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Heat Transfer from Rough Surfaces: Some Considerations on the Assumption of Logarithmic Velocity and Temperature Profiles

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Heat transfer from rough surfaces: some considerations on the assumption of logarithmic velocity and temperature profiles

by

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Abstract

The transformation of the friction data obtained with experiments in annuli can be performed either with the assumption of universal logarithmic velocity profile or of an universal eddy momentum diffusivity profile. For the roughnesses of practical interest both methods, when properly applied, give good results. For these roughnesses the transformed friction factors seem not to be unduly affected if one assumes a constant slope of the velocity profile equal to 2.5. All the transformation methods of the heat transfer data so far proposed predict too high wall temperatures in the central channels of a 19-rod bundle with three-dimensional roughness. Preliminary calculations show that the application of the superimposition principle with the logarithmic temperature profiles gives good results for the three-dimensional roughness as well. Although the measurements show that the slope of the logarithmic temperature profiles is different from 2.5, the assumption of a constant slope equal to 2.5 does not effect the transformed heat transfer data appreciably. For moderately high roughness ribs the turbulent Prandtl number, averaged over the cross section of a tube, is about the same (≈ 0.8) for rough as for smooth surfaces. The temperature effect on the heat transfer data with air cooling is stronger than originally assumed in the general correlation of Dalle Donne and Meyer. With helium cooling this temperature effect is even stronger.

Kurzfassung

Wärmeübergang von rauhen Oberflächen: einige Betrachtungen über die Annahme eines logarithmischen Geschwindigkeits- und Temperaturprofils

Experimentelle Ringspaltreibungsbeiwerte können unter der Annahme eines universellen logarithmischen Geschwindigkeitsprofils oder eines universellen Profils des Wirbeldiffusionskoeffizienten des Impulses transformiert werden. Für Rauhigkeiten von praktischem Interesse liefern beide Methoden, wenn richtig angewendet, gute Ergebnisse. Für diese Rauhigkeiten scheinen die transformierten Reibungsbeiwerte nicht zu stark von der Annahme einer konstanten Neigung gleich 2.5 bei dem logarithmischen Geschwindigkeitsprofil abhängig zu sein. Alle bisher vorgeschlagenen Transformationsmethoden für die Wärmeübergangskoeffizienten sagen zu hohe Wandtemperaturen in den Zentralkanälen eines 19-Stabbündels mit dreidimensionaler Rauhigkeit voraus. Vorläufige Rechnungen zeigen, daß die Anwendung des Superpositionsprinzips auf die logarithmischen Temperaturprofile auch für die dreidimensionale Rauhigkeit gute Ergebnisse liefert. Obwohl die Experimente zeigen, daß die Neigung des logarithmischen Temperaturprofils nicht gleich 2.5 ist, beeinflußt die Annahme einer konstanten Neigung gleich 2.5 die transformierten Wärmeübergangskoeffizienten nicht zu stark.
Für nicht zu hohe Rauhigkeitsrippen ist die turbulente Prandtlzahl, gemittelt über den Querschnitt eines Rohres, etwa gleich ($\approx$0.8) für rauhe wie für glatte Oberflächen. Der Temperatureffekt auf den Wärmeübergangskoeffizienten mit Luftströmung ist stärker als bei der Generalkorrelation von Dalle Donne und Meyer angenommen wurde. Mit Heliumströmung ist dieser Effekt noch stärker als mit Luft.

1. Transformation of annulus friction data. Assumption of universal velocity profile or universal eddy diffusivity.

The assumption of an universal logarithmic velocity profile, independent of surface curvature, for the separation and transformation*) of friction data for turbulent flow in an annulus with a inner rough rod and outer smooth tube was made originally by Maubach /1/. Subsequently this method was slightly modified by Dalle Donne /2/ and Dalle Donne, Meyer /3/ on the basis of friction factors for the outer smooth surface of the annulus given by Warburton /4/.

In a recent paper /5/ Firth, on the basis of measurements of Lawn and Hamlin /6/, of Stephens /7/ and of Lee /8/, states that a method of separation and transformation based on an universal momentum eddy diffusivity profile, similar to that originally suggested by Rapier /9/, gives more exact transformed friction factors. Firth compares the experimental f_1 values, transformed on the basis of measured velocities and position of zero-shear stress, with the data obtained with the Maubach transformation and his own transformation. The average difference between experimental f_1-values and f_1-Maubach values, and experimental f_1-values and f_1-Firth values is -3.09% (the experimental f_1-values are lower) and +0.57% respectively. However the Dalle Donne-Meyer transformation produces for the kind of roughness and Reynolds number range of references /6-8/, transformed friction factors which are 2.33% lower than those given by the Maubach transformation (see for istance Fig.2 of /2/) and therefore the average difference between the experimental f_1-values and the values transformed with Dalle Donne-Meyer is only -0.76%. The conclusion is that the Dalle Donne-Meyer transformation is just as good as the Firth transformation for two-dimensional roughnesses of practical interest.

Firth makes another point though. He plots the parameter G_1/A_M, where

$$G_1 = A_M \ln \left(\frac{r_o - r_1}{h}\right) + R(h^+) - \sqrt{\frac{2}{f_1}} \qquad (1)$$

*) Separation here means determination of the region of the annulus relative to the inner rough surface and of the region relative to the outer smooth surface, i.e. determination of the zero-shear stress line. Transformation means transformation of the experimental friction and heat transfer data for the whole annulus to data applicable to rough surfaces only.

(Firth takes A_M=2.39), versus $D = \frac{de_1}{2r_1}$ and finds that, for $D \geq 1$, G_1/A_M increases with D under the assumption of universal eddy diffusivity profile and decreases slightly with the assumption of universal velocity profile. Furthermore, he finds that the Lee's data show that $G_1-R(h^+)$ increases with D. Thus, if one assumes that $R(h^+)$ and A_M are constant, the universal eddy diffusivity assumption correlates better the data of Lee. Furthermore the $R(h^+)$ values of Lee and of other authors become more or less constant for $h/d_{e1} \leq 0.02$ when transformed with the Firth method /10/. This is confirmed by our experiments as well. Table I shows some selected friction data from our work /2/. The $R(h^+)$ values obtained with our method depend on $\frac{h}{\hat{y}}$ or $\frac{h}{d_{e1}}$. The $R(h^+)_F$ values obtained with the G_1-values calculated by Firth for Y_c=0.2 are more or less constant for $h/d_{e1} \leq 0.02$. In the case of the roughness with high $\frac{p-b}{h}$ ratios, they are constant up to h/d_{e1}=0.058.

While the Maubach /1/ and the Dalle Donne /2/ approach used a logarithmic velocity profile with constant slope A_M=2.5 on the rough side of the annulus, recent velocity profile measurements show that this slope can be different from 2.5 depending on the roughness geometrical parameters /11-14/. While Meyer /13/ and Aytekin /14/ find generally A_M values smaller than 2.5,*) Berger and Whitehead /11/ find slopes smaller than 2.5 for three rather effective roughness investigated ($5 \leq \frac{p}{h} \leq 10$) and one single value of A_M higher than 2.5 for a less effective roughness (p/h=3), and Baumann /11/ finds three slopes smaller than 2.5 and one value of A_M higher than 2.5 for the least effective roughness (p/h=4). Furthermore Baumann /11/ and Meyer /12/ find that for $A_M<2.5$, A_M decreases with $h/\hat{y}$. The general tendence seems to be that higher friction factors produce lower values of A_M.

This general statement is confirmed by the velocity profile measurements of Nunner for flow in a rough tube /15/. Although Nunner performed velocity profile measurements, he does not give explicitly A_M values. However noting that for any logarithmic velocity profile in a tube:

$$u^+-\bar{u}^+ = A_M \ln \frac{y}{R} +1.5\, A_M = A_M(1.5 + \ln \frac{y}{R}) \qquad (2)$$

+) For Meyer this is true from values obtained from integral parameters, i.e. essentially from pressure drop measurements. For direct velocity measurements also Meyer finds $A_M>2.5$ for one case with p/h=3.8 in the region where the profile is logarithmic.

it is possible to obtain from Fig.24 of /15/, which gives measured $(u^+-\bar{u}^+)$ values versus y/R, A_M values averaged over y/R. Table II shows these values. Except for one roughness, these A_M values are all higher than 2.5, especially for less effective roughnesses.

When one tries to come from these qualitative statements to quantitative assessments, the situation appears to be complicated and not quite clear. Although Meyer uses two extra coefficients to correlate the $\frac{p-b}{h}$ and $\frac{h}{\hat{y}}$ effects on A_M, his correlation (equation (5-23) of Ref./13/) does not agree with the values of Table II or those from references /11/ and /14/.*) The situation would not be much better with the use of an universal eddy diffusivity profile a la Rapier. The problem with correlating A_M comes with higher $h/\hat{y}$ values and, we have seen that the diffusivity method produces constant $R(h^+)$ values only at low h/d_{e1}, i.e. low $h/\hat{y}$,values.

Fortunately, it has been shown /13,16/ that the error in the friction factor introduced by the use of A_M=2.5, is relatively small ($\pm$1%) for $h/\hat{y} \leq 0.05$, if the Dalle Donne - Meyer transformation is used. This is confirmed by the fact that our separation and transformation method has always predicted well the pressure drops in a number of bundles of rods roughened with two-dimensional ribs /17-18/. Even though the $h/\hat{y}$ effect on the $R(h^+)$ values of three-dimensional roughness obtained with our transformation method is not monotonic and it is h^+ dependent /19/, this method predicts well the pressure drops of a bundle with rods roughened with three-dimensional ribs, providing the annulus experiments are at about the same values of $h/\hat{y}$ as in the bundle /20,21/.

2. Transformation of heat transfer data. Assumption of universal temperature profile or universal eddy diffusivity

In an analogous way to their friction data, Dalle Donne /2/ and Dalle Donne and Meyer /3/ have transformed their annulus heat transfer data on the basis of a logarithmic temperature profile. To determine the parameter $G(h^+)$ of this profile, they used two methods. Either they assumed that the logarithmic profile extends

*) L. Meyer has pointed out to the author that these discrepancies might be due to the different definitions of the origin of the velocity profile.

from the rough inner surface to the outer smooth surface:

$$G(h^+) = \frac{(T_W - T_{W2})\,\varrho_B\, c_{pB}\, u_1^*}{q_1} - A_H \ln\left(\frac{(1-\alpha)\, r_2}{h}\right) \qquad (3)$$

or they determined $G(h^+)$ from the calculated gas bulk temperature:

$$G(h^+)^* = \frac{u_1^*}{St_B\, u_B} = A_H \ln\left(\frac{(1-\alpha)\, r_2}{h}\right) - A_H \frac{(1+3\alpha)}{2(1+\alpha)} \qquad (4)$$

with A_H=2.5. They recommended the value $G(h^+)$ as more exact than $G(h^+)^*$. This method is not a transformation in the sense of the original Hall suggestion /22/, but it is simply based on the assumption that the logarithmic temperature profile holds over the whole of the annulus and that this profile is the same for an annulus or for a rod bundle.

Recently Meyer and Rehme have modified this method transforming the logarithmic temperature profile a la Hall and choosing the integration constant on the base of $G(h^+)$ and $G(h^+)^*$ respectively /23/. Table III gives some selected data from this work: for any test section two runs have been chosen for the lowest wall temperature series (lowest T_W/T_B values): one at the highest Reynolds number, the second at the lowest Reynolds number higher than 10^4. For the test section 20-33 helium (probably the most accurate series of tests) three runs have been chosen. Fig.1 shows the ratio of the transformed Stanton number for the inner rough region to the measured Stanton number of the annulus versus f_1/f_2, ratio of inner to the outer region friction factor. The lines represent averages of the experimental points, the curve for Meyer & Rehme being taken from Fig.33 of Ref./23/. Also a curve for the Firth transformation has been obtained as an average of the points of Table III. The use of the Firth transformation data at $Re=3\times10^5$ for comparison, as done in Fig.33 of Ref./23/, is not correct because St_1/St_B is not only f_1/f_2 but also Reynolds number dependent, as one can easily see by inspecting the data of Table III.

The Meyer-Rehme transformation produces transformed Stanton numbers St_1, which are on the average, about 3% higher than those of the Dalle Donne - Meyer transformation, both data being based on $G(h^+)$, and not on the less accurate value $G(h^+)^*$. The Firth transformation produces transformed Stanton numbers, which are, on the average, 8% higher than those of the Dalle Donne - Meyer transformation. Although in the first case the 3% difference could be considered within the accuracy of the experiments, a discrepancy of 8% is too high to be neglected. This difference in transformed Stanton numbers has been already noticed by Firth /24/, although it has been overestimated by Firth in range of low f_1/f_2 ratios, because presumably he uses our method with $G^*(h^+)$ and not with $G(h^+)$. The Firth method is a slight modification of the Rapier transformation method /9/ which is based on the assumption of universal eddy diffusivity of heat.

A more detailed comparison of the three transformation methods can be seen from the Table down below obtained from the data of Table III:

Annulus outer smooth tube	Ratio of inner to outer radius of the annulus	Average difference in transformed Stanton number in respect of the Dalle Donne - Meyer method /3/	
		Meyer-Rehme /23/	Firth /24/
"33"	0.547	+1.2%	+11.5%
"40"	0.454	+3.3%	+ 7.5%
"50"	0.367	+5.2%	+ 4.7%

The most accurate and recent bundle experiments performed at Karlsruhe were one with 12 rods and a two-dimensional roughness /25/ and one with 19 rods and a three-dimensional roughness /21/. For these two bundles the equivalent r_1/r_2 ratio (ratio of the rod to the equivalent annulus with the boundary condition heat flux equal zero) in the central cooling channels is 0.674 and 0.609 respectively. It is obvious therefore that for these cases there is very little difference between the Dalle Donne - Meyer and Meyer - Rehme transformation methods.

Due to the fact that the Dalle Donne - Meyer transformation method was predicting correct wall temperatures for the shroud, corner and wall channels of rod bundles with two-dimensional /25/ and three-dimensional roughnesses /21/, but too high temperatures on the walls of the central channels of these clusters, the Firth transformation method was used to evaluate these temperatures. The temperature calculated with this method agreed well with the experimental values in the case of the two-dimensional roughness /25/, however, in the case of the bundle with the three-dimensional roughness, even the transformation method of Firth predicted wall temperatures in the central channels which were still considerably higher than the experimental values /21/. The same can be said if one uses the Wilkie /26/, the Warburton-Pirie /27/ or the Meyer-Rehme /23/ transformation methods: they all predicted considerably higher wall temperatures in the central channels of the bundle with the three dimensional roughness. The method predicting the lowest temperatures, i.e. the temperatures nearest to the experimental values was the method of Firth, which is based on the assumption of an universal profile of eddy diffusivity of heat. In Ref. /21/ it was therefore suggested that a transformation method based on the eddy diffusivity profile gives better results that a method based on the logarithmic temperature profile. However it has been found by Meyer that, within the scatter of the experimental results, there no difference between eddy diffusivity of heat for two or three-dimensional roughnesses /28/, thus proving that a transformation method, based on eddy diffusivity, which works well for a two-dimensional roughness and not for a three-dimensional roughness, cannot be easily made to work for the three-dimensional roughness case. The problem of transforming single pin heat transfer data for three-dimensional roughnesses in a proper way is presently under investigation in Karlsruhe. Preliminary calculations show that the application of the superimposition method to the logarithmic temperature profiles gives good results also in predicting the wall temperatures of the central channels of the 19 rod bundle roughened with a three-dimensional roughness.

As in the case of the velocity profiles, the use of logarithmic temperature profiles with slopes different from 2.5 seems not to change the situation very much in respect of profiles with constant slope. Not much information is yet available from the literature about the slope of temperature profiles for convective turbulent heat transfer with gases in presence of rough surfaces. Nunner has performed various measurements for flow of air inside rough tubes /15/. Although he does not give the slope of his temperature profiles A_H explicitly, it is possible to obtain A_H from his data. For a logarithmic temperature profile one has:

$$t^+ = A_H \ln \frac{y}{R} + B \qquad (5)$$

and at the center of the tube:

$$t_R^+ = B \qquad (6)$$

Thus:

$$\frac{t^+}{t_R^+} = \frac{A_H}{B} \ln \frac{y}{R} + 1 \qquad (7)$$

In Fig.26 to 28 of Ref./15/ Nunner plots t^+/t_R^+ versus y/R for $Re=10^4$, 3×10^4 and 6×10^4 respectively. Meerwald has replotted these graphs in semilogarithmic scale and obtained the values of A_H/B /29/. Furthermore we can write:

$$t^+ = A_H \ln \frac{y}{h} + G(h^+) \qquad (8)$$

$$\bar{t}^+ = \frac{\sqrt{f/2}}{St} = A_H \ln \frac{R}{h} + G(h^+) - 1.5\, A_H = B - 1.5\, A_H \qquad (9)$$

Thus:

$$A_H = \frac{\sqrt{f/2}}{St\, (\frac{B}{A_H} - 1.5)} \qquad (10)$$

and

$$G(h^+)_{A_H} = \frac{\sqrt{f/2}}{St} \left[1 + \frac{1.5 - \ln \frac{R}{h}}{\frac{B}{A_H} - 1.5} \right] \qquad (11)$$

while:

$$G(h^+)_{2.5} = \frac{\sqrt{f/2}}{St} + A_H\ (1.5 + \ln \frac{h}{R}) = \frac{\sqrt{f/2}}{St} + 2.5\ (1.5 + \ln \frac{h}{R}) \qquad (12)$$

Table IV shows the A_H values obtained from the data of Nunner, as well as the $G(h^+)$ values obtained with the actual A_H and with A_H set equal to 2.5. The difference between these two values of $G(h^+)$ is relatively small, indicating that due account of the variation of A_H does not change the $G(h^+)$ values, and therefore the Stanton numbers in case of a transformation, appreciably.

In Fig.2, A_H values of Nunner have been plotted versus h_w^+. The data for the test sections 8,9, with very high and tight ribs, where the heat transfer data are probably much affected by the heat conduction in the ribs, and the data for the test section 5, which has a very little effective roughness and friction factors almost as low as those of a smooth tube, have been omitted in Fig.2. In the plot also data from Gowen an Smith /30/ and Aytekin /14/ are shown. Practically all the values are above 2.5. A slight tendency to increase with h_w^+ is visible, although not quite certain due the scatter of the points.

Table V shows the values of A_M of Nunner /15/ calculated in the previous chapter, and of A_H averaged for the three values of the Reynolds number of Table IV. Also shown are the ratios A_H/A_M and the turbulent Prandtl number:

$$Pr_t = \frac{\varepsilon_M}{\varepsilon_H} = \frac{A_H}{A_M} \; \frac{\tau/\tau_W}{q/q_W} \qquad (13)$$

Where the average value of

$T_q = \dfrac{\tau/\tau_W}{q/q_W}$ has been calculated in the following way. For a tube

$$\tau/\tau_W = \frac{r}{R} \qquad (14)$$

and

$$q/q_w = \left(\frac{r}{R}\right) \left\{1 + A_M \sqrt{f/2} \left[\left(\frac{R}{r}\right)^2 - 1\right] \ln \left(\frac{R}{R-r}\right) - \frac{R}{r}\right\} \; /31/ \qquad (15)$$

and we put:

$$\frac{1}{\bar{T}_q} = \frac{1}{\pi R^2} \int_0^R \left\{1 + A_M \sqrt{f/2} \left[\left(\frac{R}{r}\right)^2 - 1\right] \ln \left(\frac{R}{R-r}\right) - \frac{R}{r}\right\} 2\pi r dr = 1 + 0.7899 A_M \sqrt{f/2}$$

Thus

$$\bar{T}_q = \frac{1}{1 + 0.7899 \; A_M \sqrt{f/2}} \qquad (16)$$

The values of Pr_t of Table V lie between 0.73 and 0.89 for the lower roughness ribs ($h/\hat{y}$=0.08), which is in excellent agreement with the turbulent Prandtl number of air flowing inside smooth tubes (Pr_t=0.86 /32/ and Pr_t=0.78 /33/). However in the case of the higher ribs, the turbulent Prandtl numbers become higher.

3. The temperature effect on the heat transfer data

In references /2/ and /3/ it was assumed that the temperature effect T_W/T_B on the heat transfer data was acting on the $G(h^+)$ parameter only, the slope of temperature profile being taken equal to 2.5 independently of the temperature ratio T_W/T_B. Recently Meyer and Rehme /23/ have corrected the friction factors and Stanton numbers for the temperature effect, before obtaining the $G(h^+)$ and $R(h^+)$ values, which of course should be then independent of T_W/T_B. The method to perform these temperature corrections is always somewhat arbitrary, however the author of this paper feels that a correction on $G(h^+)$ and $R(h^+)$ only is better. Indeed the T_W/T_B correction is due to the temperature and therefore gas physical property variation in a cross section perpendicular to the flow. In turbulent flow this temperature variation is concentrated near the wall and presumably it affects more the wall parameters such as $G(h^+)$ and $R(h^+)$ than integral parameters such as the Stanton number and the friction factor.

If the obtained correlations are applied in the same range of application in which they were obtained, the way how the temperature correction was performed, on the wall or integral parameters, is irrelevant, because the temperatures and pressure drop calculated for a bundle are the same. Meyer and Rehme, however, calculate for the central, fully rough, channels of a 19-rod bundle at T_W/T_B=1.1 Stanton numbers which are about 10% higher than those given by the general correlation of references /2/ and /3/. This difference is only in small part given by the different transformation used by Meyer and Rehme. We have seen that this causes a difference of about 3% in the transformed Stanton numbers. Also the correction for entrance effects used by them makes very little difference. The difference is due to the higher exponent for (T_W/T_B) used by Meyer and Rehme to reduce their data. They find that the temperature effect on the Stanton numbers is given by:

$$(T_W/T_B)^{\kappa}$$

with κ=-0.25 for air and nitrogen, and κ=-0.35 for helium. The value κ=-0.25 for the Stanton number corresponds to an exponent for the temperature ratio correction on $G(h^+)$ of z=+0.68 /34/. The value κ=-0.368 for helium corresponds to z=+1 /35/. For the general correlation of Ref./2/ and /3/ it was z=0.5. Remembering that z=0 for κ=0, and assuming a linear relationship between z and κ, one has κ=-0.18 for the general correlation data and z=0.85 for the helium data of Ref. /23/.

The average value of T_W/T_B of the heat transfer experiments of Ref./23/ was about 1.68. Using their method applied to the case of a bundle cooled with helium at T_W/T_B=1.1 they correct the Stanton numbers by the multiplicative factor:

$$\left(\frac{1.68}{1.1}\right)^{0.35} = 1.16$$

while the general correlation would suggest the factor:

$$\left(\frac{1.68}{1.1}\right)^{0.18} = 1.08$$

This, and the small difference caused by the transformation method, explain the 10% discrepancy observed in Ref./23/. This difference of course decreases or even dissappear at higher values of T_W/T_B. Recently published experimental data /20,23,34,35,36/ indicate that for air and even more so for helium, z should be higher than 0.5. A value z=0.68 seems appropriate. The temperature effect in the general correlation was obtained with air tests at an average value of T_W/T_B=1.60. Due to the scatter of the experimental points, the exponent z is subjected to considerable uncertainty, which percent is considerably higher than the uncertainty in the absolute values of $G(h^+)$. The general correlation can therefore be modified to take account of this new, and probably more accurate z value:

$$G(h_W^+) = GPRO1 . Pr^{0.44} \; (T_W/T_B)^{0.68} \; \left(\frac{h}{0.01\,(r_2-r_1)}\right)^{0.053} \quad (17)$$

$$GPRO1 = K_1 \; h_W^{+\;K_2} \quad (18)$$

$$K_1 = 2.76 + 0.276 \; R(\infty)_{01} \quad (19)$$

$$K_2 = 0.32 - 0.017 \; R(\infty)_{01} \quad (20)$$

Whereby the new value of K_1 has been obtained by the old one of References /2/ and /3/ times:

$$\frac{1.60^{0.5}}{1.60^{0.68}} = 0.919$$

That is, it is assumed that the $G(h^+)$ values of /2,3/ were correct and only z was too small.
When applying the general correlation to an helium cooled bundle one should use, in place of z=0.68, the value z=0.85 in equation (17).

4. Conclusions

1. For roughnesses of practical interest the Firth transformation method for friction data , based on an universal eddy momentum diffusivity produces results which are just as good as those obtained with our transformation method.

2. However the universal eddy diffusivity assumption is more conceptually satisfactory, because it produces constant values of $R(h^+)$ for small roughness ribs ($h/d_{e_1} \leq 0.02$).

3. Various local velocity measurements indicate that the slope of the logarithmic velocity profile is sometimes higher, sometimes lower than 2.5. More effective roughnesses tend to decrease this slope. A quantitative correlation seems very difficult at this stage due also to the relatively high uncertainty of the experimental values.

4. Fortunately, in the range of practical interest, the transformed friction factors seem not to be unduly affected if one assumes a constant slope equal to 2.5. Our transformation method predicts well the pressure drops of bundles with rods roughened by two-dimensional as well as of bundles with rods roughened by three-dimensional ribs.

5. Our transformation method for the heat transfer data, based on logarithmic temperature profiles with constant slope equal to 2.5, seems adequate for the prediction of the wall temperatures of the shroud and of the rods in the corner and wall channels of the bundle.

6. The Firth transformation method for heat transfer data, based on the eddy diffusivity of heat assumed by Rapier, produces transformed heat transfer coefficients, which, on the average, are 8% higher than those obtained with our method. The measured temperatures in the central channels of a rod bundle, with two-dimensional roughness, in the best test performed recently in Karlsruhe, are well predicted by the Firth transformation method. However for a bundle with three-dimensional roughness the Firth method, like all the others,would predict too high wall temperatures in the central channels. This problem is presently under investigation in Karlsruhe. Preliminary calculations show that the superimposition principle with the logarithmic temperature profiles gives good results for the two-dimensional as well as for the three-dimensional roughness.

7. The measurements of temperature profiles of Nunner, Gowen & Smith and of Aytekin show that the slope of the logarithmic temperature profile, is higher than 2.5. Again the assumption of a constant slope equal to 2.5 does not effect the transformed heat transfer data appreciably.

8. The measurements of Nunner show that for moderately high roughness ribs the turbulent Prandtl number, averaged over a cross section of the tube, is about the same (≈ 0.8) for rough as for smooth surfaces.

9. Recently published experimental data suggest that the temperature effect on the heat transfer data with air cooling is stronger than originally assumed in the general correlation of Dalle Donne and Meyer. The general correlation can be modified to take account of these new experimental findings. With helium cooling, this temperature effect is even stronger.

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List of Symbols

Geometrical parameters

b		width of roughness rib
d_e		equivalent or hydraulic diameter
h		height of roughness ribs
p		axial pitch of roughness ribs
r		radial distance of the considered point to the axis of symmetry
r_o		radius corresponding to the zero-shear-stress position
r_1		radius of the inner rod
r_2		radius of the outer cylinder of the annulus
R		tube radius
α	=	r_1/r_2
y		radial distance from the wall of the considered point
$\hat{y}$		radial distance between the wall and the surface of zero shear
Y	=	$y/\hat{y}$
Y_c		value of Y above which ε_M is constant

Physical parameters

c_p		specific heat of the gas
q		heat flux
q_w		heat flux at the wall
T_B		gas bulk temperature
T_W		wall temperature; in case of annulus, temperature of the wall of the inner tube
u		gas velocity
u^*	$= \sqrt{\tau_w/\rho}$	friction velocity
u_B	$= \bar{u}$	velocity of the bulk of the gas, average velocity of the gas
ν		gas kinematic viscosity
ρ		gas density
τ		shear stress
τ_w		shear stress at the wall
$\varepsilon_H, \varepsilon_M$		eddy diffusivity of heat and of momentum, respectively

Dimensionless parameters

A_H	slope of the logarithmic temperature profile
A_M	slope of the logarithmic velocity profile
B	constant in the logarithmic temperature profile equation t^+ versus y/R
f	friction factor
$G(h^+)$	constant in the logarithmic temperature profile equation t^+ versus y/h
G_1	difference between maximum and average dimensionless velocity in the inner region of the annulus
$h^+ = \frac{hu^*}{\nu_B}$	roughness cavity Reynolds number
$h_w^+ = \frac{hu^*}{\nu_w}$	roughness cavity Reynolds number evaluated at the wall temperature T_w
Pr	Prandtl number
$Pr_t = \frac{\varepsilon_M}{\varepsilon_H}$	turbulent Prandtl number
$R(h^+)$	constant in the logarithmic velocity profile equation u^+ versus y/h
$R(\infty)_{01}$	value of $R(h^+)$ in the region of fully rough flow reduced to $T_W/T_B=1$ and $h/\hat{y}=0.01$.
St, St_B	Stanton number evaluated at the gas bulk temperature T_B
$t^+ = \frac{(T_W - T)\rho_B c_{pB} u^*}{q_W}$	dimensionless gas temperature
$u^+ = u/u^*$	

$\bar{u}^+$ average value of u^+ over a cross section perpendicular to the flow direction

Subscripts

B	gas properties evaluated at gas bulk temperature T_B
w	gas properties evaluated at the wall temperature T_w
1,2	it refers to the inner or outer regions respectively of the annulus
F	data transformed with Firth transformation method
A_H	data obtained with actual temperature profile slope
2.5	data obtained with the temperature profile slope set equal to 2.5.

Table I: Friction data from Ref./2/

Run number	h^+	$\frac{p-b}{h}$	$\frac{h}{b}$	$\frac{h}{\bar{y}}$	$\frac{h}{d_{e1}}$	$R(h^+)$	$R(h^+)_F$
1.40.5	106.7			.108	.0251	3.79	3.83
1.50.17	106.2			.048	.0101	3.19	3.28
1.70.14	114.7	5.21	0.96	.023	.0042	2.90	3.13
1.85.4	108.8			.017	.0029	2.78	3.11
8.40.6	196.9			.235	.0531	2.65	2.70
8.50.33	201.3	5.73	2.62	.113	.0232	2.41	2.53
8.70.6	201.1			.055	.0096	2.16	2.44
8.85.8	215.6			.041	.0065	2.05	2.47
10.40.20	199.7			.256	.0582	4.91	4.96
10.50.4	224.7	29.3	2.70	.123	.0261	4.93	5.04
10.70.4	234.2			.062	.0110	4.65	4.90
10.85.3	212			.046	.0075	4.49	4.86

Table II: Velocity profile data from Ref. /15/

Roughness Nr.	profile	$\frac{p-b}{h}$	$\frac{h}{b}$	$h/\hat{y}$	A_M
2		19.2	0.8	.080	2.58
3		80.2	0.64	.080	3.09
4		18.9	0.64	.080	2.60
5		81.7	0.18	.080	2.77
6		18.9	0.64	.162	2.37
7		8.65	0.64	.164	2.90
8		3.53	0.64	.167	2.58
9		0.43	0.64	.182	3.15

Table III: Transformed heat transfer data from Ref. /23/

Test section	Run Nr.	Re $\times 10^{-5}$	f_1/f_2	$\frac{St_1}{St_B}$ $G(h^+)$ /3/	$\frac{St_1}{St_B}$ $G(h^+)$* /3/	$\frac{St_1}{St_B}$ /24/	$\frac{St_1}{St_B}$ $G(h^+)$ /23/
19-33 helium	1 35	3.4 0.29	6.01 3.67	1.04 1.07	1.07 1.11	1.12 1.25	1.05 1.09
19-33 N_2	1 19	5.05 0.58	6.26 4.06	1.05 1.11	1.07 1.10	1.12 1.23	1.05 1.12
20-33 helium	1 15 42	0.80 0.18 2.74	4.55 3.54 5.94	1.05 1.09 1.05	1.09 1.12 1.06	1.17 1.27 1.11	1.06 1.11 1.05
20-33 N_2	1 18	5.02 0.74	6.63 4.41	1.04 1.08	1.06 1.10	1.11 1.20	1.05 1.10
20-33 Air	11 25	0.10 1.56	2.68 5.06	1.13 1.07	1.13 1.08	1.32 1.16	1.15 1.08
18-40 Air	1 16	3.27 0.30	4.78 2.90	1.09 1.14	1.07 1.11	1.13 1.26	1.11 1.18
19-40 Air	1 28	2.84 0.11	4.98 2.08	1.10 1.24	1.07 1.12	1.14 1.34	1.12 1.29
18-50 helium	13 27	0.56 8.75	2.13 5.09	1.20 1.09	1.12 1.07	1.38 1.12	1.28 1.13
18-50 N_2	1 20	13.2 2.07	5.27 3.60	1.09 1.13	1.06 1.09	1.11 1.19	1.12 1.18
18-50 Air	1 28	3.27 0.26	4.32 2.34	1.11 1.20	1.07 1.12	1.14 1.28	1.15 1.26
19-50 helium	1 19	0.59 8.56	2.66 5.02	1.22 1.11	1.12 1.06	1.26 1.12	1.30 1.14
19-50 N_2	1 15	14 2.2	5.24 3.56	1.09 1.15	1.05 1.07	1.10 1.19	1.12 1.21
19-50 Air	17 38	3.20 0.18	4.67 1.76	1.14 1.29	1.07 1.13	1.13 1.36	1.18 1.37

Table IV: Temperature profile data from Ref. /15/

$Re=10^4$, $Pr=0.705$, $T_w/T_B=1.18$

Rough Nr.	$\frac{h}{R}$	h_w^+	f	St	A_H/B /26/	A_H eq.(10)	$G(h^+)_{A_H}$ eq.(11)	$G(h^+)_{2.5}$ eq.(12)
2	.0803	43.4	.04125	.009498	.8071	2.971	12.08	12.57
3	.0801	25.6	.01437	.006011	.8071	2.772	11.27	11.54
4	.0803	39.3	.03375	.009115	.8071	2.800	11.39	11.70
5	.0803	23.3	.01187	.005671	.8071	2.667	10.86	11.03
6	.1616	102	.05675	.01106	.8071	2.993	14.26	14.42
7	.1635	119	.075	.01219	.7840	3.008	14.95	15.11
8	.1674	108	.05875	.01035	1.038	4.568	15.25	15.84
9	.1824	65.6	.01825	.006564	1.268	5.405	13.46	14.05

$Re=3\times10^4$, $Pr=0.705$, $T_w/T_B=1.18$

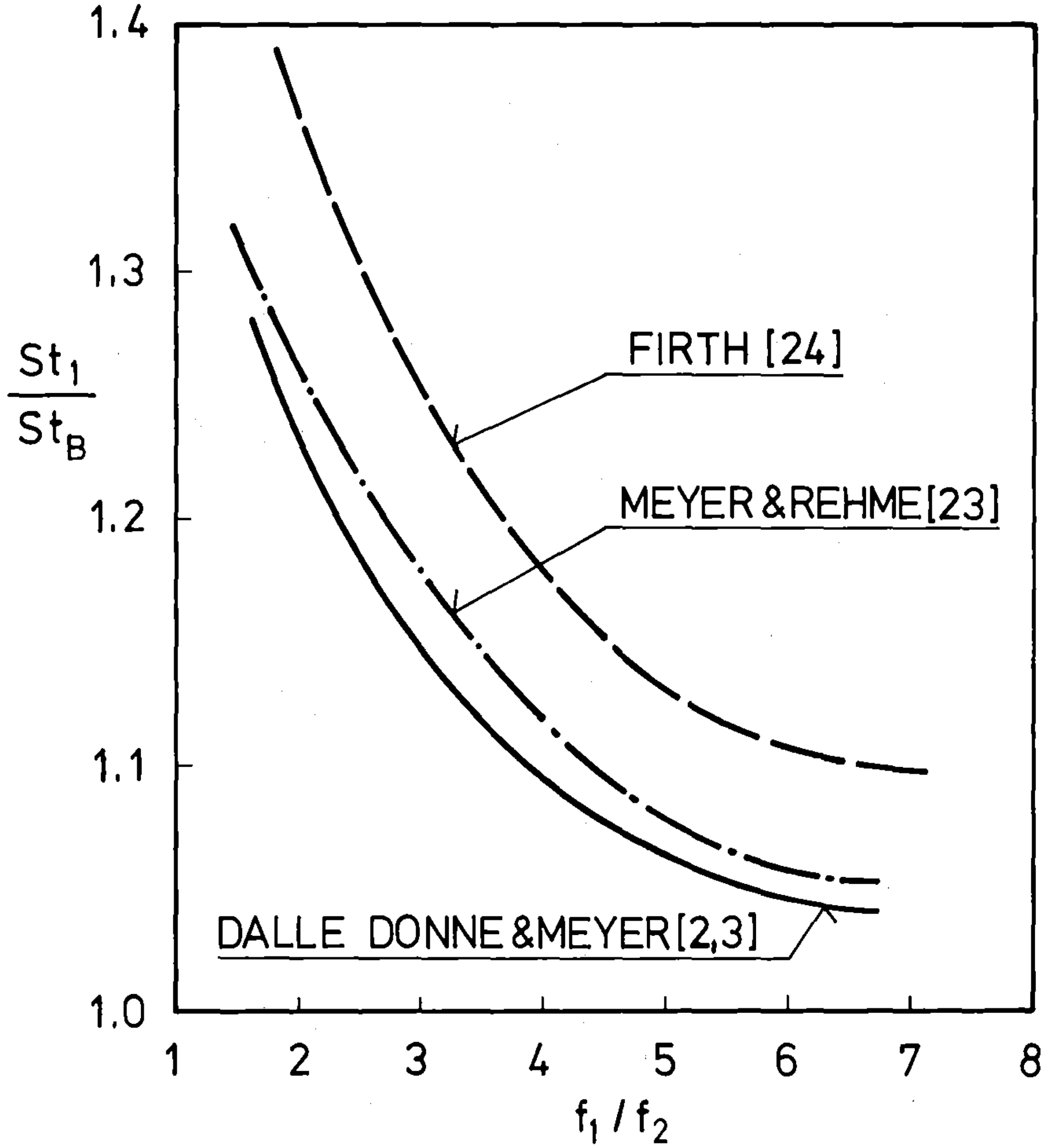
Rough Nr.	$\frac{h}{R}$	h_w^+	f	St	A_H/B /26/	A_H eq.(10)	$G(h^+)_{A_H}$ eq.(11)	$G(h^+)_{2.5}$ eq.(12)
2	.0803	127	.03925	.00780	.6918	2.903	14.99	15.41
3	.0801	76.6	.01288	.00482	.6918	2.690	13.89	14.08
4	.0803	111	.0300	.00714	.6918	2.772	14.32	14.60
5	.0803	63.3	.00975	.00435	.6687	2.489	13.51	13.50
6	.1616	309	.0575	.00803	.6687	3.273	20.06	20.31
7	.1635	362	.07675	.00921	.6918	3.438	20.20	20.49
8	.1674	316	.05575	.00803	.9224	4.875	19.39	20.07
9	.1824	203	.0195	.00614	1.038	4.438	15.19	15.58

$Re=6\times10^4$, $Pr=0.705$, $T_w/T_B=1.18$

Rough Nr.	$\frac{h}{R}$	h_w^+	f	St	A_H/B /26/	A_H eq.(10)	$G(h^+)_{A_H}$ eq.(11)	$G(h^+)_{2.5}$ eq.(12)
2	.0803	253	.0390	.006474	.6226	3.063	18.44	19.01
3	.0801	143	.0125	.004088	.5996	2.624	16.65	16.78
4	.0803	216	.0285	.005741	.6226	2.953	17.77	18.24
5	.0803	117	.008325	.003757	.5765	2.223	14.90	14.62
6	.1616	613	.0565	.006781	.5534	3.057	23.80	23.98
7	.1635	739	.0800	.008033	.5534	3.070	23.85	24.12
8	.1674	695	.0675	.007017	.8071	5.145	24.70	25.46
9	.1824	420	.02075	.005387	.9224	4.433	18.01	18.40

Table V: Turbulent Prandtl numbers from Ref. /15/

Rough. Nr.	A_M	A_H	$\frac{A_H}{A_M}$	$\bar{T}_q$	Pr_t	$\frac{h}{\hat{y}}$
2	2.58	2.98	1.15	.777	0.89	.080
3	3.09	2.70	0.87	.834	0.73	.080
4	2.60	2.84	1.09	.797	0.87	.080
5	2.77	2.46	0.89	.866	0.77	.080
6	2.37	3.28	1.38	.760	1.05	.162
7	2.90	3.17	1.09	.690	0.75	.164
8	2.58	4.86	1.88	.738	1.39	.167
9	3.15	4.76	1.51	.803	1.21	.182


1.4
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St1 / StB
FIRTH [24]
MEYER & REHME [23]
DALLE DONNE & MEYER [2,3]
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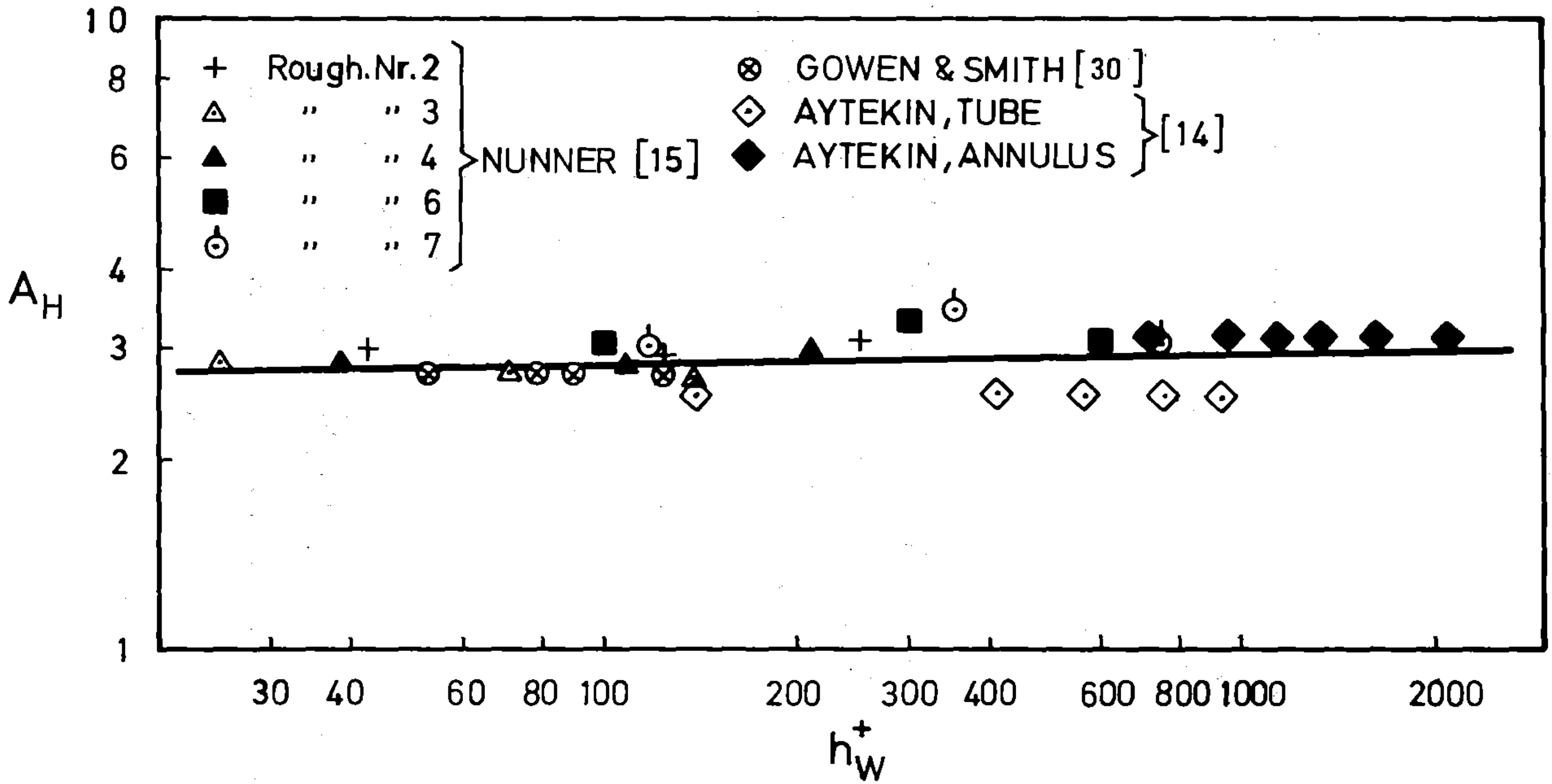
Fig. 1



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NUNNER [15]
GOWEN & SMITH [30]
AYTEKIN, TUBE
AYTEKIN, ANNULUS
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30 40 60 80 100 200 300 400 600 800 1000 2000
h_W^+

Fig. 2