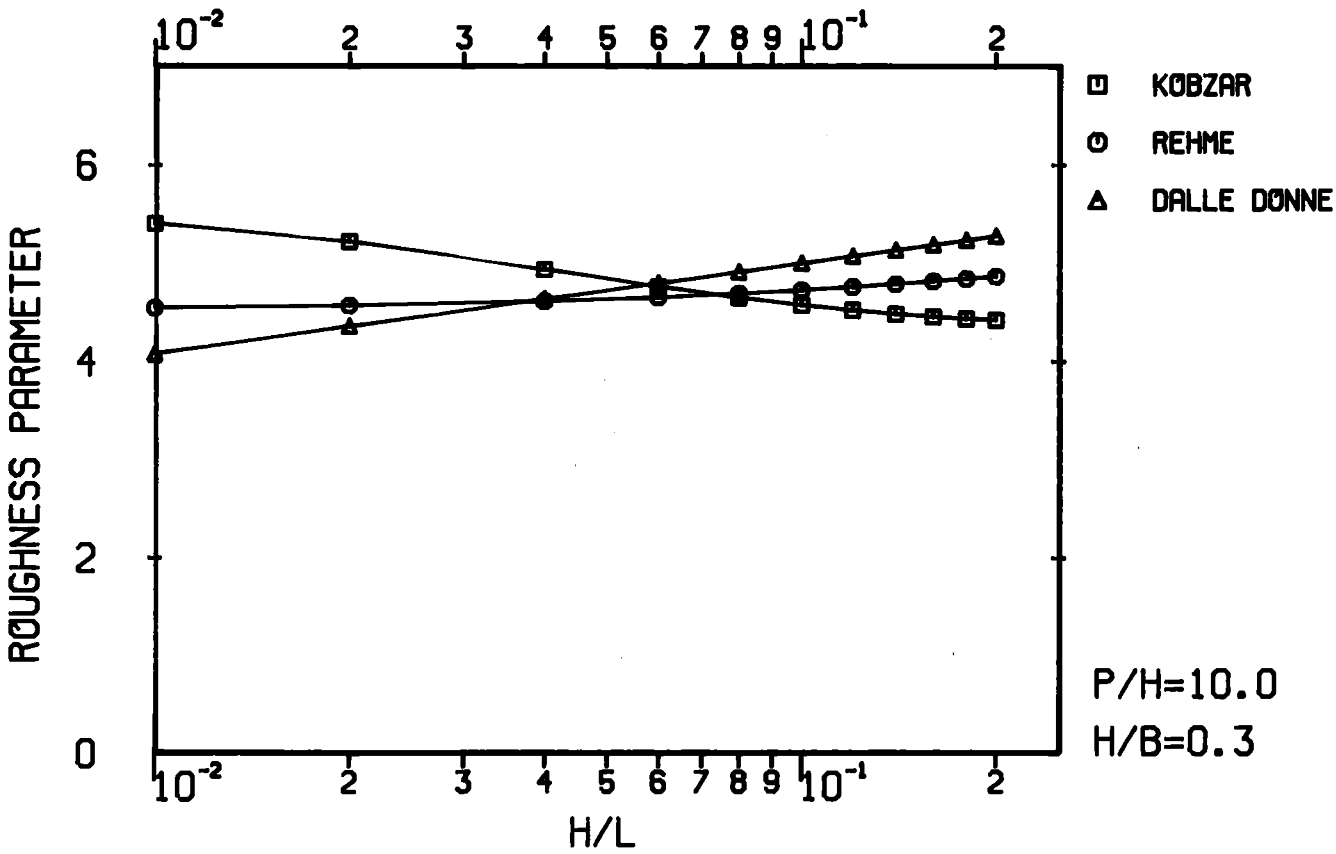


Fig.7 ROUGHNESS PARAMETER ACCORDING TO KOBZAR, REHME AND DALLE DONNE AS A FUNCTION OF H/L

Author	Roughness Type	Re_{vol} 10^{-3}	λ_{vol}
Webb	OI / IO	30	0,078
	02 / IO	30	0,I40
	04 / IO	30	0,240
	02 / 20	30	0,098
Millionshchikov	I - 5	63,I	0,0759
	I - 4	I25	0,05I3
	5-3-2	I000	0,028I
	5-3-3	I000	0,03I2
Nunner	A20	40	0,I53
	B20	50	0,II75
	Д20	50	0,226
	ДI0	50	0,3I0
	Д5	30	0,225
	Д2	30	0,0765

Author	Roughness Type	Re_{vol} 10^{-3}	λ_{vol}
Moebius	I A	I00	0,258
	I B	I00	0,204
	I E	I00	0,925
	I H	I00	0,I3I
	I J	I00	0,0787
	I K	I00	0,0973
Koch	e	20	0,53
	f	20	0,64
Gargaud	AN I	200	0,0768
	AN III-2	200	0,I0I2
	FT -I	200	0,0696

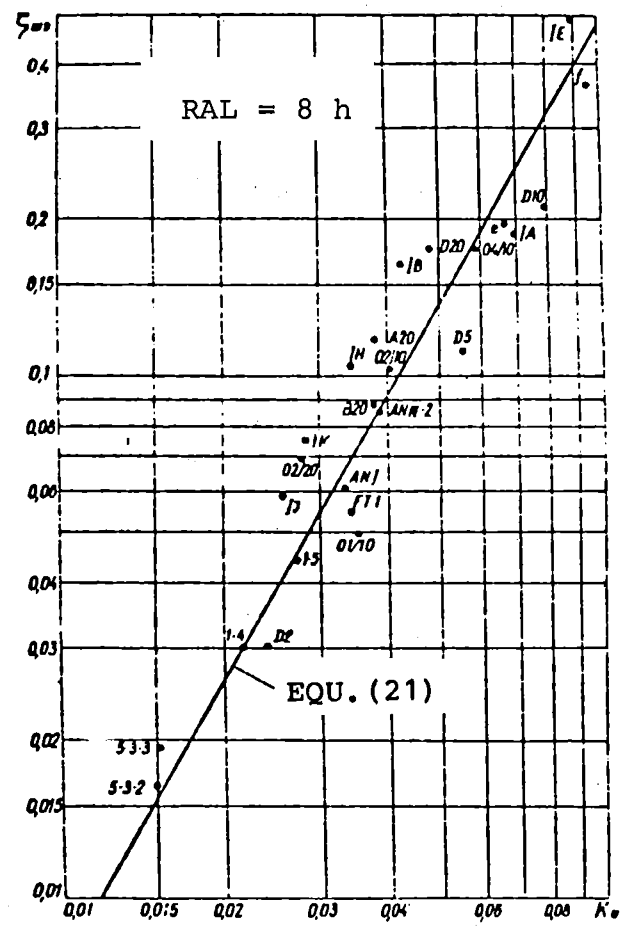
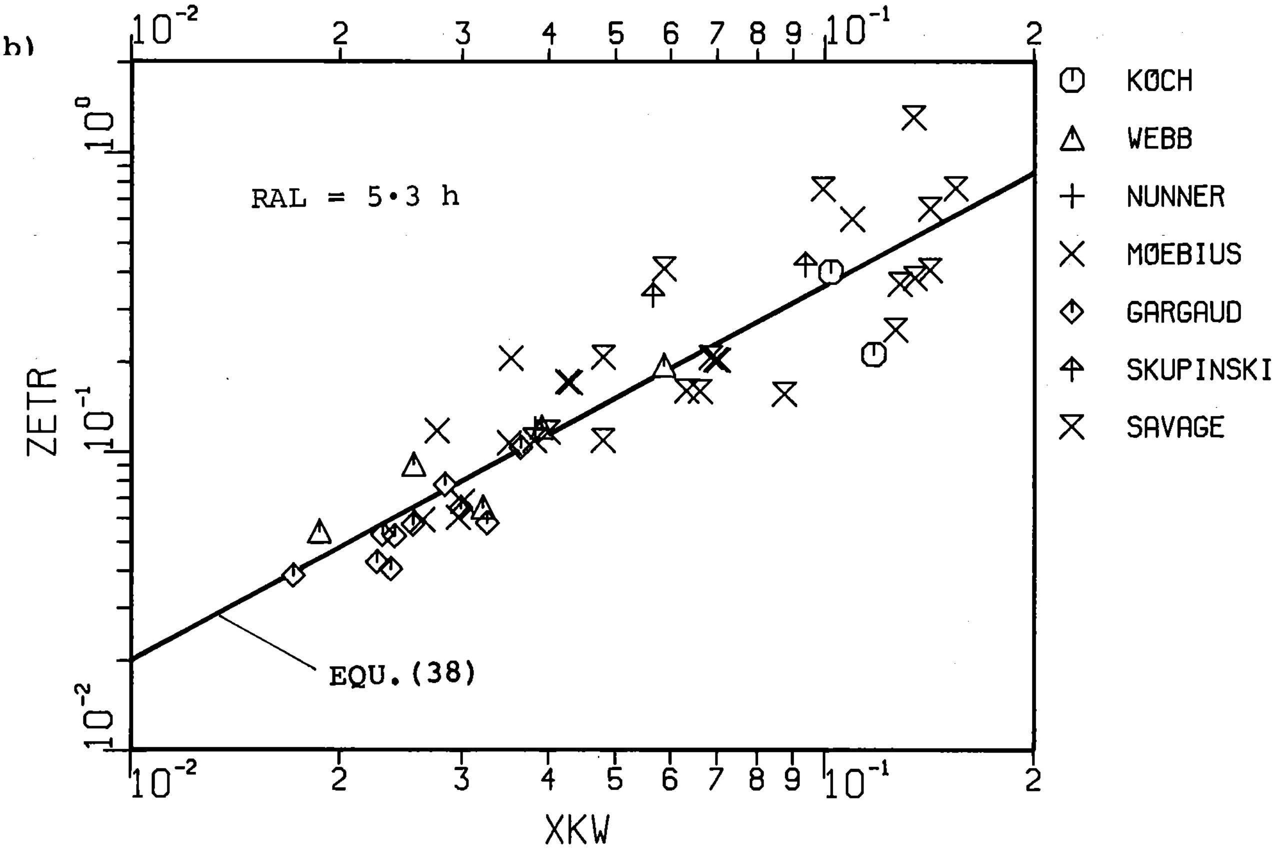


Fig.8 ROUGH FRICTION FACTOR (ζ) AS A FUNCTION OF ROUGHNESS VARIABLE (K_ω) ACCORDING TO KOBZAR

b)



a)

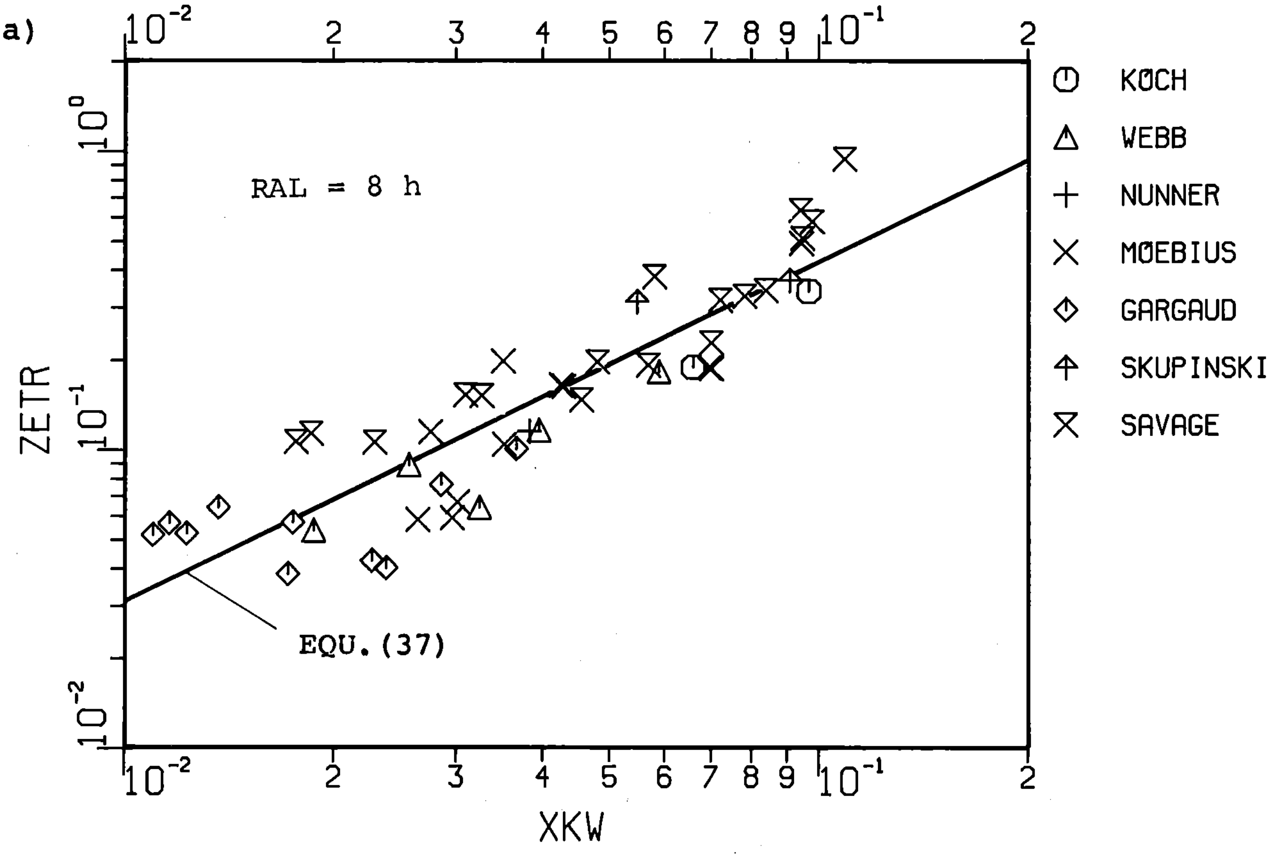


Fig.9 ROUGH FRICTION FACTOR(ZETR) AS A FUNCTION OF ROUGHNESS VARIABLE (XKW)

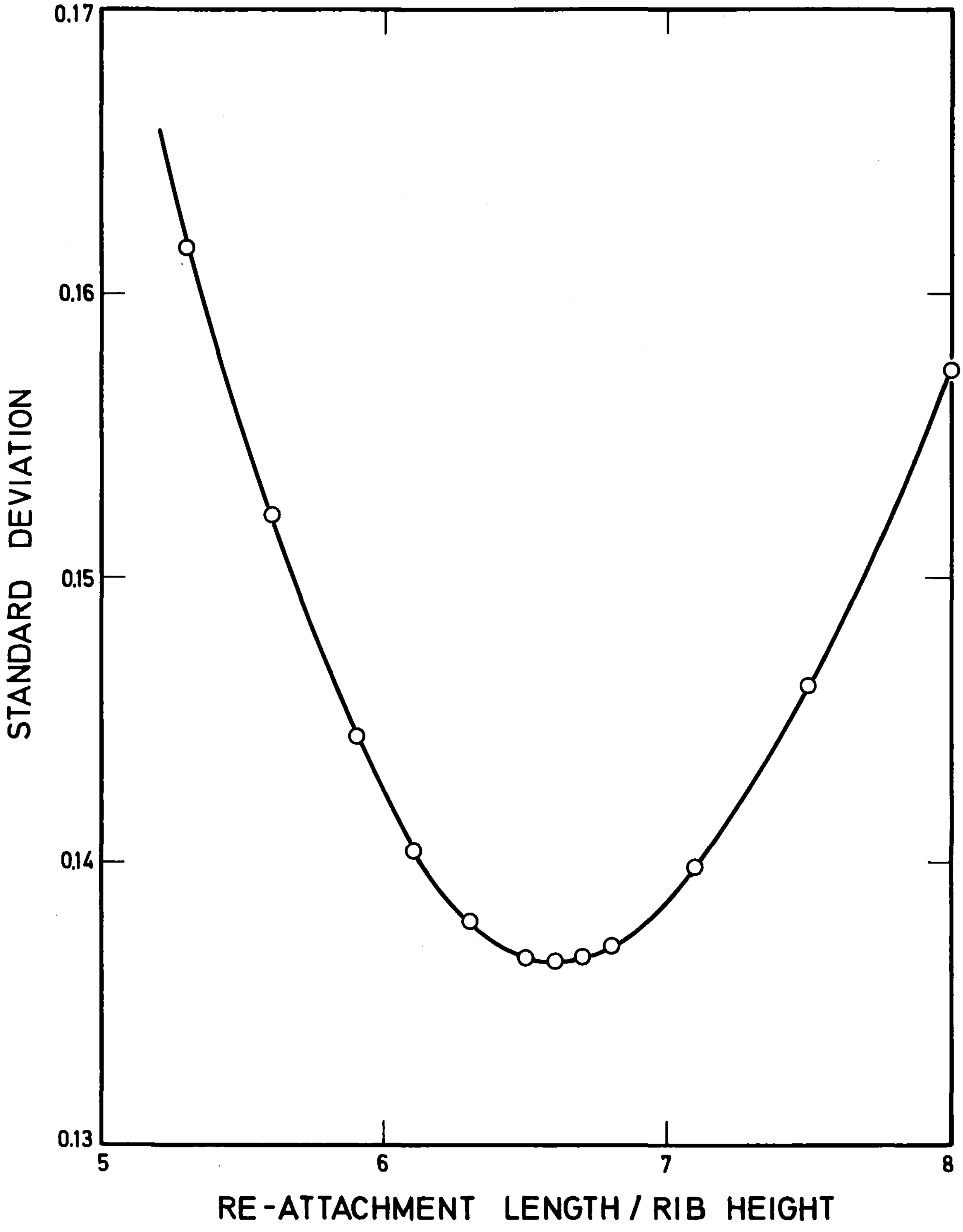


Fig.10 STANDARD DEVIATION AS A FUNCTION OF RE-ATTACHMENT LENGTH/RIB HEIGHT

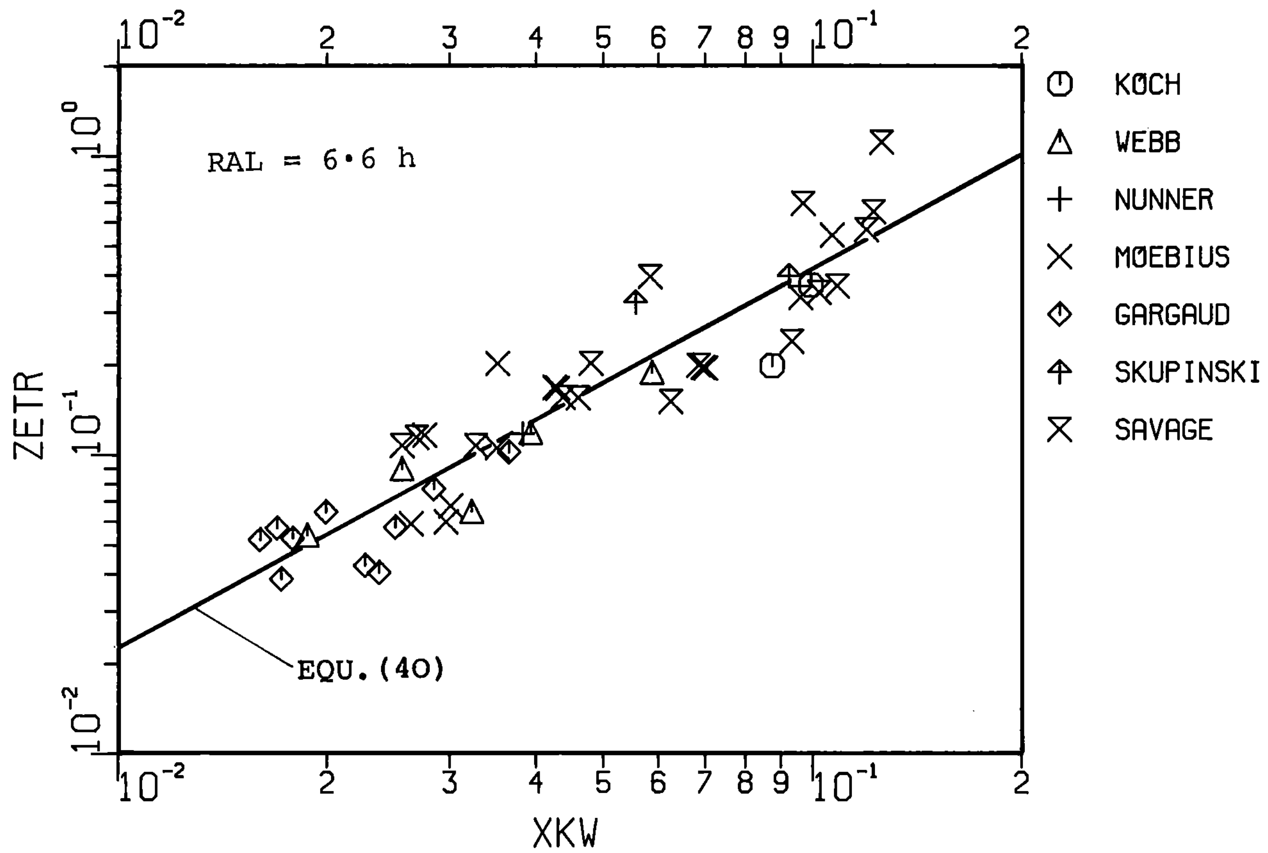


Fig.11 ROUGH FRICTION FACTOR(ZETR) AS A FUNCTION OF ROUGHNESS VARIABLE (XKW)

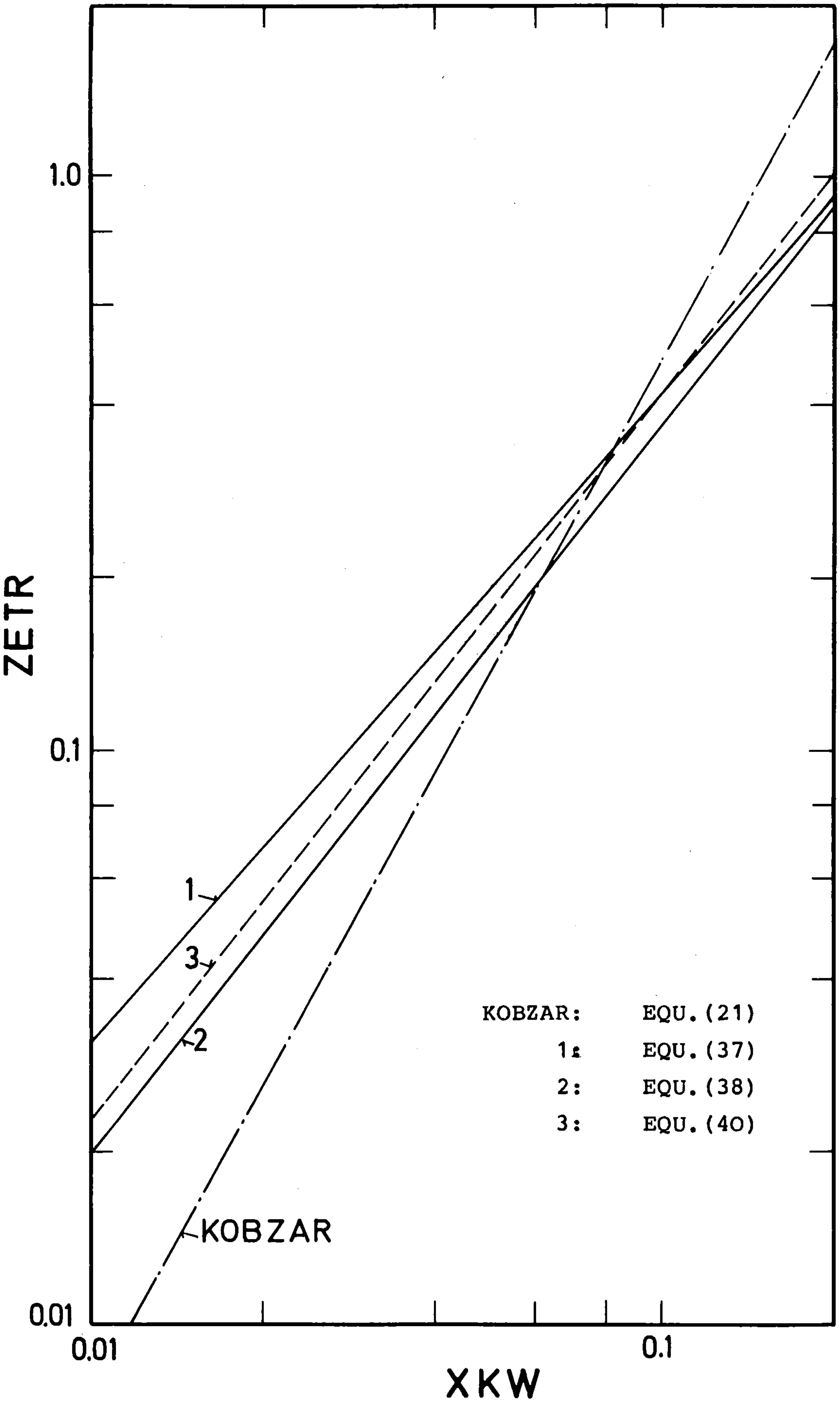
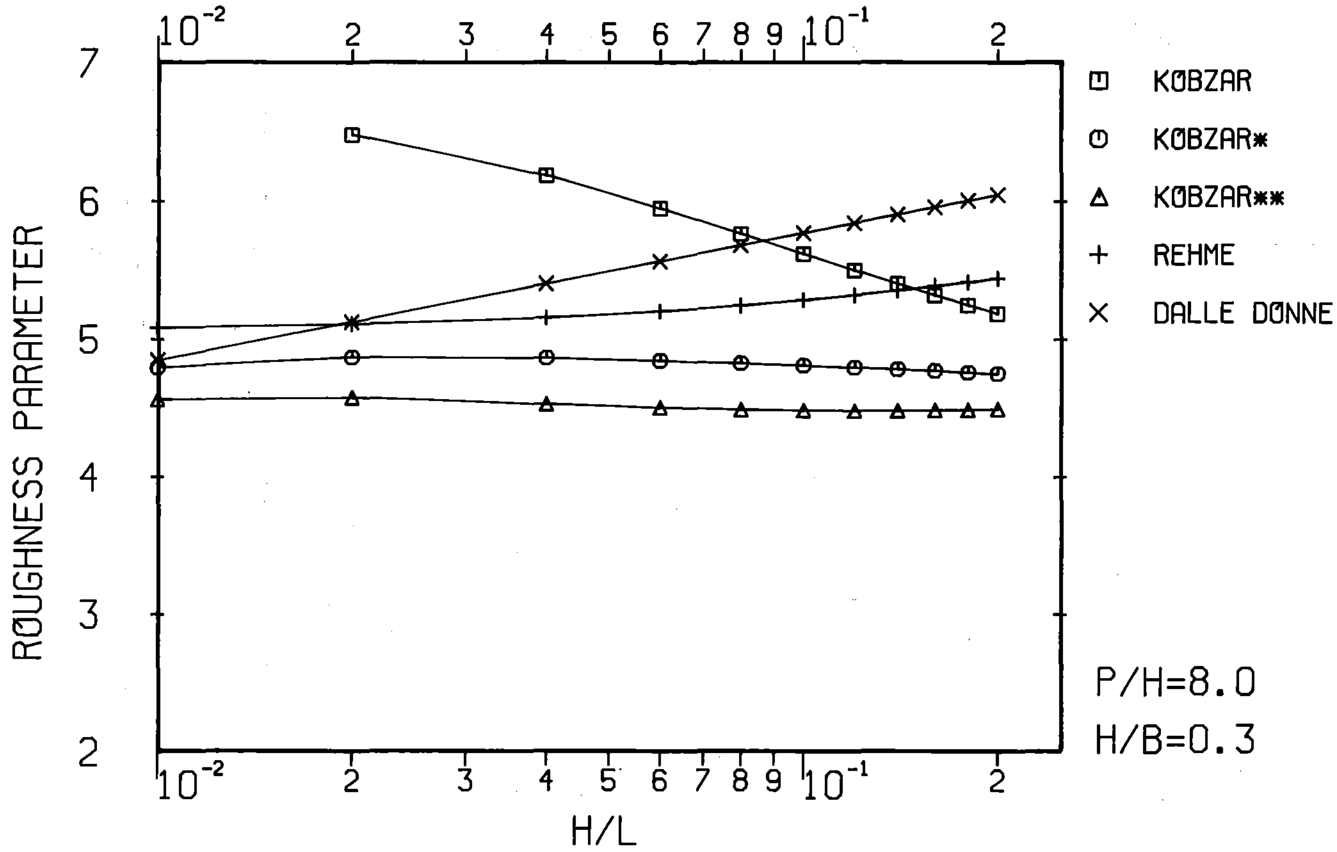


Fig.12 COMPARISON AMONG THREE MODIFIED CORRELATIONS (NO.1,2,3) AND THE CORRELATION OF KOBZAR



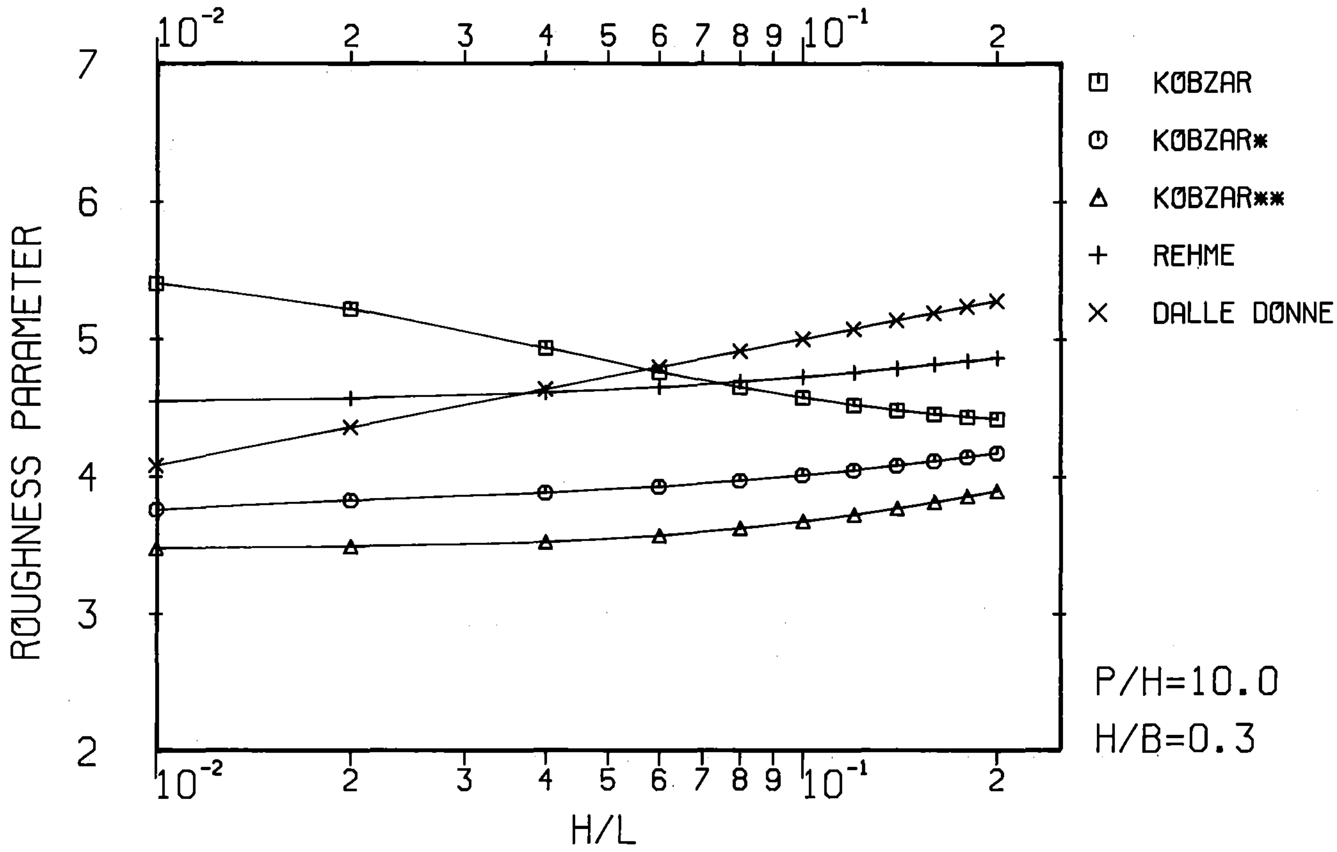
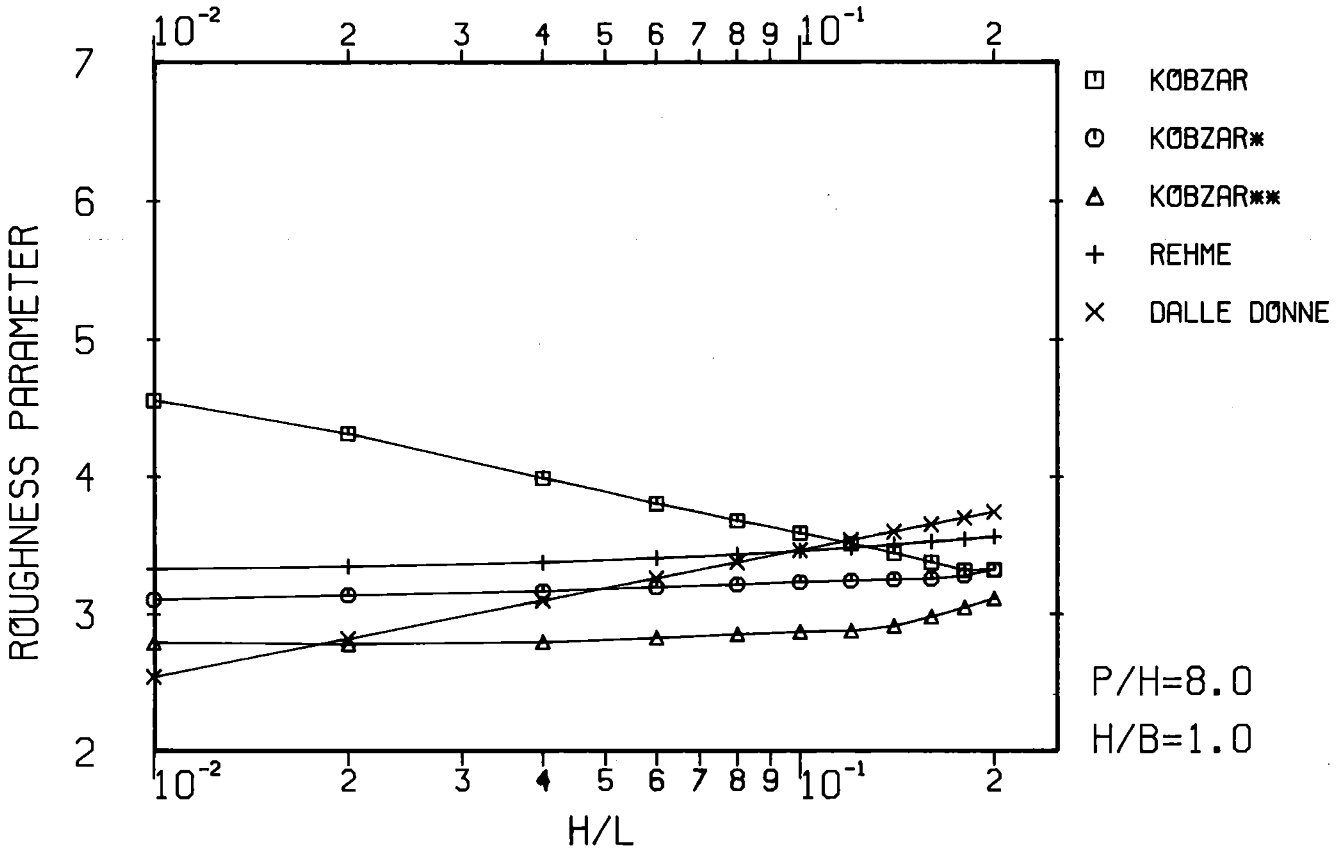


Fig.13 ROUGHNESS PARAMETER ACCORDING TO MODIFIED CORRELATIONS (NO. 1 AND 3) COMPARED WITH RK, RR AND RD



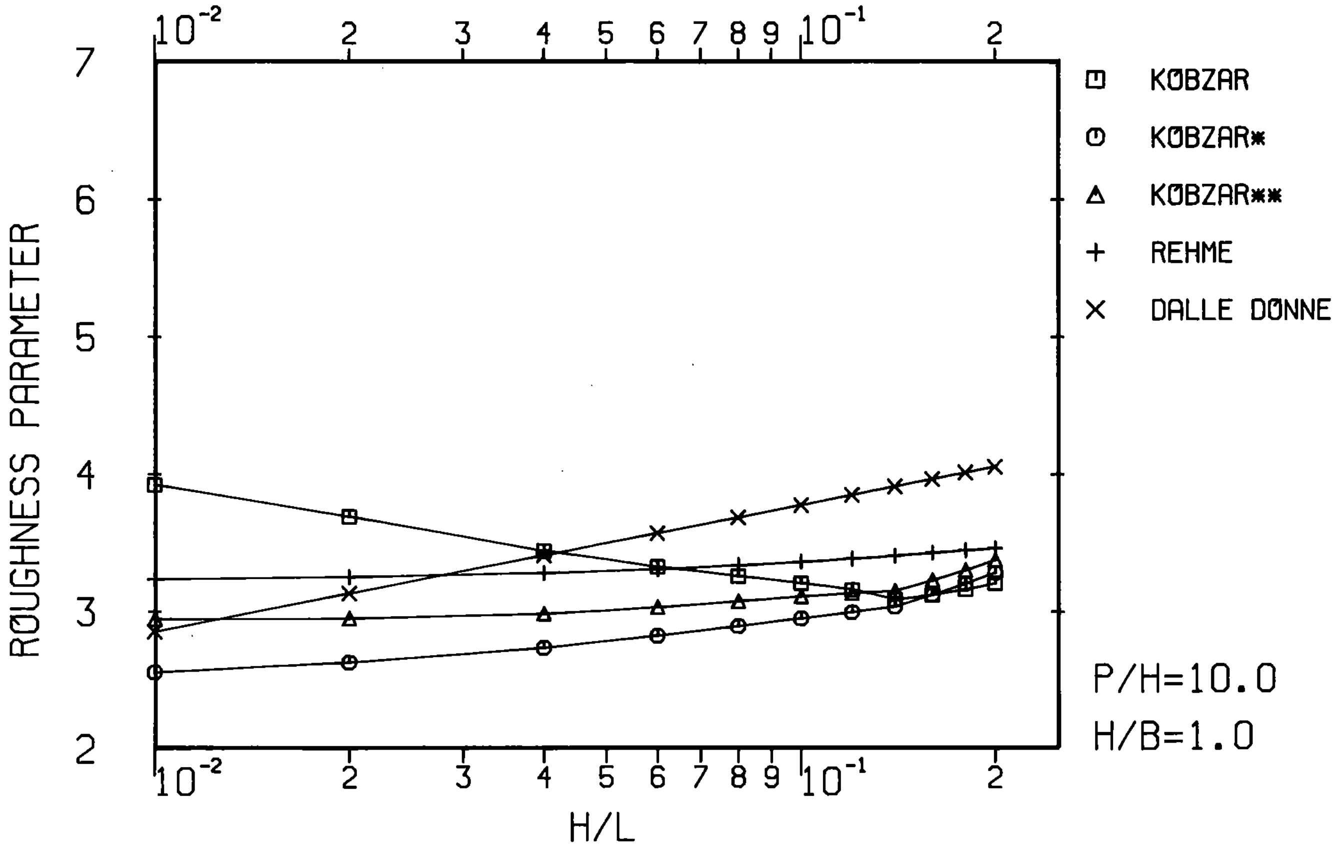
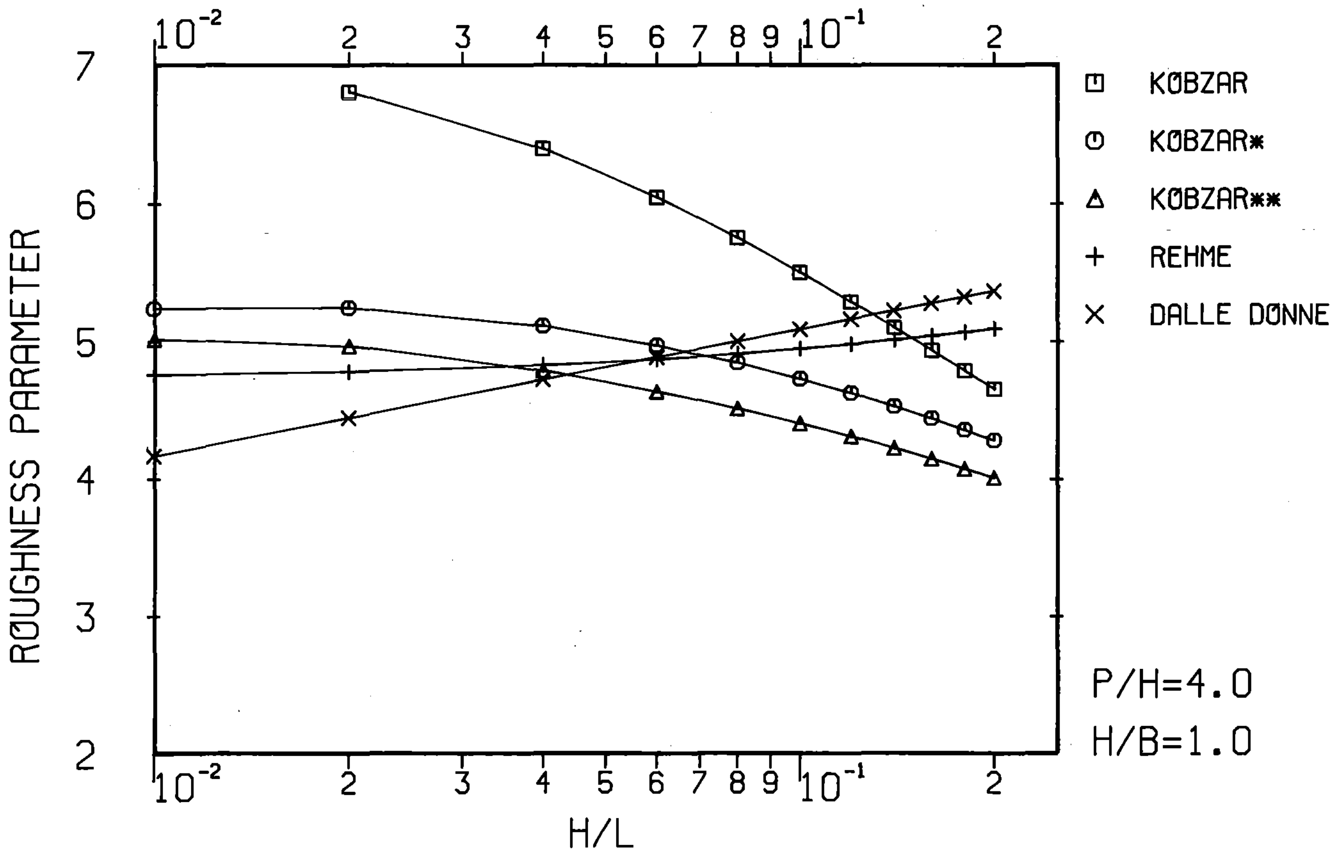


Fig.14 ROUGHNESS PARAMETER ACCORDING TO MODIFIED CORRELATIONS (NO. 1 AND 3) COMPARED WITH RK, RR AND RD



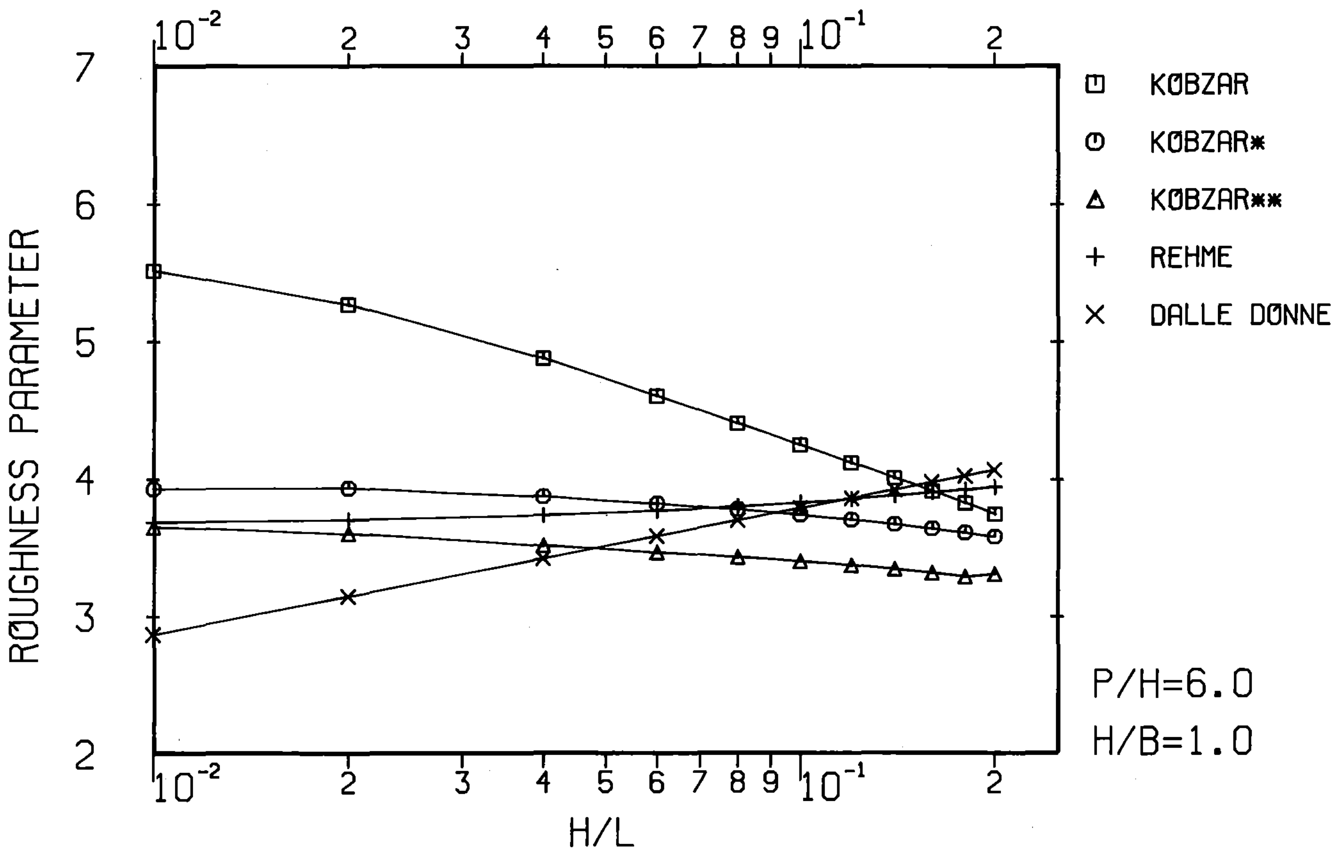
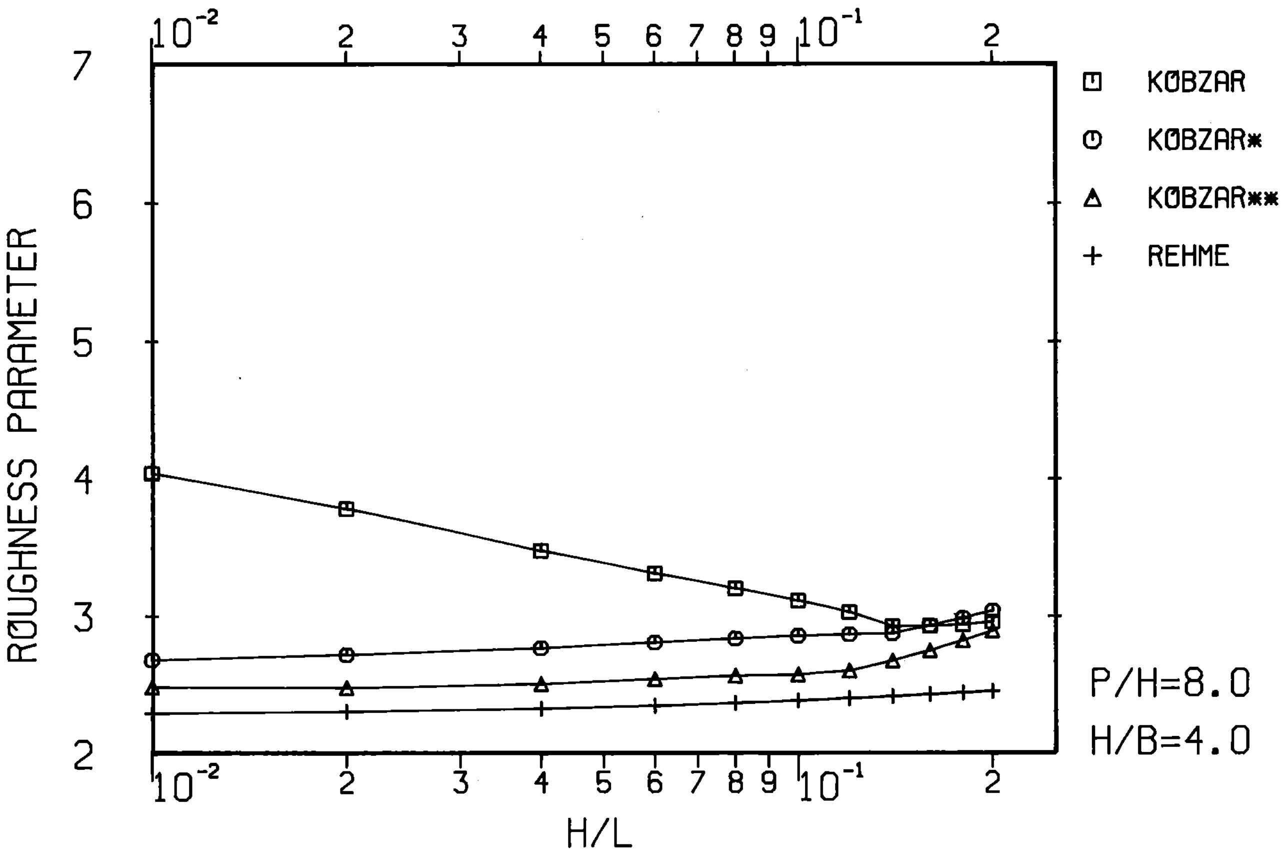


Fig.15 ROUGHNESS PARAMETER ACCORDING TO MODIFIED CORRELATIONS (NO. 1 AND 3) COMPARED WITH RK, RR AND RD



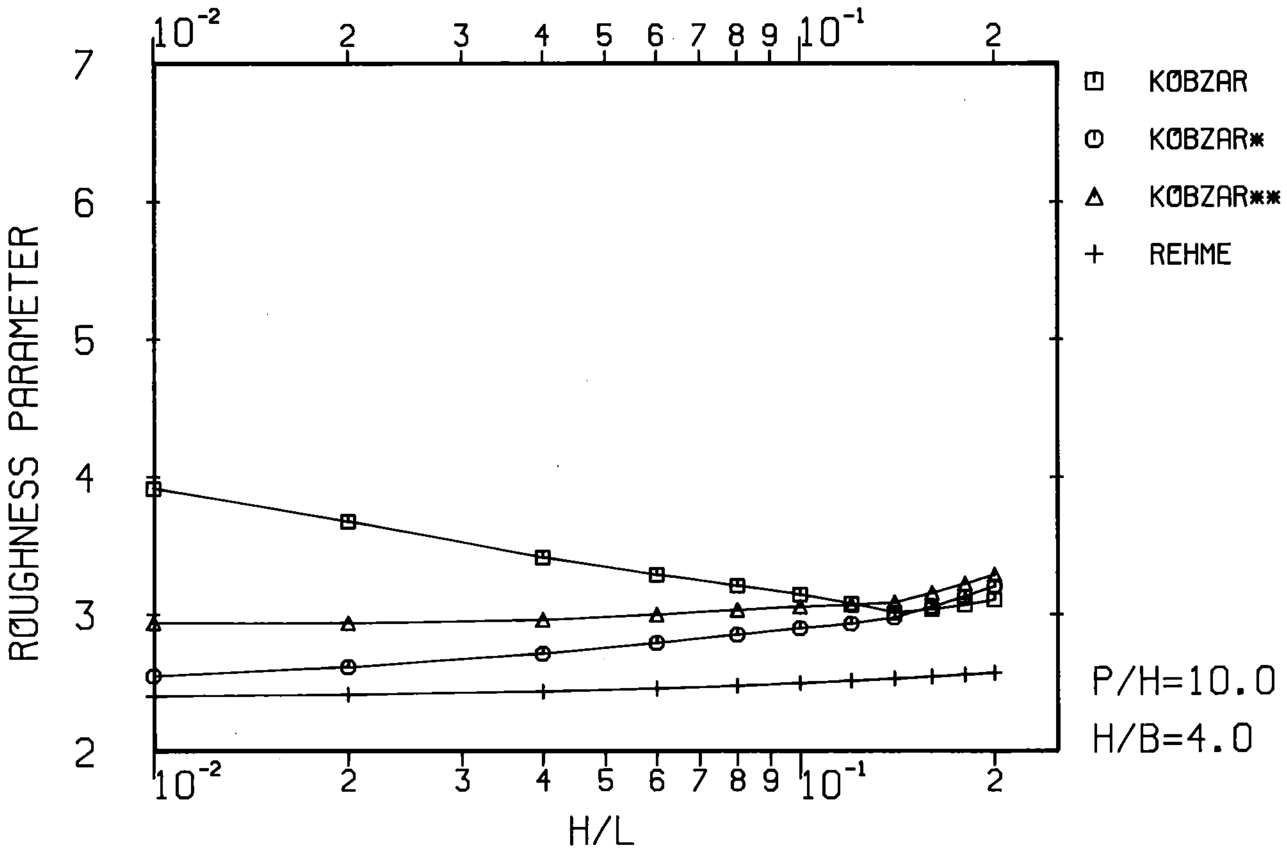
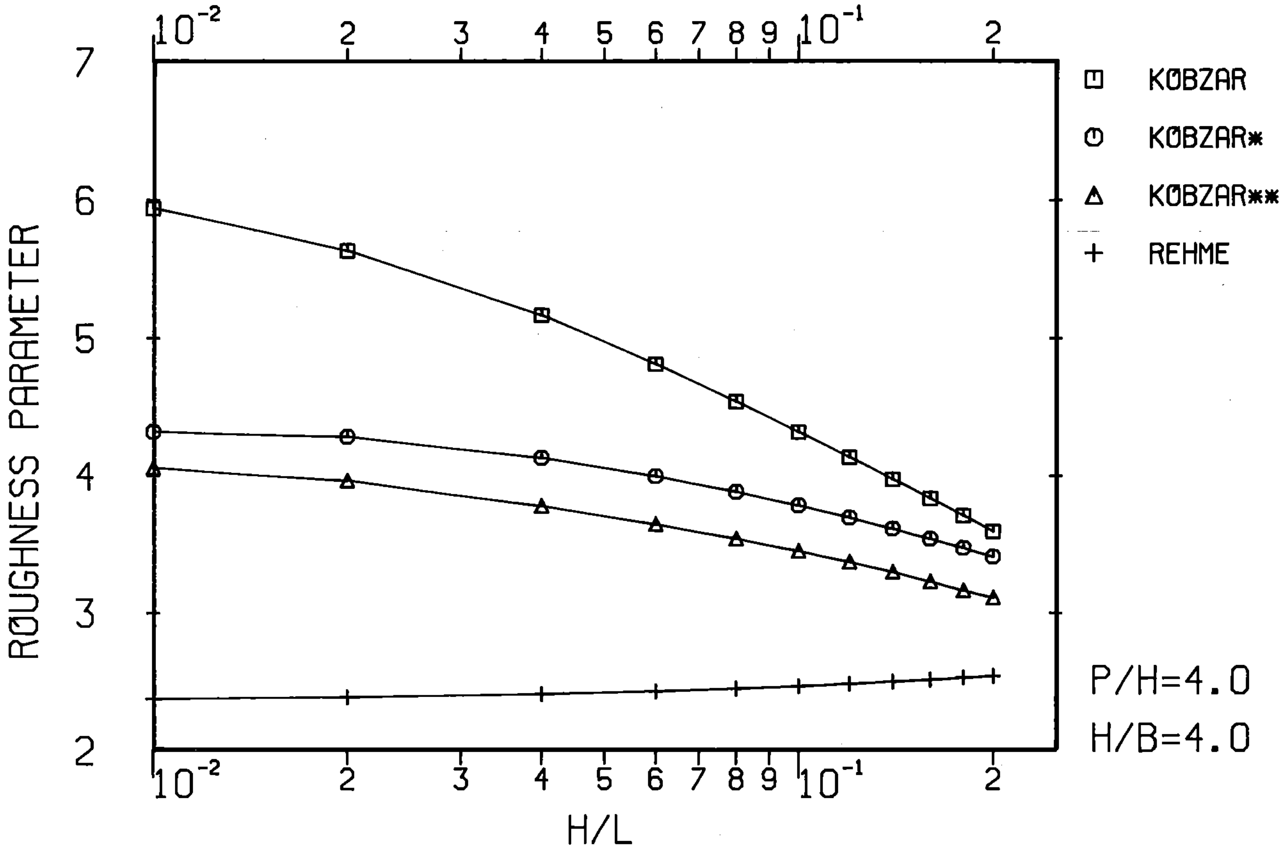


Fig.16 ROUGHNESS PARAMETER ACCORDING TO MODIFIED CORRELATIONS (NO. 1 AND 3) COMPARED WITH RK, RR AND RD



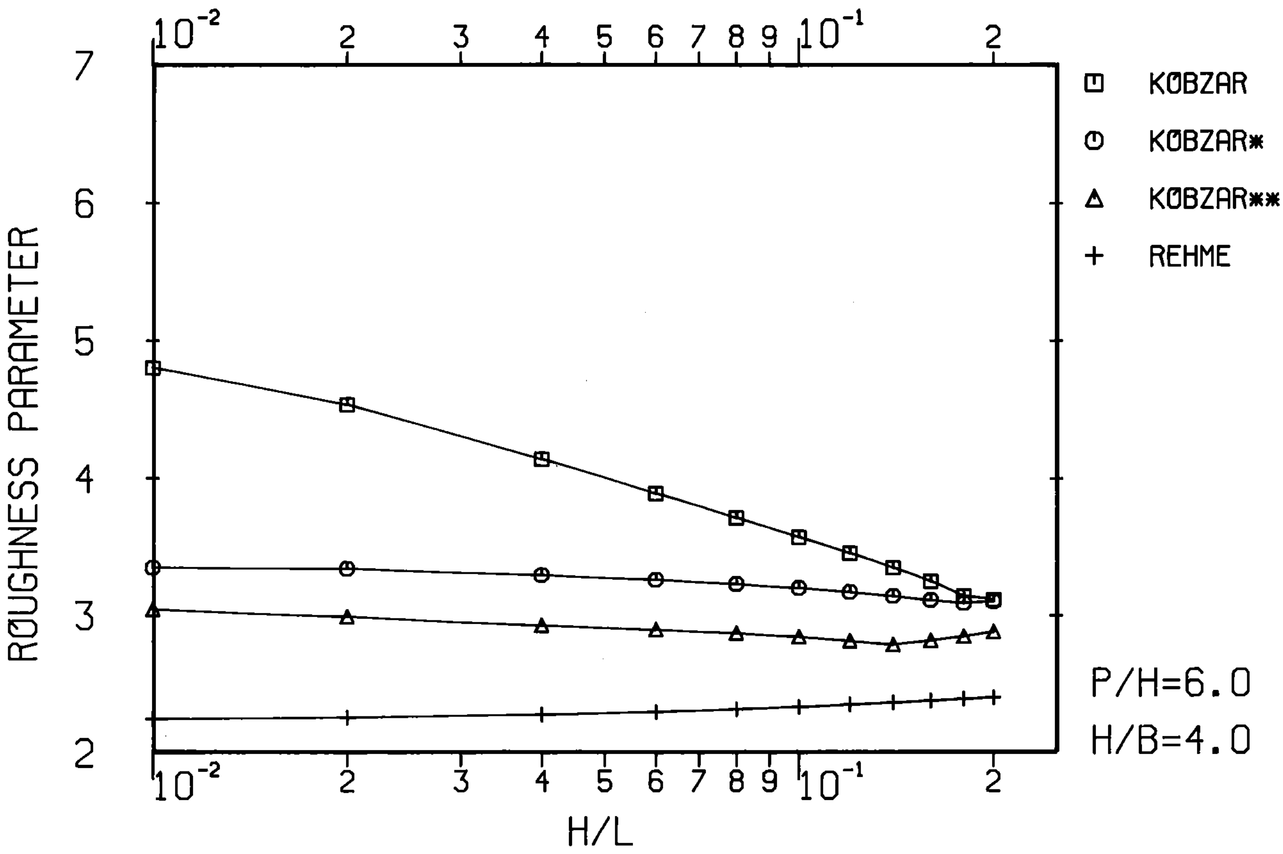


Fig.17 ROUGHNESS PARAMETER ACCORDING TO MODIFIED CORRELATIONS (NO. 1 AND 3) COMPARED WITH RK, RR AND RD

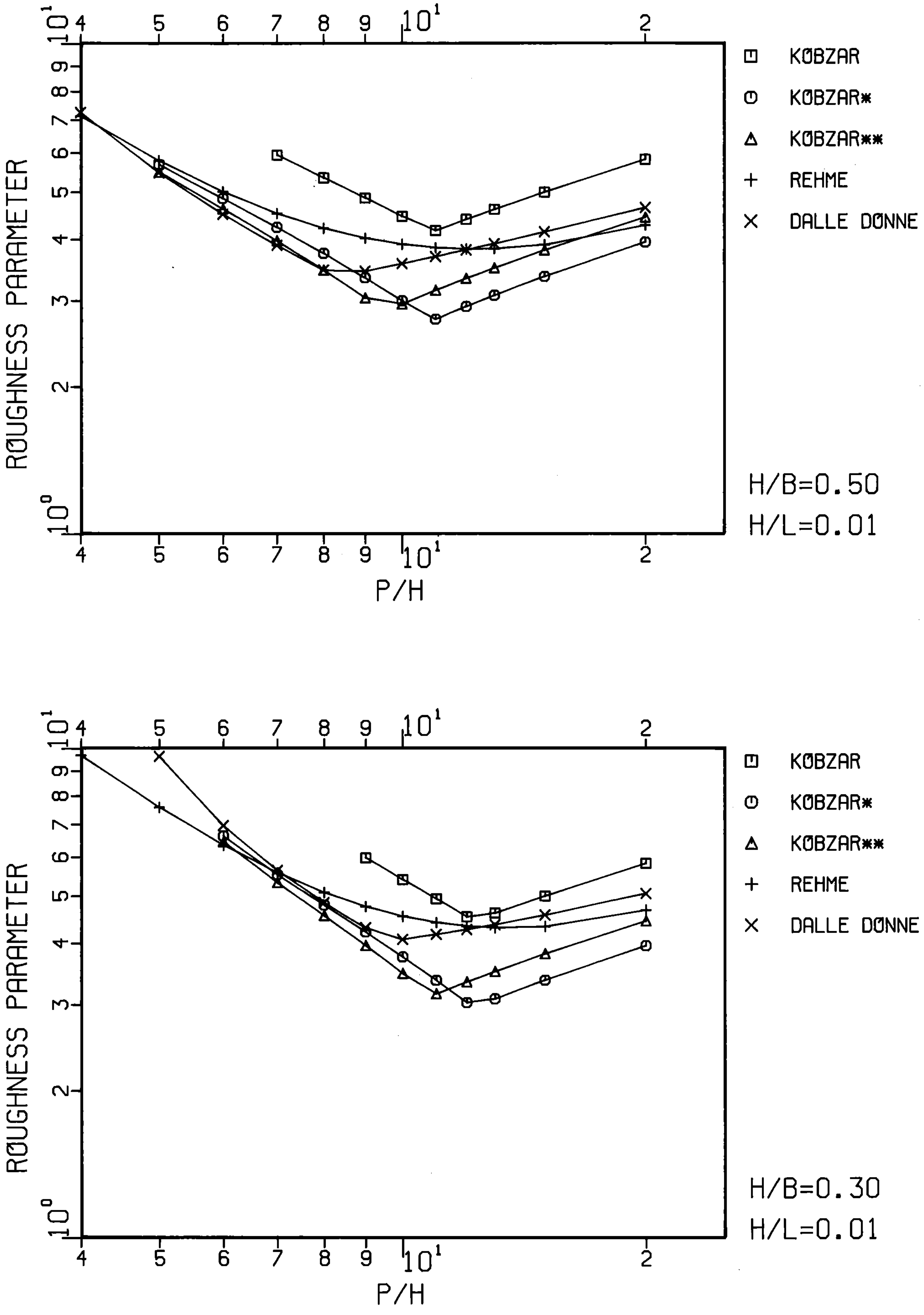
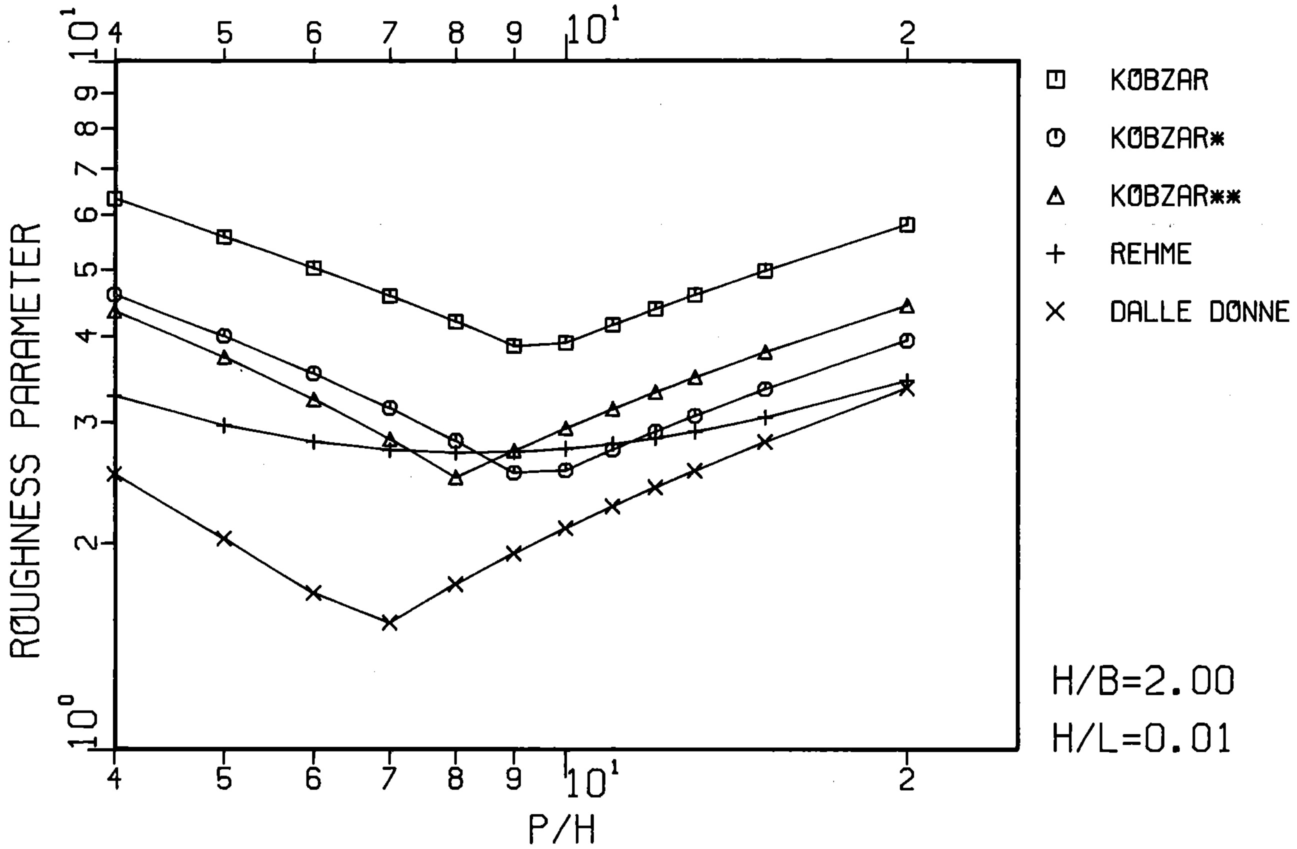


Fig.18 ROUGHNESS PARAMETER ACCORDING TO MODIFIED CORRELATIONS (NO. 1 AND 3) COMPARED WITH RK, RR AND RD



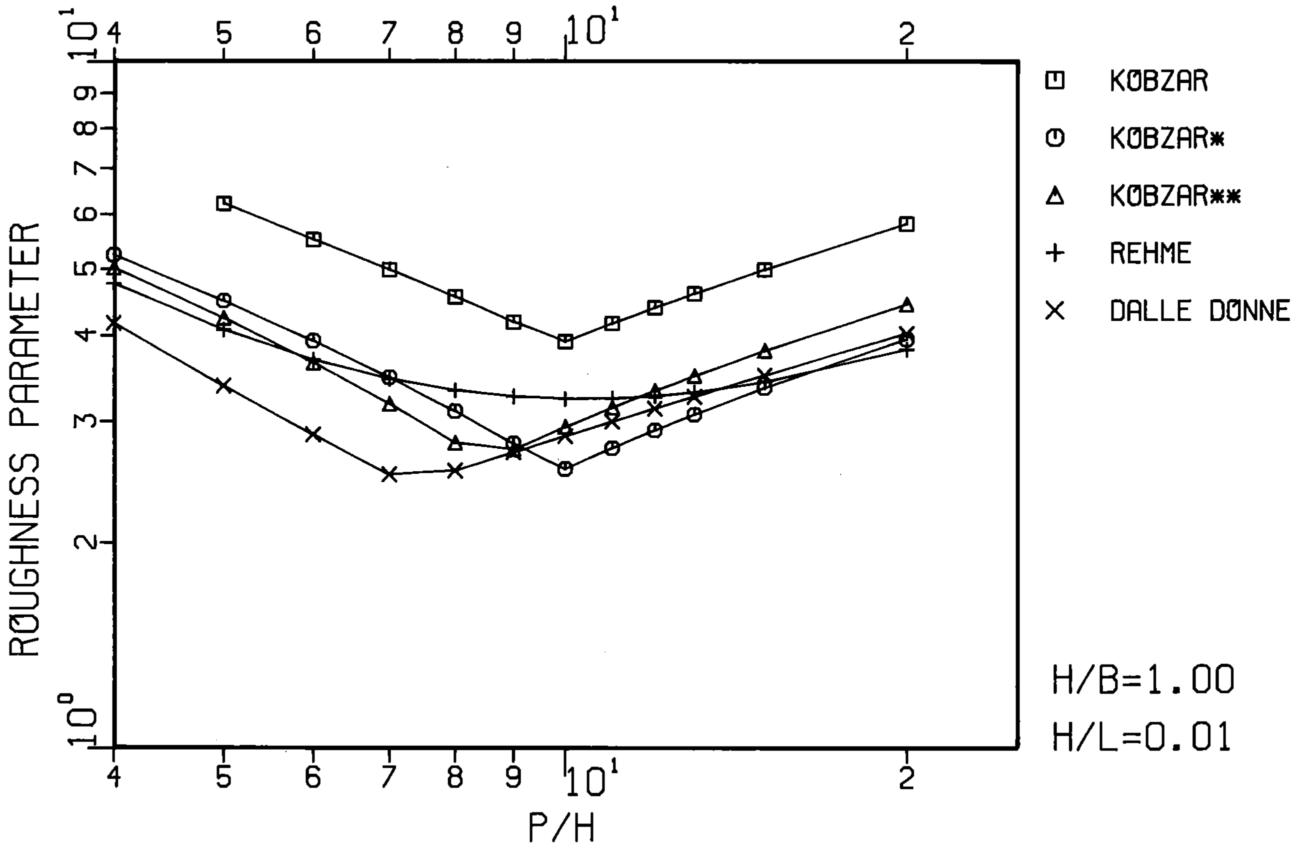
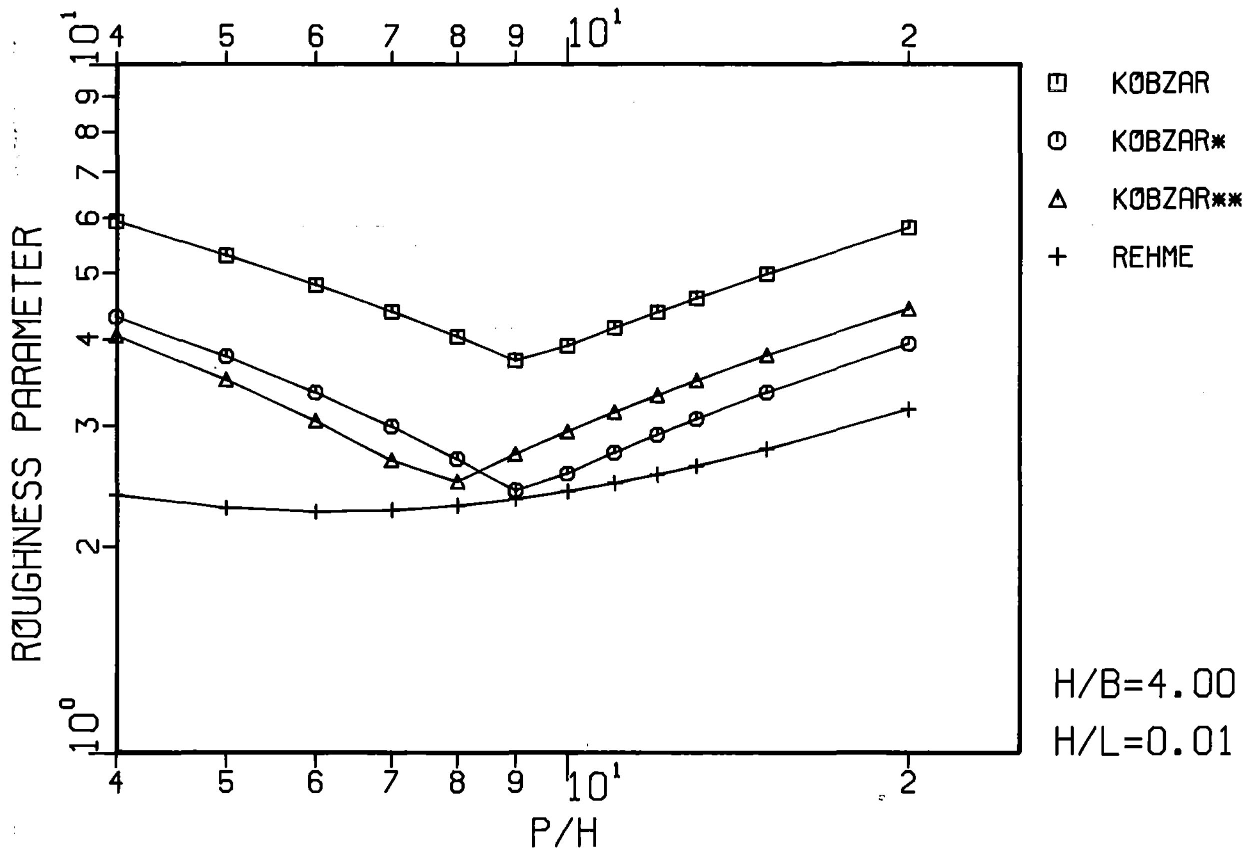


Fig.19 ROUGHNESS PARAMETER ACCORDING TO MODIFIED CORRELATIONS (NO. 1 AND 3) COMPARED WITH RK, RR AND RD



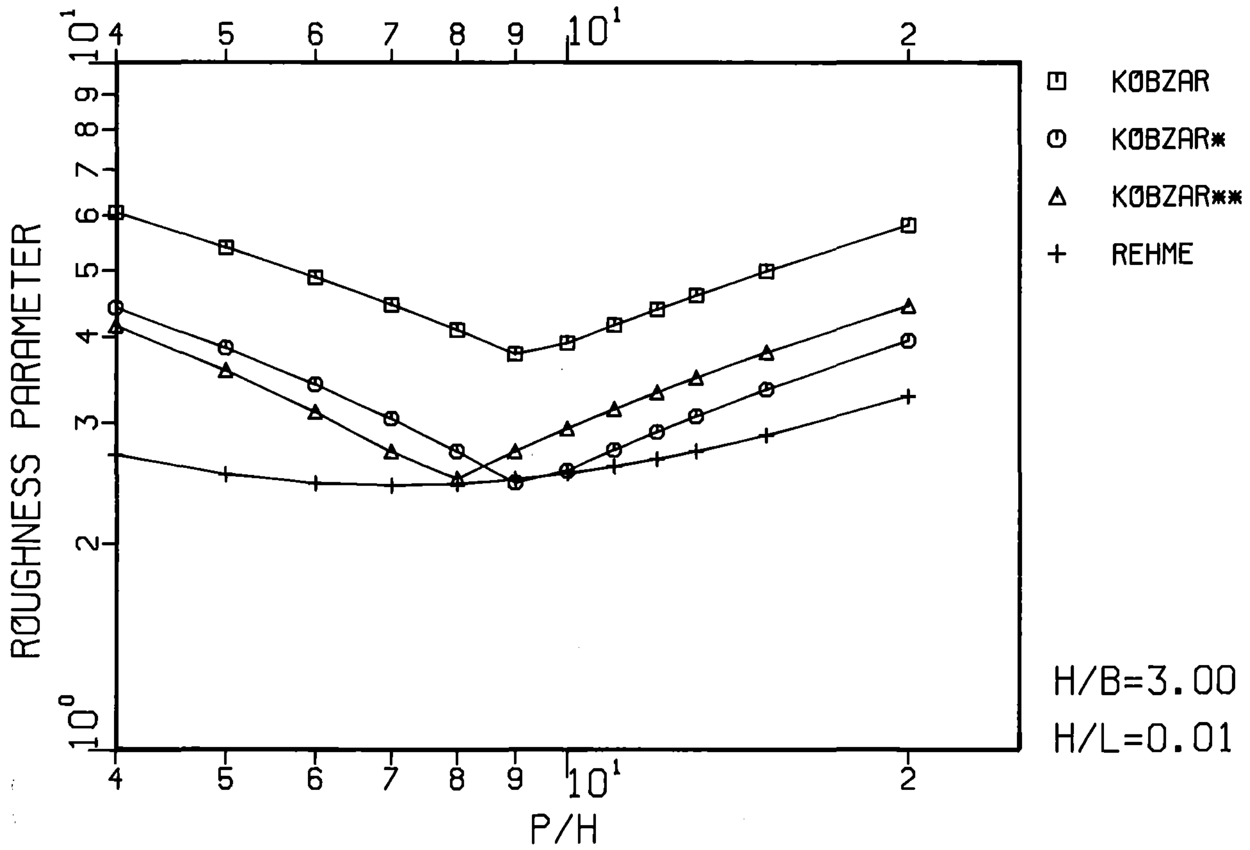


Fig.20 ROUGHNESS PARAMETER ACCORDING TO MODIFIED CORRELATIONS (NO. 1 AND 3) COMPARED WITH RK, RR AND RD

Appendix FORTRAN PROGRAM

```
C       COMPUTATION OF ROUGHNESS PARAMETER FOR ARTIFICIAL
C       ROUGHNESS (RECTANGULAR TRANSVERSE RIBS) ACCORDING TO
C       KOBZAR, REHME AND DALLE DONNE
C
C       PH= PITCH/HEIGHT(0.35.LE.P/H.LE.25.0)
C       HB= HEIGHT/WIDTH(0.02.LE.H/B.LE.5.00)
C       HEIGHT/DIAMETER(0.0.LE.2H/D.LE.0.2)
C
C       RK= ROUGHNESS PARAMETER ACCORDING TO KOBZAR
C       RR= ROUGHNESS PARAMETER ACCORDING TO REHME AND BAUMANN
C       RD= ROUGHNESS PARAMETER ACCORDING TO DALLE DONNE AND MEYER
C
        DIMENSION PH(30),XLAMTV(30),RK(30),RR(30),HB(20),
     1      DIFF(30),HDVOL2(30),RD(30),DIFF1(30),RD01(15,7)
        REAL*4 NTEXT(20)
        DIMENSION TXKW(99)
  100   FORMAT(/)
C
C  ****  INPUT DATA
        READ(5,401) (NTEXT(I),I=1,20)
  401   FORMAT(20A4)
        READ(5,402) NL,(PH(L),L=1,NL)
  402   FORMAT(I2,3X,15F5.0)
        READ(5,403) NY,(HDVOL2(J),J=1,NY)
  403   FORMAT(I2,3X,15F5.3)
        READ(5,404) NZ,(HB(K),K=1,NZ)
  404   FORMAT(I2,3X,15F5.3)
        DROOT= 3.68300
        REVOL= 100000.
C  *******************************************
C
        WRITE(6,201) (NTEXT(I),I=1,20)
  201   FORMAT(10X,20A4)
        WRITE(6,100)
C
        DO 93 J=1,NY
        WRITE(6,606) J
  606   FORMAT(10X,'*****   J= ',I2)
        WRITE(6,100)
C
        DO 96 K= 1,NZ
        WRITE(6,501) K
  501   FORMAT(10X,'*****   K= ',I2)
        WRITE(6,100)
C
        DO 98 L=1,NL
C
C  ****  DETERMINATION OF THE VOLUMETRIC DIAMETER(DVOL)
C          BY ITERATION  *
        DV= DROOT
        M1= 0
    2   H= HDVOL2(J)*DV/2
        M1= M1+1
        B= H/HB(K)
        P= H*PH(L)
        DIN= DROOT-2*H
        DVOL= SQRT(DROOT**2-(B/P)*(DROOT**2-DIN**2))
        D1= 2*H*B/P
```

contd.

```
      D2= SQRT(DVOL**2-D1**2*(P/B-1.))
      DR= D1+D2
      DELTA= ABS(DR/DROOT-1.)
      IF(DELTA.LE.1.E-5) GO TO 3
      DV= DVOL
      IF(M1.LT.30) GO TO 2
C  ****  END OF THE ITERATION
C
      WRITE(6,503) DELTA
  503 FORMAT(10X,'NO CONVERGENCE, DELTA=',E15.8)
C
   3  CONTINUE
C
      IF(B.GE.P) GO TO 4
C
C  ****  CALCULATION OF ROUGHNESS PARAMETER ACCORDING TO REHME
C           AND BAUMANN  *
      AB1= 18.5*HB(K)**(-0.9475)
      AB2= -1.143*HB(K)**(-0.147)
      AB3= 0.33*HB(K)**0.1483
      AB4= 0.758*HB(K)**(-0.11)
      RB0= AB1*PH(L)**AB2+AB3*PH(L)**AB4
      RBK1K2= 2.900+1.490*HDVOL2(J)-1.972*HDVOL2(J)**2
C     ROK1K2= 2.9
      RR(L)= RB0+(RB0/2.9)*(RBK1K2-2.9)
C  ***********************************
C
C  ****  CALCULATION OF ROUGHNESS PARAMETER ACCORDING TO
C           DALLE DONNE AND MEYER  *
      HL= HDVOL2(J)
      IF(HL.NE..01) GO TO 35
      PBH= (P-B)/H
      IF(PBH-6.3) 31,31,32
   31 IF(PBH.LT.1.) GO TO 38
      RD01(L,K)= 9.3*PBH**(-0.73)-(2+7/PBH)*ALOG10(H/B)
      GO TO 35
   32 IF(PBH.GT.160.) GO TO 38
      RD01(L,K)= 1.04*PBH**0.46-(2+7/PBH)*ALOG10(H/B)
   35 IF(HL.EQ..01) RD(L)= RD01(L,K)
      IF(HL.GT..01) RD(L)= RD01(L,K)+0.4*ALOG(HL/.01)
      GO TO 40
   38 WRITE(6,505) PBH
  505 FORMAT(10X,'THE VALUE OF PBH FALLS OUTSIDE THE RANGE,PBH='
     1  ,F10.5)
      WRITE(6,100)
      RD01(L,K)= 0.
   40 CONTINUE
C  ***********************************
C
      PI = 3.141592654
      BETA= 45.0*PI /180
      GAMA= BETA
C
C  ****  DETERMINATION OF THE EFFECTIVE REYNOLDS NUMBER(REEFF)
C           BY ITERATION  *
      RE= REVOL
      M2= 0
   5  ALPHA= ATAN((1+0.15*(1-EXP(-RE/1.E6)))/8)
```

contd.

```
      M2= M2+1
      HEFF= (P-B)*SIN(ALPHA)*SIN(BETA)/SIN(ALPHA+BETA)
      IF(HEFF-H) 11,11,12
   11 DEFF= SQRT(DIN**2+2*HEFF*(1-B/P)*(DIN+2*HEFF/3))
      GO TO 14
   12 DEFF= SQRT(DIN**2+(4/P)*(DIN*H*(P-B-H/
     1  TAN(BETA)/2-H/TAN(ALPHA)/2)
     2  +H**2*(P-B-2*H/TAN(BETA)/3-2*H/TAN(ALPHA)/3)))
      HEFF= H
   14 REEFF= (DVOL/DEFF)*REVOL
      DEL= ABS(RE/REEFF-1.)
      IF(DEL.LT.1.E-5) GO TO 7
      RE=REEFF
      IF(M2.LT.30) GO TO 5
C  ****  END OF THE ITERATION
C
      WRITE(6,203) DEL
  203 FORMAT(10X,'NO CONVERGENCE, DEL=',E15.8)
C
   7  CONTINUE
      IF(REEFF-1.E5) 15,15,16
C
C     XLAMS=FRICTION FACTOR FOR SMOOTH SECTION
C
C     BLASIUS FORMULA
C
   15 XLAMS= 0.3164/REEFF**0.25
      GO TO 18
C
C     NIKURADSE FORMULA
C
   16 XLAMS= 0.0032+0.221/REEFF**0.237
   18 CONTINUE
C
C  ****  COEFFICIENTS OF THE EQUATION NO.23 FROM KOBZAR
      A1= -0.000109577
      A2= +0.002439750
      A3= -0.017900900
      A4= +0.018932000
      A5= -0.576530000
      A6= +0.823600000
      X= ALOG10(REEFF)
C
C  ****  AA=ALOG10(DELY/REFF) AT DELETA=7.8
      AA= A1*X**5+A2*X**4+A3*X**3+A4*X**2+A5*X+A6
      REFF=DEFF/2
C
C     R=REFF(EVALUATED AT EFFECTIVE RADIUS)
C
C     C= CRITICAL(EVALUATED AT DELTA ETA=7.8)
C
      ETARC= 7.8/10**AA
C
C     XLAMT= TOTAL FRICTION FACTOR
C
      XLAMTC= 32*ETARC**2/REEFF**2
C
C     ZET= FRICTION FACTOR FOR ROUGH SECTION
```

contd.

```
C
      ZETRC= XLAMTC-XLAMS
      ZLOG= ALOG10(ZETRC)+1.2
      X= ABS(ALOG10(10**ZLOG/100))
C
C   ****  COEFFICIENTS OF THE EQUATION NO.22 FROM KOBZAR
      B1= -0.0260744
      B2= +0.1262950
      B3= -0.3422500
      B4= -0.2030400
      B5= +0.3185000
      BX= B1*X**4+B2*X**3+B3*X**2+B4*X+B5
      Y1P2= BX-AA
C
C     MN= MINIMUM,MX= MAXIMUM
C
C
C   ****  DETERMINATION OF DELETA AND ZETRTH BY ITERATION
      ZETRMN= ZETRC
      ZETRMX= 10.0
      M3= 0
   19 ZETR= (ZETRMN+ZETRMX)/2
      M3= M3+1
      XLAMR= XLAMS+ZETR
C
C     ZZ= FRICTIONAL VELOCITY/KINEMATIC VISCOSITY
C
      ZZ= SQRT(XLAMR/8)*REEFF/DEFF
      X= ABS(ALOG10(ZETR/100))
      BB= B1*X**4+B2*X**3+B3*X**2+B4*X+B5
C
C   ****  COEFFICIENTS OF THE EQUATION NO.24 FROM KOBZAR
      Y1= -0.5451
      Y2= +1.2366
      Y3= +0.1321
      Y4= +0.0052
      X= ALOG10(ZETR)-ALOG10(ZETRC)
      YX=Y1P2*(Y1*X**3+Y2*X**2+Y3*X+Y4)
      X1= ALOG10(ZETRC)
      X2= X1+1.2
      X3= ALOG10(ZETR)
      IF(X3-X2) 20,21,21
   21 DELY= REFF*10**BB
      GO TO 22
C
   20 IF(X3.LE.X1) GO TO 91
      DELY= REFF*10**(YX+AA)
   22 CONTINUE
      DELETA= DELY*ZZ
C
      IF(DELETA.LT.7.8) GO TO 92
C
C   ****  DETERMINATION OF ROUGHNESS VARIABLE XKW
C         BY NUMERICAL INTEGRATION  *
      SUM=0.
      NX= 50
      EE= 1+0.39*(DELETA-7.8)
      DO 25 I=1,NX
```

contd.

```
      YH= (FLOAT(I)-0.5)*HEFF/NX
      Y= YH*DEFF/(DIN+2*HEFF)
      ETA= Y*ZZ
      FF= 1+0.39*(ETA+DELETA-7.8)
C
C     UD= DIMENSIONLESS VELOCITY(U+)
C
      UD= ALOG(FF/EE)/0.39
      SS= (DIN+2*HEFF-2*YH)*UD**2
      SUM= SUM+SS
   25 CONTINUE
      QQ= HEFF*XLAMR*(SIN(2*GAMA))**2/2/NX/P/DEFF
     2         *(DEFF/(DIN+2*HEFF))**4
      XKW= QQ*SUM
C  ****  END OF THE INTEGRATION
C
C
C     TH= THEORETICAL
C
      ZETRTH= 30.*XKW**1.8
C
      DD= ABS(ZETR/ZETRTH-1.0)
      IF(DD.LT.1.E-5) GO TO 95
      IF(ZETR.LT.ZETRTH) ZETRMN=ZETR
      IF(ZETR.GT.ZETRTH) ZETRMX=ZETR
      IF(M3.LT.50) GO TO 19
C  ****  END OF THE ITERATION
C
      WRITE(6,205) DD
  205 FORMAT(10X,'NO CONVERGENCE, DD=',E15.8)
      WRITE(6,100)
C
   95 CONTINUE
C
C
      TXKW(L)= XKW
C  ****  CALCULATION OF ROUGHNESS PARAMETER ACCORDING TO KOBZAR
      XLAMTR= XLAMS+ZETR
      XLAMTV(L)= (DVOL/DEFF)**5*XLAMTR
      RK(L)=SQRT(8.0/XLAMTV(L))-2.5*ALOG(DVOL/2/H)+3.75
C
   99 CONTINUE
      DIFF(L)= 100.*(RK(L)-RR(L))/RR(L)
      IF(RK(L).LT.1.E-5) DIFF(L)= 0.
      DIFF1(L)=100.*(RD(L)-RR(L))/RR(L)
      IF(RD(L).LT.1.E-5) DIFF1(L)= 0.
C  *****************************************
   98 CONTINUE
C
      NP= NL
C
    8 CONTINUE
      WRITE(6,305) HDVOL2(J),HB(K)
  305 FORMAT(10X,'H/L=',F5.2,10X,'H/B=',F5.3)
      WRITE(6,100)
      WRITE(6,206) (L,PH (L),  TXKW(L),RR(L),RK (L),DIFF(L),
     1   RD(L),DIFF1(L),L=1,NP)
  206 FORMAT(T11,'L',T21,' P/H ',T36,'  XKW ',T50,'RR',T65,
```

contd.

```
     1   'RK',T80,'DIFF',T95,'RD',T110,'DIFF'//
     2   (T10,I2,T18,F10.5, T34,F10.8,T45,
     3   F10.6,T60,F10.6,T75,F10.6,T90,F10.6,T105,F10.6))
      WRITE(6,100)
      WRITE(6,109)
  109 FORMAT(60X,'SET IS COMPLETE')
      WRITE(6,100)
C
   96 CONTINUE
C
   93 CONTINUE
C
      STOP
C   ************************************
C
C   ****  ERROR MESSAGES
    4 WRITE(6,306) PH(L)
  306 FORMAT(10X,'CALCULATION IS STOPPED BECAUSE B IS EQUAL',
     1    ' OR GREATER THAN P, PH=',E13.6)
      WRITE(6,100)
      NP= L-1
      GO TO 8
   91 WRITE(6,103) PH(L),ZETR
  103 FORMAT(10X,'PH=',E13.6,5X,'X IS TOO SMALL,ZETR=',E13.6)
      WRITE(6,100)
      GO TO 99
   92 WRITE(6,105) PH(L),DELETA
  105 FORMAT(10X,'PH=',E13.6,5X, 'DELETA IS TOO SMALL',
     1   ',DELETA=',E13.6)
      WRITE(6,100)
      GO TO 99
C   ************************************
C
      END
```