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Heat transfer and friction coefficients for air flow in a smooth annulus; results of a recent experiment and comparison with previous correlations

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Heat transfer and friction coefficients for air flow in a smooth annulus; results of a recent experiment and comparison with previous correlations.

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Abstract

In the Heat Transfer Laboratory of INR various experiments on single rough or smooth rods contained in smooth annuli have been performed in the past. These experiments have been performed with rods of large diameters. Recently however a series of experiments with rough rods of 8 mm O.D. has been carried out. To check if the new experimental apparatus and the experimental techniques used were correct, an experiment was performed with an inner heated tube of 8 mm O.D. contained in the smooth outer tube of 16 mm I.D. used in the experiments with the rough rods. The results of this experiment are reported in the present paper. The friction and heat transfer data obtained with the turbulent flow runs of the present experiment agree well with previous experiments performed at INR with larger smooth annuli. The smaller size of the annulus and the improvements in mass flow and pressure drop measurements have allowed to extend the investigations to laminar flow. The laminar flow friction data can be correlated in terms of f_B versus $Re_{\bar{W}}$, where the gas physical properties in $Re_{\bar{W}}$ are evaluated at the temperature $T_{\bar{W}}$, average between the temperature of the inner surface and the outer surface of the annulus, weighted over the two surfaces. This correlation method has been already suggested by us for rough rods in a smooth tube. The laminar flow heat transfer data, correlated in terms of Nu_B versus $Gr_{\bar{W}}$ tend to be lower than the analytical prediction of Heaton, Reynolds and Kays, a fact which could be explained by the superposition of natural convection.

Wärmeübergang und Druckverlust für Luftströmung im glatten Ringspalt; Vergleich neuer Ergebnisse mit früheren Korrelationen

Zusammenfassung

An den Wärmetechnischen Versuchsständen des INR wurden in der Vergangenheit verschiedene Experimente mit rauhen und glatten Stäben, die in glatten Ringspalten eingebaut waren, durchgeführt. Bei diesen Experimenten wurden Stäbe mit großem Durchmesser verwendet.

In letzter Zeit jedoch wurde eine Reihe von Versuchen mit rauhen Stäben von 8 mm Außendurchmesser durchgeführt.

Um die Versuchsvorrichtung und die Meßtechnik zu testen, wurde ein Versuch mit einem inneren beheizten Rohr von 8 mm Außendurchmesser im gleichen glatten Mantelrohr von 16 mm Innendurchmesser durchgeführt, das bei den Versuchen mit den rauhen Stäben benutzt wurde.

Die Ergebnisse dieses Versuches werden im vorliegenden Bericht beschrieben. Die Druckverlust- und Wärmeübergangswerte, die bei dem Versuch in turbulenter Strömung gewonnen wurden, stimmen gut mit früheren Experimenten des INR an größeren glatten Ringspalten überein.

Durch Verwendung kleinerer Ringspaltabmessungen und Verbesserungen bei der Durchsatz- und Druckverlustmessung war es möglich, die Untersuchungen bis zur laminaren Strömung hin auszudehnen. Die bei laminarer Strömung ermittelten Reibungsbeiwerte sind durch eine Beziehung $f_B(Re_{\bar{W}})$ darstellbar, wobei die Stoffeigenschaften der Strömung in $Re_{\bar{W}}$ bei der Temperatur $T_{\bar{W}}$ eingehen, d.h. dem über die innere und äußere Oberfläche des Ringspaltes gewichteten Mittel der beiden Wandtemperaturen. Diese Korrelationsmethode haben wir bereits für rauhe Stäbe in einem glatten Rohr vorgeschlagen.

Die für laminare Strömung gemessenen Wärmeübergangswerte, die in der Form $Nu_B(Gr_{\bar{W}})$ dargestellt sind, liegen niedriger als die analytische Voraussage von Heaton, Reynolds und Kays, eine Tatsache, die durch die Überlagerung der Naturkonvektion erklärt werden könnte.

1. Introduction

In the Heat Transfer Laboratory of the Institute of Nuclear Physics and Reactor Engineering of the Karlsruhe Nuclear Center various experiments on single rough or smooth rods contained in smooth annuli have been performed in the past /1-4/. These experiments were performed with rods of outer diameters (O.D.) between 18 and 50 mm in annuli of inner diameters (I.D.) between 40 and 85 mm. Recently however a series of experiments has been performed on 8 mm O.D. rods in an annulus of 16 mm I.D. both for an EIR-rod /5/ and for KfK rods with two- and three-dimensional roughness ribs /6/. To check if the new experimental apparatus (mass flow and pressure measuring devices, measurements with termocouples of outer and inner tube wall temperature and of inlet and outlet air temperature, measurement of power produced in the inner tube) and the experimental techniques used (evaluation of heat losses from outer tube and of heat going by radiation from the inner tube to the inner surface of the outer tube) were correct, we have performed an experiment with an inner heated tube of 8 mm O.D. contained in the smooth outer tube of 16 mm I.D. used for the experiments with the rough rods. The results of these experiments are reported in the present paper and compared with the experiments performed in our laboratory with smooth annuli of greater dimensions (1) inner rod O.D. : 25 mm, outer tube I.D. : 50 mm, 2) inner rod O.D. : 50 mm, outer rod I.D. : 70 mm) previously reported in the literature /1/. The experimental apparatus and the procedure to evaluate the results are similar to those of reference /1/ with the exception that, due to the strongly reduced geometrical dimensions, the instruments to measure pressure and mass flow have been changed. Furthermore the thermocouples are not Platinel thermocouples with the hot junction directly connected to the inner tube as in /1/, but they are CrNi/Ni thermocouples in a stainless steel sheath, the hot junction being electrically insulated from the sheath by the Al_2O_3 insulation material.

2. Experimental Results

2.1 Friction factors

Figure 1 shows the friction factor averaged over the central portion of the annulus ($38.2 \leq \frac{l}{D} \leq 78.2$) versus the Reynolds number, all the gas physical properties being evaluated at the gas bulk temperature. The following points are of interest:

Turbulent flow ($Re_B \geq 4 \times 10^3$) (numerical data: see Tables I and II)

1) As in the case of the data of reference /1/ the experimental points agree reasonably well with the Prandtl-Nikuradse law of friction for smooth tubes /7/ for high Reynolds numbers ($Re_B \geq 6 \times 10^4$), while for lower Reynolds numbers they are somewhat higher (13% at $Re_B = 10^4$).
2) The agreement with the analytical prediction of Maubach for an annulus with $\alpha = \frac{r_1}{r_2} = 0.5$, based on the integration of the universal logarithmic velocity profiles for both the walls of the annulus /8/, is better in the whole range of the considered Reynolds numbers ($4 \times 10^3 \leq Re_B \leq 2.4 \times 10^5$). For instance at $Re_B = 10^4$ the experimental points are only 7% higher than the Maubach analytical prediction.
3) No systematic difference can be noticed between isothermal friction coefficients and coefficients with heat transfer for $Re_B \geq 10^4$ up to the maximum measured temperature $T_{WM} = 550^\circ C$. In the range $4 \times 10^3 \leq Re_B \leq 10^4$ the friction factors at higher T_W/T_B-values tend to be higher than those obtained at lower temperatures. This is probably due to the beginning of the transition to laminar flow, as we shall discuss below.
4) Comparing the present data with the experimental data of reference /1/ which were obtained in the range $8 \times 10^3 < Re_B < 2 \times 10^5$, one has a very similar behaviour in both cases as far as the previous points are concerned. Fig.1 shows the line which was obtained interpolating the experimental points of Fig.1 of Ref. /1/. The agreement with the present data is very good, the maximum discrepancy being of the order of 5%

in the whole range $8 \times 10^3 \leq Re_B \leq 2.4 \times 10^5$.

Laminar flow ($Re_B \leq 3000$) (numerical data: see Tables I,II and III)

1) The annular flow area is considerably smaller than in the case of Ref./1/, thus the pressure drops are higher. This, together with the instrument improvements at low flows, has allowed us to extend the Reynolds number range down to $Re_B \approx 650$. It should be noticed that in the evaluation of the points of Fig.1, due allowance was made for the difference between gas density in the test section and that in the pressure tubes leading to the pressure transmitter. This fact becomes important for very low flows and in presence of a vertical heated test section /4/.

2) The isothermal points agree reasonably well with the theoretical equation for flow in smooth annuli:

$$f_B = \frac{16}{Re} \frac{(1-\alpha^2)}{1+\alpha^2 - \frac{1-\alpha^2}{\ln \frac{1}{\alpha}}} \tag{1}$$

for $\alpha = 0.5$:

$$f_B = \frac{23.8}{Re_B} \tag{2}$$

However the friction coefficients at higher temperatures are considerably higher than those predicted by equation (2). Fig.2 shows the experimental points for $Re_B \leq 3000$ in the plot f_B versus $Re_{\bar{W}}$, where the air physical properties in $Re_{\bar{W}}$ have been evaluated at the temperature $T_{\bar{W}}$ average between the temperature of the inner rod surface and of the outer smooth surface, the average being weighted over the two surfaces:

$$T_{\bar{W}} = \frac{T_{W1} r_1 + T_{W2} r_2}{r_1 + r_2} \tag{3}$$

As one can see from Fig.2 the temperature effect is practically eliminated and the points agree reasonably well with the analytical prediction. Only for $Re_B \leq 10^3$ the points lie higher than the theoretical line; this could be due to errors in the measurement of mass flow and/or pressure drop along the test section at very low flows. This way of correlating the annulus friction data in laminar flow has been suggested by us previously for rough rods in a smooth tube /4/ and it is analogous to the method suggested by Dalle Donne and Bowditch for laminar flow of air and helium in smooth tubes in presence of large temperature differences between wall and gas /9/.

2.2 Heat transfer coefficient

Fig.3 shows all the obtained experimental data in a plot St_B versus Re_B. For $Re_B \geq 10^4$ the data agree well with the correlation obtained in Ref./1/ for an annulus of $\alpha = \frac{r_1}{r_2} = 0.5$:

$$St_B = 0.0186\ Re_B^{-0.2}\ Pr_B^{-0.4}\ (T_W/T_E)^{-0.2} \tag{4}$$

For $Re_B < 10^4$ (for the points at $T_{WM}=550^\circ C$ already at $Re_B = 1.6\times10^4$) the Stanton numbers start to become lower than those predicted by equation (4). This is obviously a laminarisation effect. In laminar flow the Stanton numbers at 550°C are lower than those at 160°C and 360°C.

Fig.4 shows the heat transfer data for $Re_B \geq 10^4$ in the graph $Nu_B/(Re_B^{0.8} Pr_B^{0.4})$ versus T_W/T_E. Also this plot shows clearly the good agreement with the data of Ref./1/ for $Re_B \geq 10^4$.

Fig.5 shows the heat transfer data for $Re_B \leq 3000$ in the plot Nu_B versus $Gz_{\bar{W}}$ where, as in Ref./4/, the definition of the Graetz number is:

$$Gr_{\overline{W}} = \frac{1}{D\ Re_{\overline{W}}\ Pr_{B}} \qquad (5)$$

The data are compared with the theoretical predictions for laminar flow of Coney and El-Shaarawi for an annulus of $\alpha = 0.5$ with constant temperature on the inner surface and adiabatic outer surface and $Pr = 0.7$ /10/, of Heaton, Reynolds and Kays for the same conditions but for constant heat flux on the inner tube /11/ and the prediction of McAdams for laminar flow in a tube at constant temperature and $Pr = 0.7$/12/. The experimental data were obtained in conditions approaching those of Heaton, Reynolds and Kays (in the experiment however the heat flux to the gas is not exactly constant: it is actually decreasing along the test section due to the higher heat losses at the higher wall temperatures), however the points lie below the theoretical prediction especially at high Graetz numbers. This could be due to the superposition of a certain amount of natural convection to the studied forced convection. Indeed with forced convection in the downward direction, natural convection should decrease the heat transfer.

3. Conclusions

1. The friction and heat transfer data obtained with turbulent flow experiments on a smooth annulus of aspect ratio $r_1/r_2=0.5$ agree well with previous experiments performed at INR with larger smooth annuli /1/.

2. The smaller size of the annulus and the improvements in mass flow and pressure drop measurements have allowed to extend the investigations to laminar flow.

2.1 The laminar flow friction data can be correlated in terms of f_B versus $Re_{\bar{W}}$, where the gas physical properties in $Re_{\bar{W}}$ are evaluated at the temperature $T_{\bar{W}}$, average between the temperature of the inner surface and the outer surface of the annulus, weighted over the two surfaces. This correlation method has been suggested by us for rough rods in a smooth tube /4/.

2.2 The laminar flow heat transfer data, correlated in terms of Nu_B versus $Gr_{\bar{W}}$ tend to be lower than the analytical prediction of Heaton, Reynolds and Kays /12/, a fact which could be explained by the superposition of natural convection.

Nomenclature

A = cross section area of the annulus (cm^2)

c_p = gas specific heat at constant pressure $(cal/g\,^{o}C)$

$D = 2(r_2 - r_1)$ = hydraulic diameter of the annulus (cm)

$f_B = \frac{2\tau}{\rho_B\ u_B^{\ 2}}$ = friction coefficient evaluated at the gas bulk temperature T_B

$Gr_{\bar{W}} = \frac{1}{D\ Re_{\bar{W}}\ Pr_B}$ = Graetz number evaluated at the temperature $T_{\bar{W}}$

h = convective heat transfer coefficient between inner tube surface and gas bulk $(cal/cm^2\ s\,^{o}C)$

k = gas thermal conductivity $(cal/cm\ s\ ^{o}C)$

l = axial distance parallel to the flow (cm)

M = mass flow rate of gas (g/s)

$Nu_B = \frac{hD}{k_B}$ = Nusselt number evaluated at the gas bulk temperature T_B.

$Pr_B = \frac{\nu_B \rho_B c_{PB}}{k_B}$ = Reynolds number evaluated at the gas bulk temperature T_B

Q = quantity of heat given to the gas from the entrance to the considered cross section of the annulus (cal/s)

$Re_B = \frac{u_B D}{\nu}$ = Reynolds number evaluated at the gas bulk temperature T_B.

$Re_{\bar{W}} = \frac{u_B D}{\nu_{\bar{W}}}$ = Reynolds number evaluated at the temperature $T_{\bar{W}}$.

r_1 = radius of the inner cylindrical surface of the annulus (cm)

r_2 = radius of the outer cylindrical surface of the annulus (cm)

$St_B = \frac{h}{\rho_B c_{PB} u_B}$ = Stanton number evaluated at the bulk temperature T_B

$T_B = T_E + (Q/Mcp)$ = gas bulk temperature (K)

T_E = gas temperature at test section entrance (K)

T_W = wall temperature (K)

T_{WM} = maximum wall temperature of the inner rod of the annulus (K)

$T_{\bar{W}}$ = average between the temperature of the inner surface and of the outer surface of the annulus, weighted over the two surfaces (K)

Subscripts

B = gas properties evaluated at the gas bulk temperature T_B

W = gas properties evaluated at the wall temperature T_W

$\bar{W}$ = gas properties evaluated at the average wall temperature $T_{\bar{W}}$

1,2 = it refers to the inner and outer surface respectively of the annulus.

Greek letters

$\alpha = \frac{r_1}{r_2}$ = aspect ratio of the annulus

ν = kinematic viscosity of the gas (cm^2/s)

τ = shear stress at the wall ($dynes/cm^2$)

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RE	F	F*RE
5.60E+04	.00540	302.6
2.91E+04	.00643	187.3
1.22E+05	.00454	551.9
2.36E+05	.00418	984.6
1.42E+04	.00778	110.8
4.22E+03	.01010	42.6
3.57E+03	.00951	35.1
2.98E+03	.00930	27.7
2.53E+03	.01057	26.7
1.78E+03	.01391	24.8
1.55E+03	.01565	24.3
1.22E+03	.01973	24.0
1.01E+03	.02580	26.0

Table I: Isothermal friction factors

VERS.NR.	RE*E4	REW*E4	F	RE*F	ST	TW/TE	TW/TB
1-16- 1	0.282	0.175	.01023	28.8	.00308	1.44	1.32
1-16- 2	0.734	0.458	.00936	68.7	.00341	1.43	1.31
1-16- 3	1.138	0.687	.00842	95.8	.00321	1.46	1.34
1-16- 4	1.844	1.119	.00738	136.0	.00300	1.44	1.33
1-16- 5	3.620	2.165	.00605	218.9	.00261	1.44	1.34
1-16- 6	8.143	4.718	.00494	402.3	.00219	1.46	1.37
1-16- 7	15.694	8.904	.00419	657.7	.00196	1.47	1.39
1-16- 8	0.159	0.097	.01728	27.5	.00426	1.51	1.33
1-16- 9	0.239	0.147	.01228	29.4	.00322	1.45	1.32
1-16-10	0.330	0.199	.01018	33.7	.00282	1.46	1.34
1-16-11	0.390	0.239	.01060	41.4	.00341	1.46	1.33
1-16-12	0.463	0.285	.01042	48.3	.00340	1.45	1.32
1-16-13	0.636	0.391	.00970	61.7	.00345	1.45	1.32
1-16-14	0.913	0.555	.00882	80.5	.00329	1.46	1.33
1-16-15	1.286	0.776	.00801	103.0	.00315	1.46	1.34
1-16-16	2.427	1.452	.00679	164.7	.00279	1.45	1.34
1-16-17	4.005	2.362	.00594	237.7	.00256	1.46	1.36
1-16-18	6.561	3.776	.00527	345.8	.00226	1.47	1.37
1-16-19	21.780	12.343	.00420	914.5	.00185	1.47	1.39
1-16-20	18.677	6.412	.00436	814.0	.00179	2.13	1.88
1-16-21	11.926	4.326	.00464	553.8	.00197	2.07	1.81
1-16-22	8.225	3.022	.00491	403.9	.00212	2.07	1.80
1-16-23	5.970	2.203	.00537	320.4	.00219	2.08	1.80
1-16-24	4.405	1.649	.00576	253.8	.00235	2.08	1.78
1-16-25	3.290	1.251	.00622	204.7	.00251	2.08	1.77
1-16-26	2.344	0.909	.00682	159.8	.00272	2.08	1.75
1-16-27	1.695	0.671	.00754	127.8	.00291	2.08	1.73
1-16-28	1.209	0.487	.00817	98.8	.00306	2.07	1.71
1-16-29	0.844	0.339	.00928	78.4	.00299	2.08	1.71
1-16-30	0.598	0.242	.01023	61.2	.00305	2.10	1.71
1-16-31	0.428	0.177	.01111	47.6	.00322	2.11	1.68
1-16-32	0.357	0.150	.01099	39.2	.00313	2.08	1.67
1-16-33	0.302	0.128	.01073	32.4	.00293	2.06	1.66
1-16-34	0.254	0.111	.01182	30.1	.00313	2.05	1.63
1-16-35	0.211	0.096	.01392	29.3	.00358	2.04	1.60
1-16-36	0.139	0.068	.02009	27.9	.00468	2.07	1.53
1-16-37	0.117	0.060	.02362	27.7	.00529	2.06	1.49
1-16-38	0.090	0.049	.03026	27.3	.00652	2.07	1.44
1-16-39	0.072	0.041	.03734	26.7	.00773	2.06	1.40
1-16-40	0.065	0.036	.04690	30.7	.00700	2.63	1.45
1-16-41	0.080	0.041	.03856	31.0	.00605	2.63	1.50
1-16-42	0.106	0.050	.02941	31.1	.00501	2.63	1.57
1-16-43	0.125	0.056	.02485	31.0	.00440	2.66	1.62
1-16-44	0.182	0.073	.01758	32.0	.00348	2.69	1.74
1-16-45	0.220	0.083	.01508	33.2	.00307	2.70	1.80
1-16-46	0.276	0.097	.01216	33.5	.00263	2.69	1.88
1-16-47	0.325	0.112	.01165	37.9	.00267	2.69	1.90
1-16-48	0.393	0.135	.01189	46.7	.00288	2.67	1.90
1-16-49	0.542	0.179	.01072	58.1	.00289	2.69	1.95
1-16-50	0.771	0.241	.00957	73.8	.00273	2.72	2.01
1-16-51	1.155	0.353	.00838	96.7	.00269	2.71	2.04
1-16-52	1.622	0.484	.00765	124.1	.00261	2.71	2.06
1-16-53	2.261	0.665	.00692	156.5	.00251	2.68	2.08
1-16-54	3.154	0.901	.00641	202.1	.00235	2.69	2.12
1-16-55	4.525	1.252	.00571	258.5	.00217	2.69	2.15
1-16-56	5.975	1.631	.00520	310.9	.00211	2.69	2.17
1-16-57	8.426	2.251	.00479	403.9	.00195	2.69	2.20
1-16-58	12.462	3.245	.00442	550.9	.00180	2.69	2.23
1-16-59	20.803	5.320	.00407	847.0	.00161	2.66	2.25

TableII: Results of experiments with heat transfer

$$REW = Re(T_{W1}) = \frac{u_B D}{\nu_{T_{W1}}}$$

VERS.NR.	RE*E4	REW*E4	F	RE*F	ST	TW/TB	TW/TB	GRAEZ	NUB	F*REW	NU-W	GZ-W
1-16- 1	0.282	0.251	.01023	28.8	.00308	1.44	1.32	.02952	6.11	25.7	5.76	.03336
1-16- 8	0.159	0.141	.01728	27.5	.00426	1.51	1.33	.05263	4.74	24.3	4.46	.05960
1-16- 9	0.239	0.209	.01228	29.4	.00322	1.45	1.32	.03481	5.43	25.7	5.08	.04005
1-16-10	0.330	0.286	.01018	33.7	.00282	1.46	1.34	.02515	6.56	29.1	6.11	.02926
1-16-11	0.390	0.339	.01060	41.4	.00241	1.45	1.33	.02132	9.36	36.0	8.73	.02470
1-16-12	0.463	0.401	.01042	48.3	.00340	1.45	1.32	.01797	11.06	41.8	10.30	.02090
1-16-30	0.598	0.443	.01023	61.2	.00305	2.10	1.71	.01417	12.70	45.3	10.96	.01929
1-16-31	0.428	0.324	.01111	47.6	.00322	2.11	1.68	.01983	9.59	36.0	8.36	.02638
1-16-32	0.357	0.275	.01099	39.2	.00313	2.08	1.67	.02380	7.76	30.2	6.83	.03101
1-16-33	0.302	0.236	.01073	32.4	.00293	2.06	1.66	.02815	6.16	25.4	5.47	.03611
1-16-34	0.254	0.202	.01182	30.1	.00313	2.05	1.63	.03341	5.55	23.9	4.96	.04210
1-16-35	0.211	0.172	.01392	29.3	.00358	2.04	1.60	.04046	5.24	23.9	4.74	.04968
1-16-36	0.139	0.117	.02009	27.9	.00468	2.07	1.53	.06162	4.50	23.5	4.13	.07362
1-16-37	0.117	0.101	.02362	27.7	.00529	2.06	1.49	.07302	4.29	23.8	3.98	.08514
1-16-38	0.090	0.080	.03026	27.3	.00652	2.07	1.44	.09522	4.06	24.2	3.85	.10712
1-16-39	0.072	0.065	.03734	26.7	.00773	2.06	1.40	.12028	3.81	24.3	3.64	.13190
1-16-40	0.065	0.058	.04690	30.7	.00700	2.63	1.45	.13260	3.14	27.1	2.96	.14965
1-16-41	0.080	0.068	.03856	31.0	.00605	2.63	1.50	.10815	3.33	26.4	3.09	.12627
1-16-42	0.106	0.087	.02941	31.1	.00501	2.63	1.57	.08215	3.64	25.7	3.32	.09875
1-16-43	0.125	0.101	.02485	31.0	.00440	2.66	1.62	.06960	3.77	25.2	3.41	.08457
1-16-44	0.182	0.140	.01758	32.0	.00348	2.69	1.74	.04770	4.36	24.6	3.84	.06141
1-16-45	0.220	0.164	.01508	33.2	.00307	2.70	1.80	.03929	4.67	24.7	4.04	.05259
1-16-46	0.276	0.195	.01216	33.5	.00263	2.69	1.88	.03129	5.01	23.7	4.23	.04415
1-16-47	0.325	0.226	.01165	37.9	.00267	2.69	1.90	.02651	6.00	26.3	5.03	.03806
1-16-48	0.393	0.269	.01189	46.7	.00288	2.67	1.90	.02194	7.79	32.0	6.49	.03198
1-16-49	0.542	0.364	.01072	58.1	.00289	2.69	1.95	.01590	10.78	39.1	8.90	.02361
1-16-50	0.771	0.502	.00957	73.8	.00273	2.72	2.01	.01114	14.51	48.0	11.79	.01715

Table III: Results of experiments with heat transfer for $\mathrm{Re}(T_{W1}) \leq 3000$:

$$\mathrm{REW} = \mathrm{Re}(T_{\bar{W}}) = \frac{u_B D}{\nu_{T_{\bar{W}}}}, \quad \mathrm{GRAEZ} = \mathrm{Gr}_B = \frac{\ell}{D\,\mathrm{Re}_B\,\mathrm{Pr}_B}, \quad \mathrm{NU\text{-}W} = \mathrm{Nu}_{\bar{W}} = \frac{hD}{k_{\bar{W}}},$$

$$\mathrm{GZ\text{-}W} = \mathrm{Gz}_{\bar{W}} = \frac{\ell}{D\,\mathrm{Re}_{\bar{W}}\,\mathrm{Pr}_B},$$

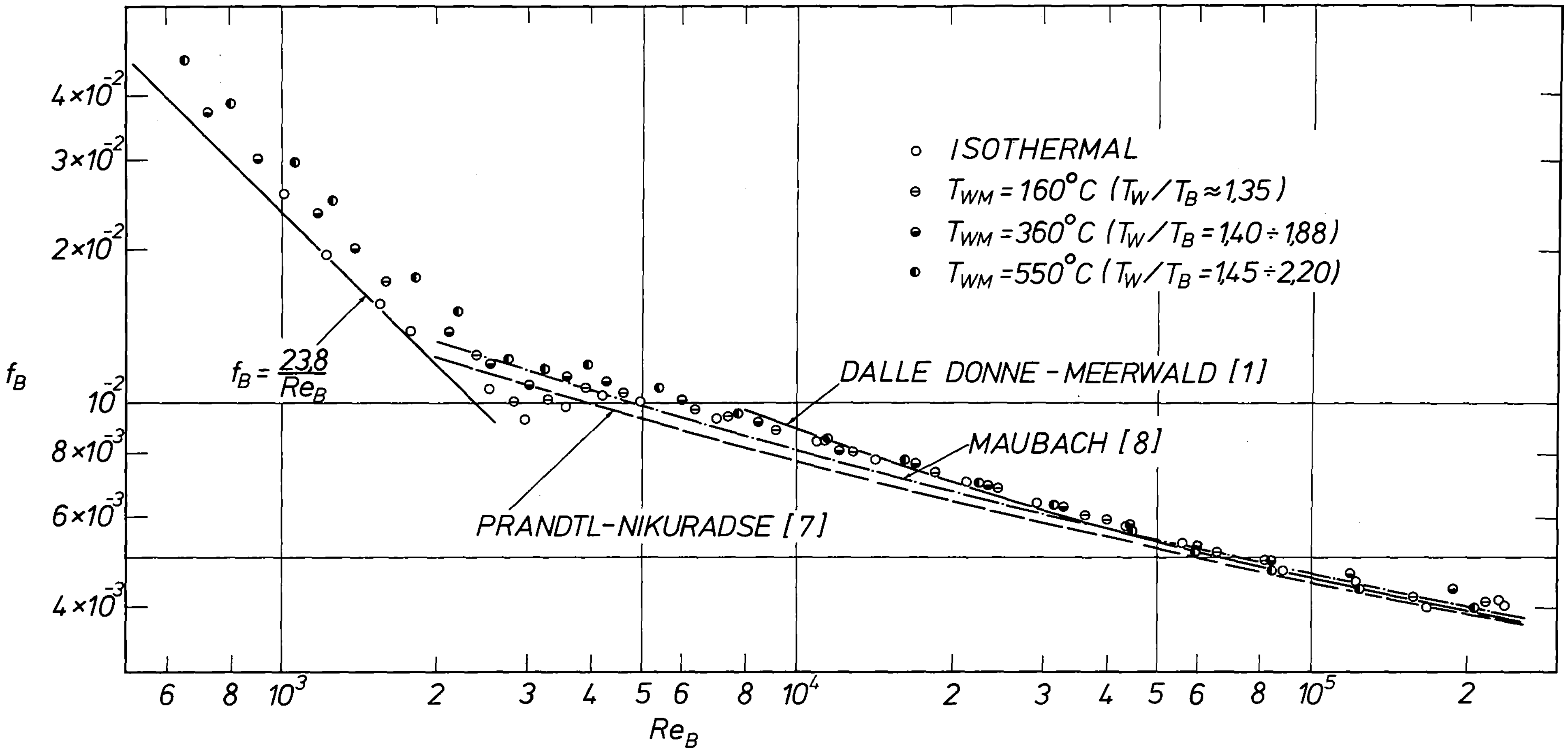

Fig. 1: Average friction factors (38.3 ≤ l/D ≤ 78.2) versus Reynolds number.

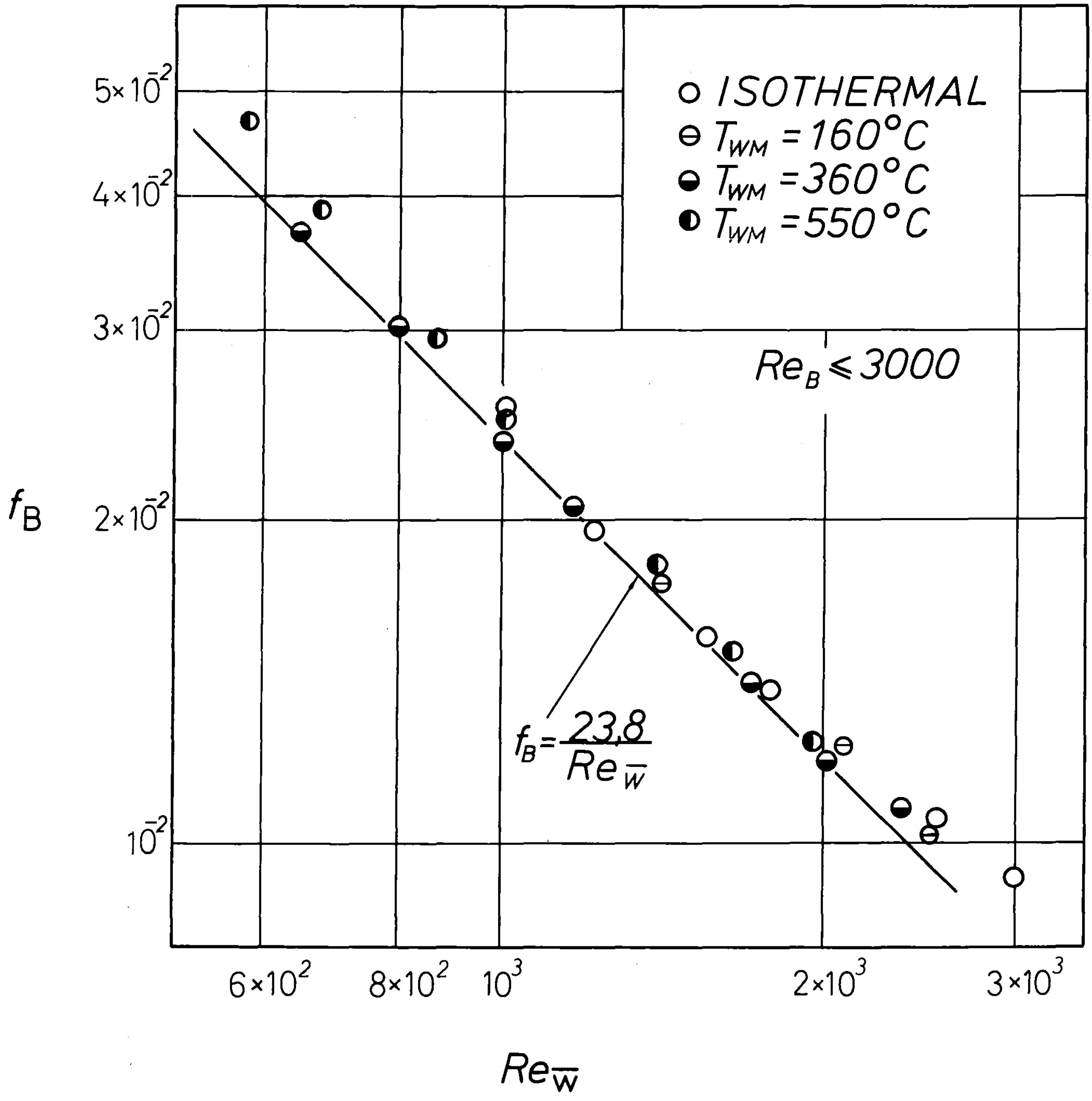

Fig. 2: Average friction factors versus Reynolds number evaluated at the average temperature of the two surfaces of the annulus. Laminar flow.

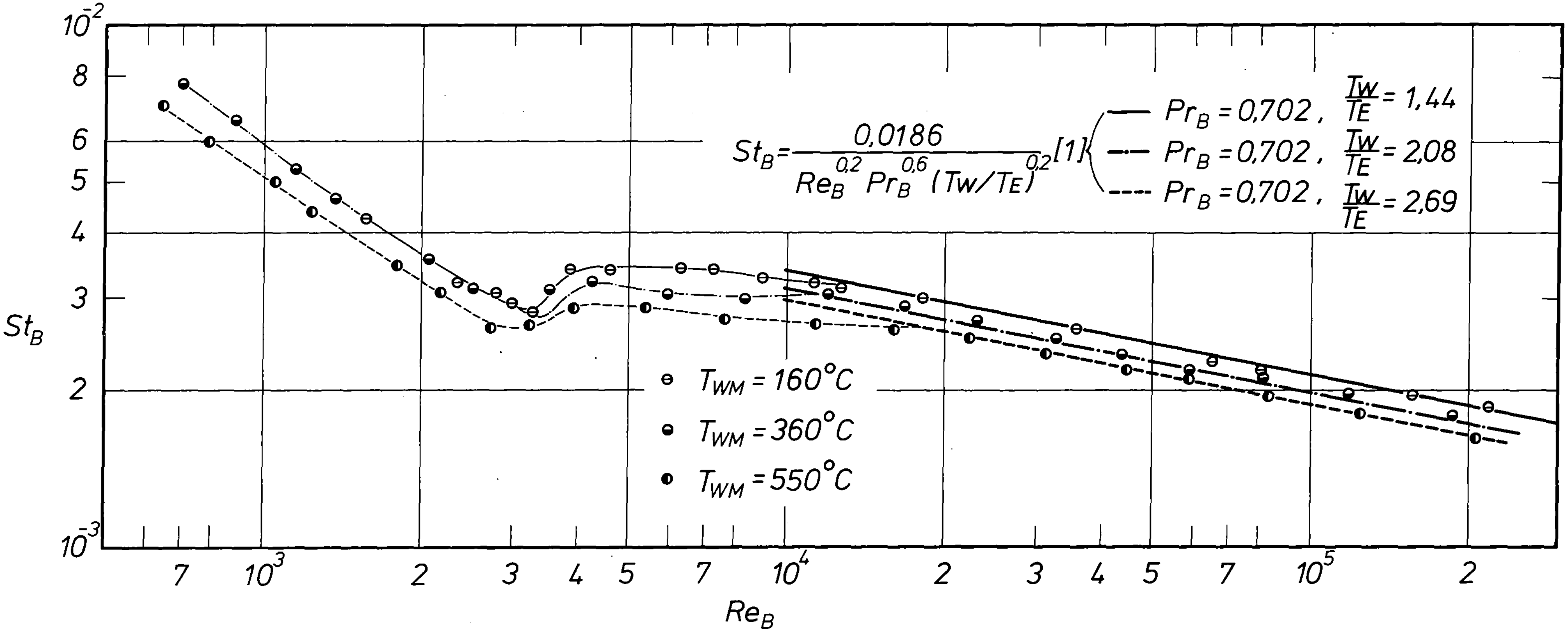

Fig. 3: Average Stanton numbers (38.2 $\leq$ l/D $\leq$ 78.2) versus Reynolds number.

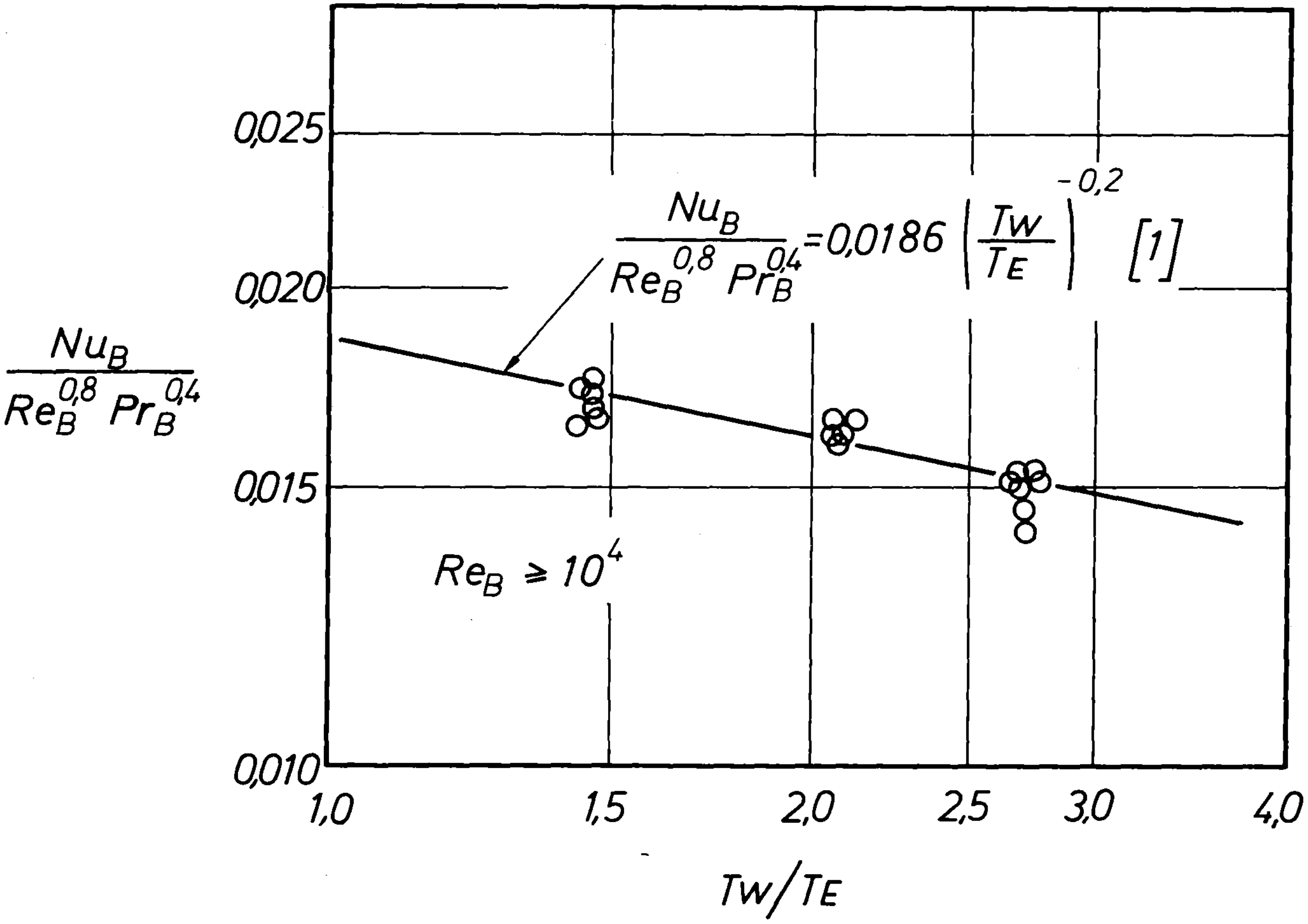

Fig. 4: Averaged reduced Nusselt numbers versus T_W/T_E. Turbulent flow ($Re_B \geq 10^4$).

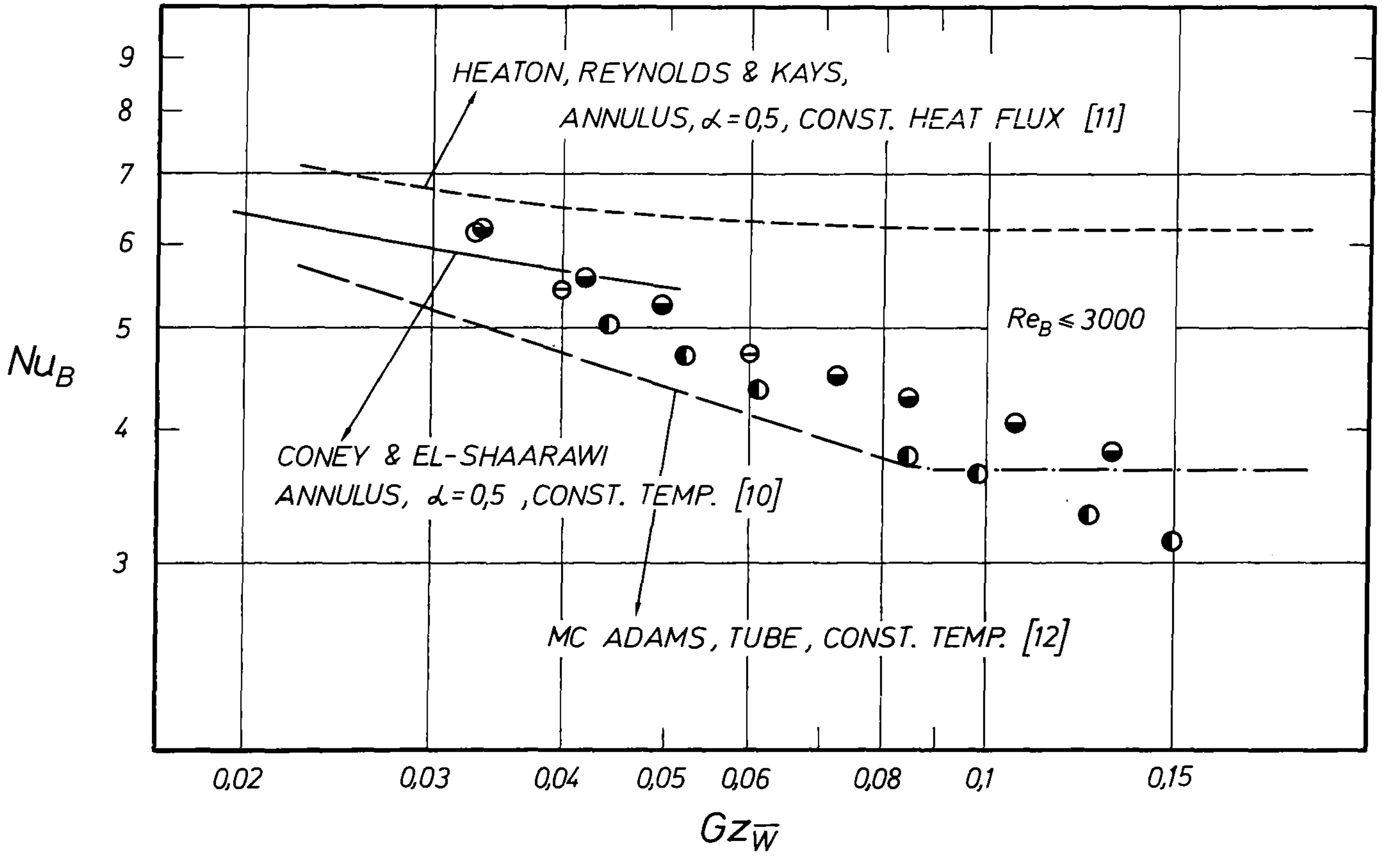

Fig. 5: Averaged Nusselt numbers versus Graetz number evaluated at the average temperature of the two surfaces of the annulus. Laminar flow.