**THEORETICAL STUDIES ON THE ROLE OF
TRANSITION IN DETERMINING FRICTION
AND HEAT TRANSFER IN SMOOTH AND
ROUGH PASSAGES**

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ABSTRACT

It has been established that transition determines the attainable friction and heat transfer in smooth and rough passages. According to the proposed law of corresponding states for friction, different types of roughness exhibit the same general behavior for friction at the same reduced conditions. This is also true of different types of smooth passages. It has been fully demonstrated that, in rough passages, the marked increases in friction factor are intimately associated with early transition and that, under reduced similarity conditions, the friction factors are considerably lower than those deduced from the familiar f vs. Re plots.

For all smooth or rough passages, the simple rule for heat transfer amounts to this: the lower the critical Reynolds number for transition, the greater the value for the average heat transfer coefficient. Consequently, for a given Reynolds number based on the hydraulic diameter, triangular passages can be expected to give heat transfer coefficients that are significantly higher than for circular, rectangular or annular tubes. For smooth and enhanced passages of complex shapes, it appears that heat transfer coefficients can be calculated accurately from the smooth circular tube relations, provided the critical Reynolds number is known.

TABLE OF CONTENTS

	Page No.
ABSTRACT	ii
Table of Contents	iii
List of Figures	iv
List of Tables	vi
Nomenclature	vii
1. INTRODUCTION	1
2. ANALYSES OF FRICTION IN FLOW PASSAGES	2
2.1 Smooth Passages	2
2.2 Rough Passages	5
3. ANALYSES OF HEAT TRANSFER IN FLOW PASSAGES	21
3.1 Smooth Passages	22
3.2 Rough Passages	27
3.2.1 Transition-Based Similarity Parameter Vs. Roughness Reynolds Number	42
4. FLUID HEATING VERSUS COOLING	52
5. DISCUSSION	56
6. CONCLUSIONS AND RECOMMENDATIONS	60
6.1 Conclusions	60
6.2 Recommendations	61
ACKNOWLEDGEMENTS	62
REFERENCES	64
APPENDIX	71

List of Figures

<u>Fig. No.</u>		<u>Page No.</u>
1	Friction factor for circular and noncircular passages.	4
2	Effect of e/D on resistance coefficient according to Koch (1960).	8
3	Variation of $\psi_R (= Re_{c,r}/Re_{c,a})$ with e/D .	11
4	Variation of $\psi_f (= f_{c,r}/f_{c,a})$ with e/D .	12
5	Variation of ψ_f with ψ_R .	13
6	Similarity plot of f_m vs. Re_m using Koch's (1960) data.	17
7	Plot of f_m vs. Re_m using Nunner's (1956) data.	18
8	Nikuradse's sand-grain roughness vs. Koch's ring inserts.	20
9	Nusselt number (Nu_m) vs. Re_m for smooth annuli.	24
10	Nusselt number (Nu_m) vs. Re_m for smooth annuli.	25
11	Effect of e/D on Nusselt number according to Koch (1960).	28
12	Nusselt number (Nu_m) vs. Re_m using Koch's (1960) data.	30
13	Nu_m vs. Re_m using Nunner's (1956) data.	32
14	Nu_m vs. Re_m using data of Blackwelder and Kreith (1970).	33
15	$(Nu_m/Pr^{0.4})$ vs. Re_m using data of Knudsen and Katz (1950).	34
16	Maximum enhancement factor, $\phi_{h,max}$, vs. ψ_R .	37
17	Variation of $\phi_{h,max}$ with $\phi_f (= f_m/f_{m,s})$.	38
18	Plot of $(\phi_{h,max}/\phi_f)$ vs. ψ_R .	39
19	Stanton number ratio versus Re_m .	45
20	Stanton number ratio versus Re_{rm} .	46
21	Stanton number ratio versus e_m^+ .	47
22	Stanton number ratio versus e^+ .	48

<u>Fig. No.</u>		<u>Page No.</u>
23	Stanton number ratio versus Re_m .	50
24	Stanton number ratio versus $Re_{\tau m}$.	51
25	Generalized plot of ψ_f vs. ψ_R for smooth and rough passages.	57

List of Tables

<u>Table No.</u>		<u>Page No.</u>
1	Summary of critical data for enhanced passages.	6
A.1	Data of Allen and Grunberg (1937).	73
A.2	Data of Cornish (1928).	74
A.3	Data of Carlson (1959).	76
A.4	Data of Hartnett et al. (1959).	79
A.5	Data of Jones (1976).	81
A.6	Data of Koch and Feind (1958).	83
A.7	Data of Koch (1960).	91
A.8	Data of Nunner (1956).	107
A.9	Data of Nikuradse (1933).	149
A.10	Data of Blackwelder and Kreith (1970).	156
A.11	Data of Knudsen and Katz (1950).	160
A.12	Data of Watkinson et al. (1974).	165

Nomenclature

A	=	cross section flow area, m^2
a_r	=	aspect ratio, w/s
b	=	base of triangular duct, m
c_p	=	specific heat, J/kg °C
D, D_e	=	maximum internal diameter, equivalent (hydraulic) diameter, m
d_i, d_o	=	inner, outer diameter of annular space, m
e	=	roughness height, m
e^+	=	roughness Reynolds number, equation (7)
e_m^+	=	modified roughness Reynolds number, equation (8)
f	=	Fanning friction factor
f_m	=	reduced friction factor, equation (2)
f_a	=	friction factor for arbitrary condition, equation (2)
h	=	height of triangular duct, m
$\bar{h}$	=	heat transfer coefficient, $W/m^2 \text{ } ^\circ C$
k	=	fluid thermal conductivity, $W/m \text{ } ^\circ C$
L_e	=	entrance length, m
Nu	=	Nusselt number, $\bar{h}D/k$ or $\bar{h}D_e/k$
Nu_m	=	Nusselt number associated with Re_m
Pr	=	Prandtl number, ν/α
P_w	=	wetted perimeter, m
p	=	roughness pitch, m
Re	=	Reynolds number
Re_a	=	Reynolds number for arbitrary condition, equation (2)
Re_m	=	similarity parameter or reduced Reynolds number, equation (2)
$Re_{\tau m}$	=	friction Reynolds number, equation (10)
s	=	channel spacing, m

St	=	Stanton number, $h/\rho c_p \bar{V}$
T_f, T	=	fluid, temperature, °C
U	=	velocity, m/s
U_τ	=	friction velocity, $(\tau_w/\rho)^{1/2}$, m/s
$\bar{V}$	=	average flow velocity, m/s
w	=	channel width, m
x	=	coordinate in flow direction
y	=	coordinate normal to flow
α	=	apex angle, deg.; thermal diffusivity, m^2/s
β	=	diameter ratio, d_i/d_o
μ	=	fluid viscosity, Pa s
ν	=	kinematic viscosity, m^2/s
ρ	=	fluid density, kg/m^3
τ_w	=	wall shear stress, N/m^2
ϕ_f	=	friction factor ratio, $f_m/f_{m,s}$
ϕ_h	=	ratio of heat transfer coefficient, Nu_τ/Nu_s
ψ_f	=	ratio of critical f , equation (1)
ψ_R	=	ratio of critical Re , equation (1)

Additional Subscripts

c,r	=	critical parameters for reference condition
c,a	=	critical parameters for arbitrary condition
max	=	maximum value
$m,s;s$	=	smooth duct
m,c	=	critical value of similarity parameter
r	=	rough condition
w	=	value at the wall

1. INTRODUCTION

Transition, a process whereby the motion of a fluid changes from laminar to turbulent flow, was successfully traced by Reynolds (1883) over a century ago. Although this remarkable process occurs naturally when the critical velocity and pressure attain some threshold values, it is also well known that its onset can be delayed or accelerated markedly. For any particular condition, be it of a natural origin or one in which the process is effected by artificial means, the most notable characteristic of transition is the marked change in the resistance to flow. Despite the extensive studies on transition (Morkovin, 1958; Dryden, 1953), and even though it is of considerable importance in convective heat transfer, the underlying physics of this phenomenon as well as its implications have eluded complete understanding.

The connection between fluid friction and heat transfer was also postulated by Reynolds in 1874, even before the very exhaustive studies on transition and the laws of resistance, and the resulting relation is generally referred to as the Reynolds analogy. Thereafter, the problem of friction and heat transfer analogy was studied by very eminent researchers (Stanton, 1897, 1913; Lanchester, 1913; Taylor, 1916; Prandtl, 1928; to mention but a few). An overview of the many contributions on the subject, prior to 1933, is given by Colburn (1933). Rather surprisingly, although there are clear indications that transition can have very profound effects on surface friction, it does not appear that hitherto any systematic investigations have been made to establish connections between transition and heat transfer, or a global mechanism for heat transfer enhancement. Consequently, the origin of the differences among the various results obtained on smooth passages or of the anomaly between the magnitudes of the increase in frictional pressure coefficients and heat transfer coefficients in the presence of roughness has been open to conjecture. For example, in connection with the latter, Owens and Thomson (1963)

argued that the rate of heat transfer is controlled by a purely molecular property of the fluid, its thermal conductivity, whereas the shear stress, augmented by roughness, is transmitted to the surface as form drag on the individual elements. The difficulty with this explanation is that it provides no insight on the physical phenomenon involved.

The work described in this paper has its origin in a thorough re-analysis of the literature on friction in smooth circular and noncircular passages which resulted in the formulation of the critical friction method or the frictional law of corresponding states, as well as the fundamental requirements for flow similarity (Obot, 1988). However, it became quite evident that the implications of transition to friction or heat transfer are far too important and more numerous than can be inferred from much that has been written on the subject. It was with this understanding that the aforementioned study was extended to include friction and heat transfer in smooth and rough passages. As with the earlier study, this analysis was carried out using existing literature data. However, in sharp contrast to the manual extraction of much of the data used therein, the data for this study were extracted digitally. A complete tabulation of all data is given in the Appendix of this report.

2. ANALYSES OF FRICTION IN FLOW PASSAGES

This treatment of the influence of transition on friction in flow passages is divided into two sections. The first gives an overview of the effects for flow in smooth channels, while a more extensive evaluation of the situation with different types of enhanced tubes is presented in Section 2.2.

2.1 Smooth Passages.

In a recent paper (Obot, 1988), the critical friction law (or the law of corresponding states), which asserts that flows having the same critical friction factor and critical

Reynolds number are dynamically similar to one another, was formulated and successfully applied to smooth tubes of complex shapes. The simple mathematical relations that are needed to effect such an analysis are given by equations (1) and (2):

$$\psi_R = Re_{c,r}/Re_{c,a} \quad ; \quad \psi_f = f_{c,r}/f_{c,a} \quad (1)$$

$$Re_m = \psi_R Re_a \quad ; \quad f_m = \psi_f f_a \quad (2)$$

In equation (1), $Re_{c,r}$ and $f_{c,r}$ are the reference values for the critical Reynolds number and critical friction factor, while the corresponding critical parameters for an arbitrary condition are $Re_{c,a}$ and $f_{c,a}$. In equation (2), the similarity parameters Re_m and f_m are independent of the length scale used to reduce the data to nondimensional form. For rectangular or annular passages, and with $Re_{c,r} = 2,100$ as the reference, ψ_R decreases with increasing aspect or diameter ratio. For fully developed flow in smooth passages, the critical limiting (Fanning) friction factor is about 0.008, provided the data are reduced using the hydraulic (or equivalent) diameter, $D_e (= A/P_w)$. For triangular passages, ψ_R increases with increasing height-to-base ratio or with decreasing apex angle in the case of isosceles channels.

To shed further light on the application of the law of corresponding state to flow passages, data for rectangular, annular and triangular passages (a total of 500 points) that were presented as three separate figures in the aforementioned paper have been consolidated into a single plot (Fig. 1). The well known laminar and turbulent relations, as well as the circular tube data of Dodge and Metzner (1959), are also included in Fig. 1 for purposes of comparison. The number of data points for each cross-section is given in brackets in Fig. 1. Given the differences in the relative entrance length (L_e/D_e), the relative roughness of the smooth duct, and the lack of geometrically similar test conditions, all of which may affect the critical Reynolds number, the results in Fig. 1 are satisfactorily consistent. As might be expected, the turbulent relation is a good

Figure 1. Friction factor for circular and noncircular passages.

approximation of the data over a limited range. It was tempting to establish an improved relation for the turbulent results on this figure; however, it was decided that such an attempt must await the results of ongoing systematic experiments.

2.2 Rough Passages.

To date, efforts to provide a generalized approach for handling experimental data obtained on rough tubes or very clear insight into the mechanism of friction/heat transfer augmentation have been frustrated by several factors. In the first place, there are far too many variables (pitch, height, shape, angular orientation, density, etc.) associated with the problem. Second, as was the case until recently with smooth passages, the contentious issue has been the choice of the length scale needed to reduce the experimental data to nondimensional form. These are further complicated by the widely held view that the conventional Reynolds number is a similarity parameter, a position that is not necessarily correct. And, finally, although there are clear indications in the literature that the origin of turbulence must be the common feature for all types of roughness, it is rather surprising that this line of reasoning has not been explored theoretically or experimentally in the past. In fact, of the extensive studies on friction and heat transfer with enhanced tubes, only a few of these covered the complete range extending from the laminar through the turbulent regime, and nearly all of these were performed on circular tubes (Nunner, 1956; Koch, 1960).

It is most instructive to begin this analysis by considering the effects of roughness on the critical parameters for transition, and the relevant data are summarized in Table 1. To gain more insight into the influence of roughness on transition, the results of Koch (1960) are reproduced exactly in Fig. 2. For these results, the pitch-to-height ratio (p/e) was held fixed at 9.8, hence the figure shows the generally expected trend with increasing height of roughness. It should be emphasized that the data of Table 1 as well as those

Table 1: Summary of critical data for rough passages.

Author(s)	L_e/D	$f_{c,a} \times 10^2$	$Re_{c,a}$	p/e	e/D	Roughness Geometry
Nunner (1956)		0.83 ¹	2510	-	-	(smooth tube)
(fluid - air)		1.31	1988 ²	20	0.04	transverse rectangular ring inserts
		1.31	198 8 ²	20	0.04	
	50	0.95	2537	80	0.04	transverse semi-circular ring inserts with no clearance at the wall
		1.14	2497	2	0.08	
		1.65	2014	5	0.08	
		1.92	1653	10	0.08	
		3.36	1022	20	0.08	
Koch (1960)		4.62	1019	3.92	0.1	
(fluid - air)		3.68	972	9.8	0.1	transverse disc-shaped inserts with no clearance at the wall
		3.72	747	65	0.1	
	50	47.33	226	3.92	0.2	
		28.88	244	9.8	0.2	
		57.86	181	26.0	0.25	
		3.16	1170	9.8	0.045	transverse ring inserts with clearance for flow near the wall
		7.17	702	9.8	0.075	
		0.80	2944	-	-	(smooth tube)
			(2900) ³			
Marner & Bergles (1978)	-	3.11	1133	6 ⁴	0.088 ⁴	forge-fin tubes
(fluid - ethylene glycol)						
Molloy (1967)	8.1	0.90	2203	-	-	(smooth)
(fluid - air)	8.1	0.78	2659	10	0.014	spirally wound wire
Knudsen & Katz (1950) ⁵	30.9	1.3	1766	-	-	(smooth)
(fluid - water)	33.0	1.5	1502	0.952	0.089	
	42.1	3.0	784	1.15	0.184	helically-finned annular tubes
	41.1	2.1	1093	0.513	0.185	
	50.1	3.9	605	0.730	0.236	
	52.9	3.5	666	0.452	0.250	
	54.3	4.4	536	0.299	0.269	
Li et al. (1982)		-	1700	11.83	0.047	
(fluid - water)		-	1700	29.6	0.048	helically-ridged tubes
(visual studies)	30	-	2200	67.7	0.058	
		-	2000	99.9	0.040	
		-	2300	-	-	(smooth)

Author(s)	L_e/D	$f_{c,a} \times 10^2$	$Re_{c,a}$	p/e	e/D	Roughness Geometry
Watkinson	29.9	3.10	938	10.0	0.097 (1) ⁶	
et al. (1974)	35.6	2.77	756	13.0	0.105 (2)	
(fluid - oil)	43.6	3.21	989	20.0	0.118 (3)	
	51.6	3.18	949	14.5	0.157 (4)	High Spiral Fins (HSF)
	57.1	2.83	693	33.3	0.144 (5)	
	24.0	3.44	886	6.0	0.088 (9)	
	20.1	11.35	731	6.6	0.149 (18)	
	33.8	1.65	1464	-	0.099 (11)	
	52.9	2.18	1299	-	0.148 (13)	
	42.9	2.63	1112	-	0.111 (4)	High Straight Fins (STF)
	52.5	1.97	1290	-	0.094 (16)	
	24.1	2.53	1483	-	0.073 (20)	
	23.8	2.37	2010	162.2	0.037 (15)	
	30.5	1.81	1296	206.9	0.037 (17)	
	19.4	3.71	2127	242.0	0.026 (19)	Low Spiral Fins (LSF)
	24.6	1.93	1482	164.6	0.042 (21)	
	41.5	1.49	1579	444.4	0.047 (22)	
	41.3	1.54	1478	181.8	0.057 (23)	

¹ The conventional definition of friction factor was not adopted in this study.

² Characterized by the same profile in the laminar and transition regions.

³ Smooth tube critical value reported in original study.

⁴ Values were deduced from Watkinson et al. (1974) for Tube # 9.

⁵ The characteristic dimension is the hydraulic diameter, $D_e = d_o - d_i$.

⁶ Numbers in brackets correspond to tube numbers in the original paper.

Figure 2. Effect of e/D on resistance coefficient according to Koch (1960).

on Fig. 2 were obtained in the absence of heat transfer (isothermal conditions). Also, to provide a consistent basis for viewing of the critical parameters, the characteristic length for the results in Table 1 is the maximum internal tube diameter. The only exception occurs with the results of Knudsen and Katz (1950) which, due to the use of annular passages, have the hydraulic diameter as the linear parameter.

From a comparison of the results (Table 1) of Nunner and Koch, both of which were obtained using the same experimental facility, it may be noted that Nunner's $f_{c,a}$ data are much lower, while the values for $Re_{c,a}$ are substantially higher, than those determined from Koch's results. These cannot be attributed solely to differences in the details of roughness. Nunner defined the resistance coefficient in terms of the difference between the conventional pressure drop and the work due to acceleration; the latter being expressed as a function of both the pressure and temperature at the inlet and exit of the test section. Obviously, even for isothermal conditions, with nearly the same temperature at the inlet and exit, the latter term always enters into the calculation since the inlet and exit pressures are unequal. Without data for pressure and temperature at the two end points for each trial, the usual friction factor cannot be established from his data. Also, the characteristic length in the Reynolds and Nusselt number was the mean diameter, d_m , defined as the equivalent diameter of a smooth pipe having the same volume per unit length. Using the d_m values in his paper (c.f. Table 2), all of his results were re-computed using the internal diameter as reference. Even with this revision, the critical Re values are still considerably higher than would be expected for the test conditions. The reader may wish to compare the values in Table 1 with those in Table 2 of the original paper. By contrast, in the subsequent study of Koch, the usual definition of friction factor was used and the length parameter was the tube diameter. Suffice it to state that using the empirical relation provided by Koch, it has been estimated that

$Re_{c,a} = 1700$ represents the upper limit to the range of critical Reynolds numbers for Nunner's test conditions. The results of other investigations (Table 1) definitely support this view.

A study of the results in Table 1 and Fig. 2 reveals a number of important trends. The most obvious of these is that, the critical friction factors are considerably higher, while the critical Reynolds numbers are substantially lower, than the values for smooth tubes. In other words, $\psi_f < 1$ and $\psi_R > 1$ when the data are reduced using the internal diameter. In this regard, it is worthy of note that, if the hydraulic diameter D_e were used as the linear parameter, the critical friction factor can be lower than the smooth tube value, and the values for $Re_{c,a}$ would be even lower than those in Table 1. At this point it is useful to recall that for smooth passages and with D_e (i.e. $\psi_f \simeq 1$), $\psi_R < 1$ for rectangular or annular tubes, but $\psi_R > 1$ for triangular passages.

Another important trend is that $f_{c,a}$ increases, while $Re_{c,a}$ decreases, markedly with increasing height of roughness, regardless of whether one is dealing with transverse repeated-rib inserts, fins, or spirally ridged surfaces. From these results it appears that the roughness height is by far the single most important parameter, at least insofar as the influence on transition is concerned, with moderate effect of pitch-to-height ratio, p/e . Given the available data base, the fact that the effects of all relevant parameters cannot be established definitely is of little consequence to the present considerations. It is, however, correct to state that the global effect of roughness is to bring about early transition, regardless of the geometric configuration of roughness or the prevailing local flow conditions (i.e. separation and reattachment, swirl, etc.).

To shed further light on the influence of roughness on transition, the results in Table 1 are presented in several ways in Figs. 3-5. The first of these is a plot of the normalized critical Reynolds number, $\psi_R (= Re_{c,r}/Re_{c,a})$, versus the relative height of

Figure 3. Variation of $\psi_R (= Re_{c,r}/Re_{c,a})$ with e/D .

Figure 4. Variation of $\psi_f (= f_{c,f}/f_{c,a})$ with e/D .

Figure 5. Variation of ψ_f with ψ_R .

roughness (e/D) while the second shows the variation of $\psi_f (= f_{c,r}/f_{c,a})$ with e/D . Figure 5 is a plot of ψ_f versus ψ_R for all e/D . The line in this figure represents a logarithmic least squares fit using the data of Koch. For the data of Nunner and Koch, the appropriate smooth tube values (Table 1) were used to compute ψ_f and ψ_R , while the data of Marner and Bergles, and Watkinson et al. were scaled with the limiting smooth tube values (i.e. $f_{c,r} = 0.008$ and $Re_{c,r} = 2,100$). Although Watkinson et al. (1974) reported a critical Reynolds number of 1300 for smooth tubes, it was determined from the presentation therein that this value was most likely deduced from their heat transfer data for Tube #10 with a relative entrance length of $L_e/D = 24$. Since ten of their tubes were characterized by $L_e/D > 30$ (Table 1), use of the circular tube values is justified, at least for those tubes.

Excluded from the analysis are the qualitative results of Li et al. and the results of Molloy. The critical Reynolds numbers of Li et al. were determined via flow visualization, hence no data for the critical friction factor are available. Given the difficulty in obtaining accurate pressure drop measurements in the laminar and transition regions, as noted by Molloy in his report, and the rather unusual trends with increasing Reynolds number, his data are unreliable and hence must be rejected. His claim that there is a range in the transition region where the rough tube could actually give lower friction factors than the smooth tube is neither correct when the tube diameter is the linear parameter nor consistent with his heat transfer results.

Fig. 3 shows that ψ_R increases with e/D and that, for a given e/D , disc inserts which are essentially repeated-rib roughness give values that are generally higher than for finned tubes. In this regard it is useful to recall that the lower the critical Reynolds number, the greater the critical parameter, ψ_R . Consistent with the effects of e/D on $f_{c,a}$ (Fig. 2) and the general trend of Fig. 3, the behavior in Fig. 4 is one of decreasing

ψ_f with increasing e/D based on the results of Koch, while no marked variation with e/D can be established from the data for finned tubes. From this lack of strong effect of e/D on ψ_f or ψ_R , it is reasonable to speculate that a similar trend would result from an analysis of heat transfer data. The most useful information that can be inferred from the results of Fig. 5 is the possible existence of a unique relation between ψ_f and ψ_R for all types of roughness. Using the nine data points of Koch, i.e. inclusive of the smooth tube value $(\psi_f, \psi_R) = (1,1)$, the applicable relation is:

$$\psi_f = 1.108\psi_R^{-1.541} \quad (3)$$

The correlation coefficient for equation (3) is -0.988. It is worthy of note that the remaining data tend to cluster around this regression line. It is a fact of striking significance that the results on each of Figs. 3-5 follow two distinct trends: one for all finned tubes and the other for transverse repeated-rib inserts. It is also quite evident that some of Nunner's data tend to lie above or below those for finned tubes, clearly supporting an earlier observation about his results. Since the critical parameters are central to a proper interpretation of the role of transition on heat transfer, we will return to Figs. 3-5 in Section 3.2.

Having discussed the influence of roughness on the critical parameters for transition, it is necessary to consider the fundamental requirement for flow similarity which, as noted previously on several occasions, asserts that the critical parameters must be the same. On this basis, it is quite clear that the three flows of Fig. 2 are not similar, at least not for the $Re > 700$ region, because the onset of transition occurs at $Re = 702$, 1170 and 2944 for $e = 3.75\text{mm}$, 2.25mm and 0.0 (smooth), successively. This observation makes it perfectly clear that, for a given Re based on D_e , the number obtained from the division of the roughened tube data by the corresponding smooth tube value is not truly representative of the overall influence of roughness. To obtain realistic informa-

tion on the physical situation, it is necessary to reduce the data using equations (1) and (2). Accordingly, the original results of Koch (1960) and Nunner (1956), which are the most extensive, have been re-analyzed, and these are shown graphically in Figs. 6 and 7 respectively where, in each case, the reduced friction factor f_m is plotted against the reduced Reynolds number Re_m . The fact that Nunner's definition of the resistance coefficient is different and the somewhat higher $Re_{c,a}$ values from that study, do not preclude this general treatment of his data. Since the friction factor is practically independent of Reynolds number in the fully rough regime, these discrepancies are not expected to have a marked effect on the qualitative interpretation of Nunner's results.

Figs. 6 and 7 show that, when reduced according to the law of corresponding states, f_m in the laminar region is almost independent of the geometric details of the roughness elements and its profile with increasing Re_m is approximated by the smooth tube relation. In the turbulent regime, it is especially noticeable that, relative to the smooth tube data, the absolute increases in f_m are considerably smaller than can be inferred from the conventional f vs. Re plots (Fig. 2). This fully demonstrates that the marked enhancement factors, as is widely documented in the literature, are intimately associated with transition. For example, whereas Fig. 2 gives enhancement factors of about 17.5 and 20 for $e = 2.25$ and 3.75 mm and $Re = 50,000$, the corresponding $f_m/f_{m,s}$ ($= \phi_f$) values from Fig. 6 are about 5.8 and 4.5, respectively. In fact, on Figs. 6 and 7, the largest value for ϕ_f is no more than 10. And, further, it is quite evident that f_m depends solely on the geometric parameters of the roughness.

It should be noted that the $p/e = 9.8$ results for $e/D = 0.045$ and 0.075 (Fig. 6) are for the situation where a flow path (2.7 mm in width) was provided between the external circumference of the ring insert and the tube wall, while for $p/e = 9.8$ and $e/D = 0.1$, the disc-shaped inserts were rigidly supported to the inner surface of the tube with no

Figure 6. Similarity plot of f_m vs. Re_m using Koch's (1960) data.

Figure 7. Plot of f_m vs. Re_m using Nunner's (1956) data.

clearance. Also, in the case of Nunner's results (Fig. 7), the shape of the roughness elements and the number of such elements in a tube were additional parameters. For instance, with $e/D = 0.08$, the number of rings for $p/e = 10$ was double that for $p/e = 20$, while that for $p/e = 20$ was 4 times that for $p/e = 80$ with $e/D = 0.04$. For these reasons, it would be unwise to draw any definite conclusion concerning the trend with increasing e/D or p/e from Figs. 6 and 7.

From Fig. 6 or 7 the striking evidence is that the onset of the so-called fully rough regime is almost definite in character and in value, beginning right after the end of the transition region. In this regard the general features of these curves are remarkably similar to those presented by Nikuradse (1933) for the largest heights of sand-grain roughness (Fig. 8). In fact, even for the relatively small heights of roughness of that study, where the various curves progressively leave the smooth profile and where the points of successive departure vary with roughness height, it appears that the fully rough regime begins almost at the points at which the individual curves leave the smooth profile.¹ Although many of the curves exhibit maxima and minima, in line with some of the profiles reported by Nikuradse, the depressions are such that, in each case, the error around the mean value is small. The only exception to this consistent trend can be seen in Fig. 7 for $p/e = 3.92$ with $e/D = 0.1$ and 0.2 . These curves are characterized by more pronounced maxima and minima. No definite statement can be made at this point about these trends.

The assertion that different types of roughness exhibit the same general features is strikingly illustrated in Fig. 8, which is a comparison of the reduced results of Fig. 2 with the data of Nikuradse (1933). Given the structural differences between sand-grain roughness and repeated-rib inserts as well as the attendant effects on transition, it would

¹See, for example, H. Schlichting, *Boundary Layer Theory*, 7th ed., McGraw-Hill Book Company, N.Y., 1979, p. 617.

Figure 8. Nikuradse's sand-grain roughness vs. Koch's ring inserts.

be unwise to draw definite conclusions concerning the modest agreement that is evident from this figure in the turbulent regime. Nevertheless, the comparison is important in two respects. First, it provides clearer insight as well as possible explanation as to why it has been possible to correlate experimental data using the friction similarity concept advanced by Nikuradse. Second, it definitely confirms an observation that the law of resistance in the fully rough regime should be of a universal nature for all pipes (Obot, 1988). Here, the relevant feature is the dependence of f_m only on the geometric details of roughness, a trend that must also be expected for noncircular passages (Knudsen and Katz, 1950).

In summary, according to the law of corresponding states the reduced frictional pressure coefficients are essentially independent in laminar flow of, but are dependent in turbulent flow only on, the geometric parameters of roughness. In addition to establishing that the marked increases in friction factor are intimately associated with transition, the rather unique nature of the so-called fully rough regime has been isolated from similarity plots of f_m vs. Re_m .

3. ANALYSES OF HEAT TRANSFER IN FLOW PASSAGES

Prior to the presentation and discussion of the heat transfer data, there are two important comments. First, for each of the studies used in the following analysis, the bases for the comparisons and conclusions are the smooth duct data for the particular study. Since the original smooth tube data for some of the studies were not approximated by the Dittus-Boelter or Petukhov-Popov correlation, it can be readily appreciated that the reduced data may not follow either correlation. Second, in the absence of the appropriate temperatures for these studies, no attempt was made to incorporate the Prandtl number effect. As with the treatment of friction, this evaluation of the heat transfer

results is divided into two main sections, one dealing with smooth and the other with enhanced passages.

3.1 Smooth Passages.

The role of transition in determining heat transfer in passages is best illustrated using the modified empirical Filonenko correlation, equation (4), and the Petukhov and Popov (1963) correlation, equation (5)

$$f_m = (1.58 \ln \psi_R Re_a - 3.28)^{-2} \quad (4)$$

$$Nu_m = (f_m \psi_R Re_a Pr / 2) [1.07 + 12.7 (f_m / 2)^{1/2} (Pr^{2/3} - 1)]^{-1.0}. \quad (5)$$

Equations (4) and (5) are valid for circular and noncircular passages and, in the case of friction, the alternative form of equation (4) is verified in Fig. 1. It must be noted as a matter of particular importance that, by introduction of f_m and $Re_m = \psi_R Re_a$ into the well known Petukhov-Popov correlation, the fundamental flow similarity requirement for all passages is satisfied.

Clearly, for a given Re based on D_e and quite consistent with the general effect of aspect ratio (a_r) on friction factor (Obot, 1988), it is especially noticeable that Nu_m decreases with increasing aspect ratio. This is consistent with the results reported by several investigators (Drexel and McAdams, 1944; Washington and Marks, 1937). Likewise, for tubes of annular section which are characterized by $\psi_R < 1$, the Nu_m trend with increasing diameter ratio (β) is the same as noted above for rectangular channels, and this is definitely confirmed by the results of several researchers (Petukhov and Roizen, 1963; Koch and Feind, 1958). It is also quite apparent that as β and a_r approach zero and unity, respectively, the Nu_m values approach those for circular tubes, as might have been inferred from the general trend for ψ_R with increasing β or a_r (Obot, 1988).

Koch and Feind reported data for heat transfer and frictional pressure coefficients for $0.212 \leq \beta \leq 0.838$. The results for the latter were thoroughly discussed in Obot (1988). For heat transfer coefficients, laminar and turbulent data exhibit marked dependence on β , decreasing as β is increased. Allowing for the fact that the critical Reynolds number increases with diameter ratio, their results have been re-analyzed and the Nu_m vs. Re_m plots are given in Figs. 9 and 10. To obtain the corrections for the data of Fig. 9, the critical Reynolds numbers given in the paper cited above (c.f. Table 4) were used along with the rounded value of 2,100 for a circular tube. For Fig. 10, $Re_{c,r} = 2719$ and this was extracted from the original paper.

For Figs. 9 and 10, although the results with and without the central core are almost indistinguishable, it may be noted that the data of Fig. 9 are about 25% higher than, while those for the latter figure are closely approximated by, equation (5). Fig. 10 indicates that, to calculate heat transfer coefficients for ducts of arbitrary shapes, equation (5) can give satisfactory results provided the appropriate critical parameters (ψ_f, ψ_R) are used to account for the role of transition. The closeness with which the data for all β are approximated by a single regression line also supports the view that heat transfer coefficients decrease with increasing $Re_{c,a}$. The trend on Fig. 9 also establishes the importance of determining the $Re_{c,r}$ value for any particular duct geometry.

For triangular passages, $\psi_R > 1$ and Re_m increases with increasing h/b (or with decreasing apex angle in the case of isosceles ducts) for a given Reynolds number based on D_e . Consequently, Nu_m values can be substantially greater than for circular, rectangular or annular geometry with the same Reynolds number. For instance, using the α (apex angle) = 38.8° data of Carlson (1959) which gives $\psi_R = 1.197$ and for $Re = 80,000$ (i.e. $Re_m = 95,760$), the calculated Nu_m is about 163, which is about 15% higher than with a circular tube. Infact, for the same Re , the calculated value for the narrowest, $\alpha =$

Figure 9. Nusselt number (Nu_m) vs. Re_m for smooth annuli.

Figure 10. Nusselt number (Nu_m) vs. Re_m for smooth annuli.

4.01° passage ($Nu_m = 196$) is about 40% and 60% higher than for a cylindrical and rectangular ($a_r = 10$) geometry, respectively. The common basis for these calculations is $Pr = 1$. This observation of great practical importance, though clearly at variance with the heat transfer results of Eckert and Irvine (1960) or Tokarev (1979), is not altogether surprising for several reasons. In the first place, to maintain a fixed Reynolds number (based on D_e) the average flow velocity must rise with increasing h/b , due to the reduction in flow area. And, further, the critical Re attains its lowest value for these narrow passages (Obot, 1988) and, even at such relatively low Re , the coexistence of laminar and turbulent flow (Eckert and Irvine, 1956; Bandopadhyay and Hinwood, 1973) should cause a marked improvement in heat transfer over that for completely laminar flow.

In summary, details such as those provided in this section, though totally obscured by the straightforward application of the Reynolds number similarity as well as insufficient understanding of the role of transition, are of considerable importance in several respects. First, they establish that the attainable friction factors and turbulent heat transfer coefficients in passages are determined largely by transition. For heat transfer the simple rule amounts to this: the lower the critical Reynolds number for transition, the greater the turbulent heat transfer coefficients. This provides the first concrete evidence that a comparative evaluation of the thermal performance of surfaces can be made simply from knowledge of the critical Re for transition. And, second, there are clear indications that, for a given Reynolds number based on D_e , heat transfer coefficients may be greatest in triangular passages, lowest for ducts of annular or rectangular geometry, with intermediate values for circular tubes. It remains, however, to generalize the role of transition by considering other flow situations and this will be considered in the

following sections.

3.2 Rough Passages.

Having discussed the general treatment of friction in rough passages, attention is now directed to heat transfer enhancement, a problem that has been studied quite extensively for well over half a century. Reviews of some aspects of the widespread literature have been carried out by several researchers (Rabas, 1989; Webb, 1987; Ravigururajan and Bergles, 1986; Dalle Donne and Meyer, 1977). The general view is that varying degrees of improvement can be realized with roughness. For instance, for tests with air, the improvements in heat transfer are rarely more than a factor of five (Koch, 1960). It was established in the preceding section that there exists a definite connection between transition and heat transfer in smooth passages. On the basis of such a complete treatment, it is reasonable to question whether a similar link exists for rough passages. The answer to such a question is the subject of this section.

As with enhanced tube friction, we begin the discussion by considering Koch's complementary heat transfer data for the friction results of Fig. 2, and these are reproduced on Fig. 11. From this figure, the most obvious conclusion is that Nu_r is not significantly affected by the variation in e/D . For $Re > 10,000$, the enhancement factors, $\phi_h (= Nu_r/Nu_s)$ are roughly constant for a given e/D , and can be stated as 1.98 and 2.23 for $e = 2.25$ and 3.75mm respectively. Since these ratios are much lower than the corresponding friction factor ratios of Fig. 2, and since no meaningful conclusions can be reached from such comparisons, these ϕ_h values must be viewed in light of the results on Fig. 6. In this connection it is of some interest to note that, in each case, ϕ_h is no more than one-half the friction factor ratio, $\phi_f (= f_m/f_{m,s}; f_{m,s} = \text{smooth tube value})$. We will elaborate on this later. Although there are no large differences between the heat transfer results for the two roughness heights, the consistent trend in the turbulent

Figure 11. Effect of e/D on Nusselt number according to Koch (1960).

region is that the results for $e = 3.75\text{mm}$ are higher than for $e = 2.25\text{mm}$, in line with the depression of the onset of transition.

In order to gain clearer insight into the influence of transition on heat transfer, and in line with the presentation of Fig. 9 or 10, some of the results of Koch for which the critical Reynolds numbers were determined precisely have been re-analyzed and these are shown on Fig. 12 where Nu_m is plotted against the reduced Reynolds number, Re_m . It should be emphasized that as with Fig. 9 or 10, the correction has been applied only to the familiar Reynolds number. The $e = 2.25$ and 3.75mm results of Fig. 11 correspond to those for $e/D = 0.045$ and 0.075 , respectively, and these are almost coincident with the smooth tube data. For the moment, the fact that some of the reduced data lie moderately above and below the smooth tube data does not matter, since the transition parameter (ψ_R) is based on isothermal friction data. Although the fact that ψ_R varies according to whether the fluid is being heated or cooled will be considered in Section 4, it should be emphasized that whatever might be the effects of heat transfer on ψ_R , these must be more pronounced for rough than smooth passages.

The general trends on Fig. 12 imply several things, virtually all of which are not easily predicted from much that has been written on the subject of convective heat transfer. That the reduced data with roughness cluster around the smooth tube data, with an average error of under 20%, fully demonstrates that the marked increases in heat transfer coefficient are intimately associated with transition to turbulence. Second, it suggests that heat transfer coefficients can be predicted from the smooth tube relation provided the critical Reynolds numbers are known precisely. Third, from the critical Re data of Table 1 and Fig. 12 it is easily established that the fundamental law, which asserts that the lower the critical Reynolds number, the higher the heat transfer coefficient, is satisfied for all cases. Finally, the law of corresponding state dictates that, in the

Figure 12. Nusselt number (Nu_m) vs. Re_m using Koch's (1960) data.

turbulent regime, there should be almost no departure from the conventional Reynolds number dependence for smooth tubes, and this has been carefully documented by numerous researchers (Knudsen and Katz, 1950; Koch, 1960; Gomelaury, 1964; Savage and Myers, 1963).

Figs. 13 and 14 which are alternative representations of the results of Nunner (1956) and Blackwelder and Kreith (1970) complement one another in that, unlike the use of ψ_R values deduced from isothermal friction factor data, the ψ_R values for these results were determined from the heat transfer data. In principle, this would be one of the preferred methods for determining ψ_R because it eliminates its dependence on heat transfer (heating or cooling) and temperature. The difficulty, however, is that when $Re_{c,r}$ is unusually low, as was the case with some of Koch's test conditions, it becomes almost impracticable to obtain accurate heat transfer coefficients at such low flow rates. Whereas Nunner used repeated-rib inserts (Table 1), Blackwelder and Kreith tested twisted tape inserts and the relative lengths (p_t/D), where p_t is the length required for a 360° rotation of the tape, are given on Fig. 14. In each case, it may be noted that virtually all of the reduced data lie in a band about $\pm 15\%$ around the smooth tube data, fully supporting the view that good estimates of average heat transfer coefficients can be made provided the critical Re for transition is known.

Another study uncovered during the exhaustive literature search, that by Knudsen and Katz (1950), dealt with heat transfer and pressure drop in annuli with transverse fins. The significance of this study relates to the use of water as the working fluid, in contradistinction to the air studies of Figs. 12-14. Another distinction between the air and water studies relates to the use of annular passages instead of circular tubes, inasmuch as the analysis should provide at least partial verification of the law of corresponding states for rough passages of complex shapes. In this connection it may be noted that

Figure 13. Nu_m vs. Re_m using Nunner's (1956) data.

Figure 14. Nu_m vs. Re_m using data of Blackwelder and Kreith (1970).

Figure 15. $(Nu_m/Pr^{0.4})$ using data of Knudsen and Katz (1950).

Smith and Gowen (1965) reported very limited results for high Prandtl number fluids, but the friction factor trend does not appear to be demonstrative.

Since the smooth duct relative entrance length (L_e/D_e) of Knudsen and Katz was 31.0, not sufficiently long to give fully developed flow for their well-rounded entrance, and since the critical Re was about 1770, it was necessary to establish a reference fully developed flow value for a passage of $\beta = 0.278$. Using isothermal friction factor results presented in Fig. 7 of their paper, this reference $Re_{c,r}$ was estimated to be 2989, and it corresponds to the value at which the critical friction factor attains the smooth duct value of 0.008. It may be noted that the above $Re_{c,r}$ value is not significantly different from that ($Re_{c,r} = 2873$) determined from the results of Koch and Feind (1958) for $\beta = 0.212$ and $L_e/D_e = 50$ (Obot, 1988). The reduced data for the smooth and finned tubes are presented in Fig. 15. In the absence of the Pr value for each test trial, the ordinate ($Nu_m/Pr^{0.4}$) is the same as in the original paper. Again, the outcome of the analysis is essentially the same as charted already in Figs. 12-14, with about a $\pm 20\%$ spread around the authors' smooth tube data.

It is quite evident that, in each of Figs. 12-15, the reduced data lie above and below the smooth tube line. From a careful analysis of the results presented in Koch (1960) for a range of conditions, it appears that the reduced data may lie well below the smooth data for certain values of $Re_{c,a}$. Whether there exists a definite $Re_{c,a}$ range below which the Nu_m data would deviate markedly from the smooth tube curve, or how far down the Reynolds number scale such a value may occur, is difficult to ascertain from the results available. Suffice it to state that the existence of such a limiting critical Reynolds number would not in any way weaken the general conclusion regarding the decisive role of transition. Bearing in mind that the ratio Nu_m/Nu_s will always vary from slightly above to below unity, such information may be useful in the assessment of

the thermal efficiency of various geometries of roughness.

To shed further light on the connection between transition, friction and heat transfer, the results of several investigators are presented differently on Figs. 16-18. The first of these is a plot of $\phi_{h,max} = (Nu_r/Nu_s)_{max}$ versus the critical parameter $\psi_R (= Re_{c,r}/Re_{c,a})$, while $\phi_{h,max}$ is plotted against $\phi_f (= f_m/f_{m,s})$ on Fig. 17. On Fig. 18 the ordinate $(\phi_{h,max}/\phi_f)$ is equivalent to the so-called efficiency index (Webb et al., 1971; Gee and Webb, 1980), with ψ_R as the abscissa. Naturally, since the smooth duct friction factor $(f_{m,s})$ decreases with Re_m for turbulent flow, with a nearly constant f_m for a given set of roughness geometry, an arbitrary value of $Re_m = 50,000$ was used for calculations of ϕ_f . In going from $Re_m = 50,000$ to $Re_m = 100,000$, $f_{m,s}$ changes by no more than 20%; hence the use of the latter Re_m value does not modify the observations to be drawn from these figures. To generate the results of Watkinson et al. which are given in Fig. 16, the turbulent flow heat transfer data of an earlier study (Watkinson et al., 1973) were matched tube by tube with the data of Table 1. Although the earlier study was carried out with water, the use of isothermal ψ_R data obtained on the same tubes with oil (Table 1) is not expected to alter the general picture to any significant extent (Dodge and Metzner, 1959). Since $Nu_m/Nu_s \rightarrow 1$ (Figs. 12-15), it was considered more practical to define $\phi_{h,max}$ using Nu_r and Nu_s .

The general picture on each of Figs. 16-18 may appear somewhat confused at first, but such confusion almost disappears as soon as the results of any particular study are viewed separately. Thus, with respect to the results of Koch or Knudsen and Katz, the trend on Fig. 16 supports the view that $\phi_{h,max}$ increases with increasing ψ_R , paralleling the trend established in Fig. 3 for the variation of ψ_R with e/D . Another consistent trend is that the various finned surfaces give $\phi_{h,max}$ and ϕ_f values that are generally lower than those with transverse repeated-rib roughness. Also, although there is no

Figure 16. Maximum enhancement factor, $\phi_{h,max}$ vs. ψ_R .

Figure 17. Variation of $\phi_{h,max}$ with $\phi_f (= f_m/f_{m,s})$.

Figure 18. Plot of $(\phi_{h,max}/\phi_f)$ vs. ψ_R .

clear distinction between high (HSF) and low (LSF) spirally finned tubes of Watkinson et al., the data suggest that either of these is superior to high straight (STF) finned tubes. It should be emphasized that, unlike the definite trend exhibited by the data of Knudsen and Katz for tests on five ducts with $L_e/D_e \geq 41$ and one with $L_e/D_e = 33$ (Table 1), the results of Watkinson et al. are marred by a residual effect of L_e/D_e .

Whereas Fig. 16 reinforces the closeness between the $\phi_{h,max}$ values of Nunner and those of Koch as well as the possible measurement errors of the critical Reynolds number for rough tubes, as discussed in Section 2.2, Fig. 17 shows that any such errors are almost cancelled out when the results are presented in terms of $\phi_{h,max}$ and ϕ_f . It is pertinent to note that, since Nunner defined the resistance coefficients similarly for both smooth and rough tubes, the ratio (ϕ_f) so formed is independent of his definition and is analogous to the usual friction factor ratios. It is quite remarkable that, with the present method, it has been possible to compare two of the most important studies in the literature.

Figs. 17 and 18 show some scatter, but nothing that is unexpected considering the differences between the three studies, the lack of geometrically similar test conditions and of knowledge of the effect of heat transfer on transition. It is of considerable importance to note that $\phi_{h,max}$ attains a value of no more than 5 for $1 < \psi_R \leq 12$ and $1 < \phi_f < 9$ (Figs. 16 and 17). As to whether there should be a unique relation between f_m and Num or between $\phi_{h,max}$ and ϕ_f ; although no relation of a universal nature can be established from Fig. 17, the trend on this figure clearly suggests that a definite relation might result from systematic measurements.

From Fig. 18 a condition of remarkable simplicity can be stated as follows:

$$\phi_{h,max} \geq \frac{1}{2}\phi_f \quad \text{or} \quad \frac{\phi_f}{\phi_{h,max}} \leq 2. \quad (6)$$

This condition, which bears a striking similarity to the well known Reynolds analogy

except of course for the sign, is satisfied by almost all but four data points. Three of these are Nunner's data, and this is most likely due to errors in ψ_R (since $\phi_f = f_m/f_{m,s}$ and $f_m = \psi_R f_a$). The other point, due to Koch, does not lie far below the 0.5 line. It is of some interest to note that, in terms of the reduced parameter ($\phi_{h,m} = Nu_m/Nu_s \rightarrow 1$), the above condition is: $\phi_{h,m}/\phi_f \geq 1/5$ or $\phi_f/\phi_{h,m} \leq 5$.

Contrary to the numerous claims regarding the magnitudes of the improvements in heat transfer, the discussion here makes it clear that the maximum increase in heat transfer is limited by ϕ_f , the value of which is determined by the depression of the critical Reynolds number. So, for the first time, a definite upper limit has been established for the ratio $\phi_f/\phi_{h,max}$. It is also especially noticeable that most of the data on Fig. 18 lie in the $0.5 \leq \phi_{h,max}/\phi_f \leq 1$ range. Interestingly, according to the results of Knudsen and Katz, $\phi_{h,max} \simeq \phi_f$ (Fig. 18), which clearly suggests that helically finned tubes may be more effective than transverse repeated-rib roughness for the same ψ_R . Further studies are clearly needed to establish these trends precisely.

In summary, it is quite evident that the difficulty in reconciling the results of numerous investigators is not to be explained solely by any peculiarity of the duct cross-section or configuration of roughness tested. It has indeed been established that differences among the various results arise from transition, a phenomenon which hitherto has been almost overlooked in the general treatment of friction and convective heat transfer. The presentation in this section has provided at least partial understanding of the connection between transition and heat transfer. The proposed law of corresponding states has the peculiar advantage that it affords, even over the widest range of geometric and flow conditions, a consistent basis for comparison of data obtained on enhanced

passages.

3.2.1 Transition-Based Similarity Parameter Vs. Roughness Reynolds Number.

The friction similarity concept for rough pipes was developed by Nikuradse (1933) and successfully used to correlate his data for sand-grain roughness. For similarly roughened tubes, Dipprey and Sabersky (1963) also derived essentially the same expression and extended the treatment to heat transfer. Thereafter, researchers (Webb et al., 1971; Han et al., 1978; Withers 1980a,b; to mention a few) have correlated their heat transfer data using this concept. For rough passages, it has been the practice to use the roughness Reynolds number (e^+) which is given by equation (7) to correlate heat transfer data:

$$e^+ = Re_a(e/D)(f_a/2)^{1/2} \quad (7)$$

With the knowledge that the conventional Reynolds number is not a generally valid similarity parameter, as thoroughly documented in the preceding sections, one possible modification to equation (7) is to replace Re_a and f_a by $Re_m = \psi_R Re_a$ and $f_m = \psi_f f_a$, respectively, to obtain:

$$e_m^+ = Re_m(e/D)(f_m/2)^{1/2} \quad (8)$$

To fully appreciate whether such a modification can be applied satisfactorily to rough passages, several observations must be made. First, for a given e/D , f_m assumes almost a constant value for $Re_m > 2,100$, hence e_m^+ will always be directly proportional to Re_m . In this regard it is important to note that f_m is dependent only on the geometric configurations of roughness for $Re_m > 2,100$. However, in the laminar regime, f_m is inversely proportional to Re_m but is essentially independent of e/D or other geometric parameters of roughness; hence $e_m^+ \propto \sqrt{Re_m}$. And, further, since transition appears to

be the main mechanism which determines friction and heat transfer in passages and since its effects should be almost totally accounted for by introduction of the parameters ψ_R and ψ_f , it should be possible to establish an equivalent form of equation (7) only in terms of f_m and Re_m . These considerations raise considerable doubts about the wisdom of retaining e/D in equation (8).

Since e^+ is obtained by simply grafting on the ratio e/D to the result of a force balance relation, it seems more logical to eliminate e/D totally from equation (8). Using the fact that $2\pi r\tau_w = (dP/dx)\pi r^2$ and $f = (dP/dx)(D/2\rho\bar{V}^2)$, it is easily established that

$$Re\sqrt{(f/2)} = U_\tau D/\nu = Re_\tau \quad (9)$$

where the friction velocity $U_\tau = (\tau_w/\rho)^{1/2}$ and τ_w = wall shear stress. The so-called roughness Reynolds number is obtained by multiplying equation (9) by e/D . Consistent with the general treatment of friction in smooth passages, the modified form of equation (9) which satisfies the basic requirement for flow similarity is given by:

$$Re_m\sqrt{(f_m/2)} = Re_{\tau m} \quad (10)$$

The significance of equation (10) must not be overlooked. In the first place, Re_m in turbulent flow is directly proportional to the friction Reynolds number, $Re_{\tau m}$; an indication that when sets of data are plotted against $Re_m (= \psi_R Re_a)$ and against $Re_{\tau m}$, the two plots should be fully equivalent, regardless of whether the results were obtained on smooth or rough passages. Second, it reinforces the dependence of the friction velocity and hence the wall shear stress on the critical parameters for transition. Third, it provides a straightforward means for determining the friction Reynolds number from which the wall shear stress can be calculated.

To shed some light on the use of these parameters ($Re_m, Re_{\tau m}, e^+$ and e_m^+), one

approach would be to attempt to correlate results of systematic experiments using each of these definitions. This method is not adopted here for two reasons: first, it obscures the physical situation; and, second, our main interest at this stage is to fully establish the role of transition to turbulence which, hopefully, should lead to better understanding of the transfer processes. Instead, straightforward calculations of the Stanton number ratio (St_r/St_s ; r = rough, s = smooth) were made using the results of Koch (1960) for transverse disc-shaped and ring inserts. Note that some of these results were presented as Nu_m vs. Re_m on Fig. 12.

In Figs. 19-24, the heat transfer results of Koch are presented differently for a range of height-to-diameter (e/D) and pitch-to-height (p/e) ratios. Since Koch's study covered moderate as well as unusually high values of values of e/D and p/e (Table 1), two distinct trends resulted from the present analysis. Accordingly, and for the sake of clarity, Figs. 19-22 show results for moderate geometric parameters while those for high e/D and p/e are given in Figs. 23 and 24. For Figs. 19-22, the abscissa corresponds to Re_m , $Re_{\tau m}$, e_m^+ and e^+ , successively, while plots of Stanton number ratio versus Re_m and $Re_{\tau m}$ are presented in Figs. 23 and 24, respectively. To compute Re_m , $Re_{\tau m}$ or e_m^+ , the appropriate critical parameters and the f_m data in Section 2.2 were used.

To begin the discussion, attention may be turned to Figs. 19-22 where comparison from figure to figure reveals one basic difference between Re_m or $Re_{\tau m}$ and e^+ or e_m^+ . Fig. 19 shows that St_r/St_s is almost independent of e/D or p/e for $Re_m < 6,000$, a fact that is also strikingly illustrated in Fig. 20 for $Re_{\tau m} < 1,000$. By contrast, the effect of e/D is quite evident from the comparison of the $p/e = 9.8$ results for $e/D = 0.045$ and 0.075 (Figs. 21 and 22). In the case of e^+ , the trend on Fig. 22 is consistent with previous results (Webb et al., 1971; Dawson and Trass, 1972). Clearly, there is no advantage to using e_m^+ instead of e^+ . This arises from the fact that, although Re_m is greater than Re ,

Figure 19. Stanton number ratio vs. Re_m .

Figure 20. Stanton number ratio vs. $Re_{\tau m}$.

Figure 21. Stanton number ratio vs. e_m^+ .

Figure 22. Stanton number ratio vs. e^+ .

f_m is generally lower than the conventional friction factor f_r . The result is that there are no large differences in the calculated values between e_m^+ and e^+ . Thus, Fig. 21 is nearly identical to Fig. 22. Given the general trend displayed here in Figs. 19-22, it is difficult to make a strong case in favor of the continued use of the conventional roughness Reynolds number. On the contrary, the use of the modified friction Reynolds number has the peculiar advantage that, over a wide range of geometric conditions, the reduced data are almost generalized.

Of the common features on Figs. 19-22, one is that a profile for St_r/St_s passes through a maximum in some range of Re_m , $Re_{\tau m}$, e_m^+ or e^+ . In the case of Re_m , it is especially noticeable that this maximum occurs between $Re_m = 5,000$ and $15,000$ which, expressed in terms of the conventional Reynolds number (Re), corresponds to between $Re = 3,000$ and $7,000$. For St_r/St_s vs. e^+ , the existence of peak values in these profiles can be inferred from the results of the two studies that are cited in the preceding paragraph. Another feature is that, beyond the locations of the peak values, the spread around a mean line is on the order of 25%. And, further, although the effect of e/D is more pronounced in Fig. 21 or 22 than on Fig. 19 or 20, it is quite evident that St_r/St_s is almost independent of p/e up to e_m^+ (or e^+) = 1,000.

In Figs. 23 and 24, which show results obtained with large values of e/D and/or p/e , St_r/St_s values are plotted against Re_m and $Re_{\tau m}$, respectively. With these data, since the effects of e/D were even more pronounced in plots using e_m^+ and e^+ than those on Figs. 21 and 22, such plots are not given. As with Figs. 19 and 20, Figs. 23 and 24 are completely similar. It is of some interest to note that, in sharp contrast to the trends on Figs. 19-22 for moderate geometric parameters, the results on Fig. 23 or 24 show no definite maximum. In Section 3.2, it was noted that, for some range of geometric conditions, the reduced data of Koch were closely approximated by the

Figure 23. Stanton number ratio vs. Re_m .

Figure 24. Stanton number ratio vs. Re_{tm} .

smooth tube relation (Fig. 12), but that such a resolution was not realized for some of the test conditions. This fact is seen more clearly here from comparisons between Figs. 19 and 23 or Figs. 20 and 24.

From the foregoing comparison and discussion, it is quite clear that the choice is between Re_m and $Re_{\tau m}$. Of these two, Re_m is much to be preferred for two reasons. The first relates to simplicity, inasmuch as the critical Reynolds numbers ($Re_{c,r}$ and $Re_{c,a}$) and Re_a are all that are needed to compute Re_m . By contrast, to compute $Re_{\tau m}$, all critical parameters ($Re_{c,r}$, $Re_{c,a}$, $f_{c,r}$ and $f_{c,a}$) as well as f_a and Re_a must be known. A second reason concerns engineering practice. Since Re_m is simply the product of the conventional Reynolds number and the ratio of the critical Reynolds numbers, there is absolutely no difficulty with its use in practice. Given the amount of information that is needed to compute $Re_{\tau m}$, it can be readily appreciated that the same is not true of $Re_{\tau m}$.

In summary, this comparative evaluation reinforces the significance of the corresponding states law as well as the role of transition in determining heat transfer in enhanced tubes. Specifically, it has been demonstrated that, in terms of Re_m or $Re_{\tau m}$, the Stanton number ratios for a range of p/e and e/D can be represented by a single regression line. Also, there are clear indications that the Stanton number ratio profiles attain peak values over the range of Reynolds numbers between 3,000 and 7,000 for small and moderate values p/e and e/D .

4. FLUID HEATING VERSUS COOLING

Certainly, an analysis of the role of transition on heat transfer will be incomplete without a discussion of the effects of heating and cooling of a fluid for several reasons. First, just as the Reynolds number arises naturally from dimensional analysis on the

equations of motion, a similar treatment of the energy equation gives rise to the Prandtl number, Pr . Second, it is widely reported in the literature that the dependence of Nusselt or Stanton number on Pr varies according to whether the fluid is being heated or cooled. Third, in addition to the Pr dependence, many correlations include a viscosity (or temperature) ratio as suggested by Sieder and Tate (1936) based on an analysis of oil data for $Re \leq 2100$. That the validity of the Reynolds number similarity concept is determined by transition was demonstrated for friction (Obot, 1988) and reinforced here. It is, therefore, natural to suppose that a similar situation might occur for Prandtl number.

Although this presentation is intended to provide information that is little more than qualitative, due largely to lack of experimental data for tubes, it should nevertheless be sufficient to show that the limit of stability, and hence the critical Reynolds number, depends on whether a fluid is being heated or cooled. Of considerable importance to the present consideration is the well known fact that the stability of a boundary layer is determined largely by the curvature of the velocity profile at the wall. At the wall, the streamwise equation of motion reduces to:

$$\mu_w \left(\frac{d^2 U}{dy^2} \right)_w = - \left(\frac{dU}{dy} \right)_w \left(\frac{d\mu}{dy} \right)_w + \frac{dp}{dx} \quad (11)$$

Using the fact that $(dU/dy)_w = \tau_w / \mu_w$ and $\tau_w = (dp/dx)(A/P_w)$, equation (11) becomes:

$$\left(\frac{d^2 U}{dy^2} \right)_w = - \frac{1}{\mu_w} \frac{dp}{dx} \left[\frac{A}{P_w \mu_w} \left(\frac{d\mu}{dy} \right)_w - 1 \right] \quad (12)$$

Since $(A/P_w \mu_w)(d\mu/dy)_w \gg 1$, at least for air and water, equation (12) can be approximated by:

$$\left(\frac{d^2 U}{dy^2} \right)_w = - \frac{A}{P_w \mu_w^2} \frac{dp}{dx} \left(\frac{d\mu}{dy} \right)_w \quad (13)$$

When a gas is heated ($T_w > T_f$): $(\partial T / \partial y)_w < 0$, $(d\mu/dy)_w < 0$, and the curvature of the velocity profile is positive. On the other hand, $(\partial T / \partial y)_w < 0$, $(d\mu/dy)_w > 0$ and

$(d^2U/dy^2)_w$ is negative for a liquid. It follows that the limit of stability or the critical Reynolds number may be higher for a liquid than for a gas when $T_w > T_f$. However, since viscosity decreases as the temperature rises for liquids, but increases with increasing temperature for gases, it is quite evident that the above situation is reversed when $T_w < T_f$, i.e., the limit of stability for a liquid is lower than for a gas. These observations, which are definitely confirmed by numerical calculations on boundary layers with air and water by Cebeci and Smith (1968) and Wazzan et al. (1968) respectively, should also be applicable to flows in channels. The calculations by the latter also indicated that the critical Reynolds number increased markedly with T_w , reached a maximum around $T_w = 60^\circ\text{C}$ with $T_f = 15.6^\circ\text{C}$, and decreased gradually as T_w was increased beyond the maximum value.

From the above discussion and that in Section 3.2, the general picture can be summed up as follows: average heat transfer coefficients should be higher for heating than cooling of gases while heating of a liquid should give coefficients that are lower than for cooling. This observation is not entirely consistent with the usual empirical treatment which, with a fixed exponent on Reynolds number, gives $Nu \propto Pr^n$, where $n = 0.4$ and 0.3 are widely quoted for heating and cooling, respectively. In this regard, the existing literature on heat transfer in channels is not particularly useful partly because of the almost total neglect of the laminar and transition regions and partly because, even when measurements did cover these regions, the results are not sufficiently accurate to permit precise determination of the critical parameters. From a careful study of the available results, the following observations can be made. For water (Knudsen and Katz, 1950), the critical Reynolds number with heating can be significantly higher than without heating, a trend that is consistent with stability calculations. For air, whereas the inference from the results of Koch or Nunner is that heating can lower the critical

Re, as might be expected, Washington and Marks (1937) reported exactly the opposite trend. Clearly studies with liquids and gases are needed before the correct picture can be established.

It must not be inferred, however, that if $\tau_w = -(A/P_w)(dp/dx)$, the conclusions drawn above will remain unchanged, for obviously, since the curvature of the velocity profile is controlled by the pressure gradient, these observations will be modified when there is a favorable ($dp/dx < 0$) gradient. Thus, when $\tau_w = -(A/P_w)(dp/dx)$, heat transfer coefficients should be greater for cooling than for heating of a gas, while the trend should be exactly the opposite for liquids. So, the effect of heat transfer on transition, a problem which has received very meager treatment in the past, is quite complicated and certainly deserves further studies.

In conclusion, our view is that the dependence of heat transfer coefficient on Prandtl number, if any, and like that on flow velocity, should be definite for both heating and cooling. Any departure from such a unique Prandtl number effect, such as the inclusion of viscosity or temperature ratio, has its origin in the differences in heat transfer coefficients that are brought about by variations in the critical parameters for transition. In this regard, the reader is probably aware of the fact that, even in the case of smooth passages, a temperature (or viscosity) ratio is often used to reconcile differences between isothermal and nonisothermal friction factors (Campbell and Perkins, 1968). As with heat transfer, this is a manifestation of the influence of transition, for obviously differences in friction factors can only be brought about through changes in the onset of transition.

5. DISCUSSION

In this report, efforts have been made to clarify and to explain the role of transition in determining friction and convective heat transfer in flow passages. That transition has a decisive influence on convective heat transfer and certainly paints a good picture of the process should not be altogether surprising. In the first place, it has been documented in virtually every text on the subject (see, for example, McAdams, 1942) and it is almost of universal knowledge that a marked increase of heat transfer coefficient with flow velocity occurs only after the onset of transition. In other words, as with friction, there are two fundamentally different trends for heat transfer due to transition. And, second, studies on the effect of free stream turbulence indicate that an increase in turbulence intensity causes earlier transition and this appears to be the physical phenomenon responsible for the corresponding increase in heat transfer coefficients (Kestin and Maeder, 1957; Kestin et al., 1961). Indirect support for this view comes from the work of Dryden (1953) who carefully re-analyzed the critical Reynolds number results for a single roughness element on a flat plate at zero incidence and different free stream turbulent intensities. He showed that, when plotted as $Re_{c,r}/Re_{c,s}$ (c,r = rough, c,s = smooth) versus e/δ_1 (δ_1 = boundary layer displacement thickness at the element), the results with different intensities of turbulence were completely generalized, being a function of the single parameter e/δ_1 . So, the effect of roughness on transition is analogous to that of free stream turbulence. Strangely enough, although a lot is known about transition, there has been almost no systematic analysis of its role on heat transfer, and, until recently, no general treatment of its influence on friction has been made.

The numerous observations on the dependence of heat transfer coefficients on the critical parameters for smooth and rough passages can best be integrated with the help of Fig. 25. This figure contains the same information as Fig. 5 but with one exception, that

Figure 25. Generalized plot of ψ_f vs. ψ_R for smooth and rough passages.

is, the inclusion of a few results for smooth rectangular, annular and triangular passages as well as the three data points obtained by Hartnett et al. (1962) with a smooth entrance. This additional information was determined from tabulations in a previous paper (Obot, 1988). Since ψ_f (i.e. $f_{c,r}/f_{c,a}$) is almost unity for all smooth passages, these data are located along $\psi_f = 1$. For clarity, the data have not been identified according to the aspect, diameter or height-to-base ratio. It is important to note, however, that the focal point on this figure is $(\psi_f, \psi_R) = (1,1)$ and this corresponds to a reference condition with $f_{c,r} = 0.008$, $Re_{c,r} = 2,100$. The aspect (or diameter) ratio of the smooth passage is increasing with decreasing ψ_R , while the triangular duct height-to-base ratio is increasing monotonically with ψ_R , from this focal point.

In terms of (ψ_f, ψ_R) , the parametric description of the heat transfer process amounts to this: heat transfer coefficients are higher than smooth circular tubes for $\psi_f < 1$ and $\psi_R > 1$, while the trend is exactly the opposite for $\psi_f > 1$ and $\psi_R < 1$. It is especially noticeable that smooth triangular passages produce an effect on transition ($\psi_R > 1$) which is similar to that due to roughness, fully supporting the conclusions in Section 3.1 on the smooth duct heat transfer trends. In this report, the situations: $\psi_f \leq 1$, $\psi_R \geq 1$ have been addressed satisfactorily. The rather unique condition, $\psi_f > 1$ and $\psi_R < 1$, is a special case and this corresponds to the situation where special precautions are taken to delay transition. Relative to the reference, $(\psi_f, \psi_R) = (1,1)$, no improvements in heat transfer should be expected for $\psi_f > 1$ and $\psi_R < 1$, and this has been confirmed by numerous results (Liu et al., 1988; Matthys et al., 1987). We are therefore led to the first general law of convective heat transfer which, simply stated, amounts to this: to alter the existing heat transfer for a given set of conditions, be it in the direction of higher or lower rates, it is necessary to change the critical Reynolds number or critical friction factor for transition. In passing, it is of interest to note that the data of Hartnett et al.

for a very smooth entrance do not lie far from the line obtained by the extrapolation of equation (3), suggesting that, if systematic measurements were made, a unique relation between ψ_f and ψ_R may exist for all situations where the onset of transition is effected artificially.

In general, the conditions of the local flow over roughness elements depend, to a large extent, only on the geometric details of the elements. For transverse protrusions or grooves, the dominant features are separation and reattachment, while visual studies have confirmed the existence of flow rotation and separation for spirally-ridged surfaces. From much that has been presented so far, it is quite evident that the geometric parameters of roughness, in determining the prevailing local flow conditions, also produce a global effect on transition, in a manner that is consistent with the well established influence of single and two-dimensional roughness in incompressible boundary layer flows (Schlichting, 1979). Although it is by now conclusive that transition to turbulence is the main physical phenomenon which determines the attainable friction and average heat transfer coefficients, the question as to whether it also determines the complex local heat transfer trends in rough passages may appear at first to be open to conjecture. But, since average heat transfer coefficients are simply the area integrated values of the local coefficients, it is reasonable to expect that transition would play a decisive role on the local trends. Studies with smooth and rough cylinders support this view (Kestin and Maeder, 1957; Achenbach, 1977; 1975).

Another general comment deals with the conventional Reynolds number similarity which, until recently, has been the sole basis for determining whether two or more channel flows are similar. It was demonstrated conclusively that this requirement, which asserts that flows having the same Reynolds number must be similar, is valid only when the critical friction factor and critical Reynolds number for transition are the same,

but totally breaks down if the latter conditions are not satisfied (Obot, 1988). The connection between transition and flow similarity, which is also covered thoroughly in this paper, should be considered for all flows (boundary layers, cross-flow over tube banks, etc.) that are characterized by transition from laminar to turbulent motion. For rod bundles, the critical Reynolds numbers are significantly lower than the smooth tube values (Rehme, 1973) and the prevailing heat transfer coefficients are also determined by transition. In the case of boundary layers, since the flow development on a wind tunnel model can be markedly different from that on a full scale unit, at least insofar as the onset of transition is concerned, the results in this report make it perfectly clear that application of the law of corresponding states may be central to a proper interpretation of experimental data as well as scale-up.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The determination of the role of transition on friction and convective heat transfer, which was the objective of this study, has been to a considerable extent accomplished satisfactorily. The most important observations are as follows:

1. The onset of transition to turbulence determines the attainable friction and heat transfer coefficients in smooth and rough passages.
2. According to the frictional law of corresponding states, different types of roughness exhibit the same general features at the same reduced conditions. The onset of the fully rough flow regime is almost definite in value and character, beginning at about $Re_m = 1.3Re_{m,c}$.
3. For rough passages, the marked increases in frictional pressure coefficient are intimately associated with early transition, and when this role of transition is accounted

for, the reduced friction factors are considerably lower than the values deduced from the conventional f vs. Re plots.

4. For heat transfer, the simple rule amounts to this: the lower the critical Reynolds number for transition, the greater the average heat transfer coefficients, regardless of whether the passage is smooth or rough. The practical implication of this observation is that definite conclusions on the thermal performance of various surfaces and geometries can be reached based solely on knowledge of the critical Reynolds numbers for transition.
5. For smooth passages, heat transfer coefficients may be greatest with triangular passages, lowest with ducts of annular or rectangular geometry, but intermediate values should be expected for circular tubes.
6. For rough passages, there are clear indications that estimates of the average heat transfer coefficient, that are quite satisfactory for design purposes, can be obtained from the smooth tube data by simply replacing the familiar Reynolds number (Re) with the reduced value (Re_m) computed from $Re_m = \psi_R Re_a$. Furthermore, expressed as the ratio $\phi_f/\phi_{h,max}$, where $\phi_f = f_m/f_{m,s}$ and $\phi_{h,max} = (Nu_r/Nu_s)_{max}$, the condition $\phi_f/\phi_{h,max} \leq 2$ is satisfied by most of the data considered in the analysis.

6.2 Recommendations

The law of corresponding states for friction, like all other theories, demands extensive experimental verification and clear statements of the ranges over which it is applicable before it can be used with confidence. For smooth passages, that aspect of the theory which deals with friction has been validated conclusively (Obot, 1988). There is need, however, for detailed heat transfer studies to establish the effects of duct geometry; notably, for triangular passages, the past studies of which have resulted in conflicting conclusions. Given the amount of experimental information in the literature for rough passages, the almost total neglect of the laminar and transition regions by

researchers, even in the case of pressure drop, is difficult to explain. Studies on pressure drop and heat transfer with various geometries of roughness are needed. Even if heat transfer measurements do not cover the laminar or transition region, it is most desirable to obtain very accurate pressure drop measurements for the laminar, transition and turbulent flow regimes. For such measurements, the following points are worthy of note: first, sufficient taps should be used to obtain truly representative mean pressure drop; second, precise locations of the upstream and downstream taps, relative to the roughness elements, should be noted and reported (Obot et al., 1987); third, it is most desirable to obtain data with and without heat transfer.

With regard to the phenomenon of transition, experimental and theoretical studies are needed to improve the current state of knowledge on the subject. Specifically, there is the need to establish simple and direct experimental methods for accurate determination of the critical parameters at the onset of transition. The prediction of transition has received very meager treatment in the past. This unfortunate situation must be corrected to provide better understanding of the transition process, turbulence and the attendant heat/mass transfer.

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APPENDIX

TABULATION OF DATA

This appendix gives a complete tabulation of the data used in the preparation of the illustrations presented in Sections 2.1 through 5. There are twelve tables, A.1 through A.12, each of which gives the data for a particular study. Several points are worthy of note. First, for smooth or enhanced tubes, f_m or Re_m are independent of the length scale used to reduce the original data to nondimensional form. For the heat transfer data, Nu_m is the Nusselt number for a particular value of Re_m ($= \psi_R Re$). Since it is an unscaled parameter, it has the same numerical value as the conventional Nusselt number (Nu). To emphasize this important point, both Nu and Nu_m are given in the appropriate tables.

Because of the large amount of information, the use of additional coding to identify some of the data sets was unavoidable. The following comments will be helpful to the reader.

1. For the heat transfer data of Koch and Feind (1958), Table A.6(b), the columns labeled Re_m (9) and Re_m (10) correspond to the data for Figs. 9 and 10 respectively. It should be noted that the original (conventional) Reynolds numbers were scaled with the rounded reference value ($Re_{c,r}$) of 2,100 for Fig. 9, while the $Re_{c,r}$ value (2719) of the original data was used for Fig. 10.

2. For Table A.7, which gives Koch's friction and heat transfer data, some of the data blocks are assigned letters (e.g., (e), (f), (g), etc.) in addition to the geometric parameters of the roughness. These correspond to letters in the original publication. Also, in the summary of the Stanton number ratios, the values for the friction Reynolds number ($Re_{\epsilon m}$) are not given because these can be easily calculated from $Re_{\epsilon m} = Re_m(f_m/2)^{1/2}$. And, further, there are differences in ψ_f or ψ_R values between friction and heat transfer data. For all friction data, the reference $f_{c,r}$ and $Re_{c,r}$ values were 0.008 and 2,100 (Figs. 6 and 7). For heat transfer, it was more appropriate, as demonstrated from comparison between Figs. 9 and 10, to use the actual $f_{c,r}$ and $Re_{c,r}$ values determined from the original papers.

3. For Table A.8, which gives Nunner's data, the blocks are also identified using the original labeling of the author (i.e., A20, B80, etc.), the description of the elements as well as our in-house identification numbers (i.e., (1), (2), (3), etc.). For friction, ψ_f and ψ_R were determined using $f_{c,r} = 0.008$

and $Re_{c,r} = 2,100$; the same approach as with Koch's data. As noted already in Section 3.2, for heat transfer calculations, ψ_R values were deduced from heat transfer data; hence there are significant differences between the values for friction and heat transfer.

Table A.1

Allen and Grunberg (1937)
Smooth rectangular duct friction factor data

$$a_r = 3.92, \psi_R = 0.907, \psi_I = 1.0$$

Re	f	Re _m	f _m
493	0.0332	544	0.0332
630	0.0262	695	0.0262
778	0.0202	858	0.0202
907	0.0180	1000	0.018
1096	0.0146	1208	0.0146
1291	0.0124	1423	0.0124
1385	0.0115	1527	0.0115
1575	0.0104	1736	0.0104
1879	0.00827	2072	0.00827
2016	0.00789	2223	0.00789
3715	0.0092	4096	0.009
4132	0.0092	4556	0.0092
4877	0.0089	5377	0.008
5964	0.00894	6576	0.00894
10650	0.0076	11742	0.0076
13655	0.00727	15055	0.00727
15010	0.00727	16549	0.00727
16115	0.00692	17767	0.00692

Table A.2

**Cornish (1928)
Smooth rectangular duct friction factor data**

Series 1: $a_r = 2.92$, $\psi_R = 0.944$, $\psi_f = 1.0$

Re	f	Re_m	f_m	Re	f	Re_m	f_m
270	0.06320	255	0.06320	3716	0.00946	3507	0.00946
282	0.05760	266	0.05760	3996	0.00946	3771	0.00946
296	0.05740	279	0.05740	4020	0.00944	3794	0.00944
313	0.05320	295	0.05320	4900	0.00892	4625	0.00892
371	0.04400	350	0.04400	6568	0.00836	6199	0.00836
419	0.04160	395	0.04160	7780	0.00802	7343	0.00802
445	0.03820	420	0.03820	8600	0.00782	8117	0.00782
553	0.03020	522	0.03020	10000	0.00756	9438	0.00756
584	0.02904	551	0.02904	13720	0.00710	12949	0.00710
796	0.02068	751	0.02068	20200	0.00648	19065	0.00648
804	0.02072	759	0.02072	26120	0.00604	24652	0.00604
1372	0.01264	1295	0.01264	33320	0.00574	31447	0.00574
1400	0.01244	1321	0.01244	33599	0.00570	31711	0.00570
1861	0.00972	1756	0.00972	34320	0.00566	32391	0.00566
2004	0.00944	1891	0.00944	41480	0.00542	39149	0.00542
2099	0.00898	1981	0.00898	42080	0.00532	39715	0.00532
2224	0.00864	2099	0.00864	42280	0.00534	39904	0.00534
2484	0.00874	2344	0.00874	42960	0.00538	40546	0.00538
2540	0.00900	2397	0.00900	53280	0.00512	50286	0.00512
2544	0.00904	2401	0.00904	55040	0.00512	51947	0.00512
2932	0.00956	2767	0.00956	56160	0.00506	53004	0.00506
3152	0.00974	2975	0.00974	63240	0.00492	59686	0.00492
3268	0.00982	3084	0.00982	63720	0.00494	60139	0.00494

Series 2: $a_t = 2.92$, $\psi_R = 0.944$, $\psi_t = 1.0$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
359	0.047	339	0.047	2636	0.00936	2488	0.00936
366	0.0452	345	0.0452	2636	0.00914	2488	0.00914
619	0.0278	584	0.0278	2651	0.00916	2502	0.00916
953	0.0175	899	0.0175	2828	0.0098	2669	0.0098
1004	0.0166	948	0.0166	3524	0.00978	3326	0.00978
1496	0.0116	1412	0.0116	5000	0.00894	4719	0.00894
1648	0.0105	1555	0.0105	5040	0.00888	4757	0.00888
1751	0.00986	1653	0.00986	5056	0.00902	4772	0.00902
1964	0.0089	1854	0.0089	7156	0.00826	6754	0.00826
2140	0.00824	2020	0.00824	8384	0.00802	7913	0.00802
2143	0.0082	2023	0.0082	8960	0.00792	8456	0.00792
2176	0.00826	2054	0.00826	9320	0.00782	8796	0.00782
2392	0.00822	2258	0.00822	10480	0.00756	9891	0.00756
2400	0.00814	2265	0.00814	11960	0.00738	11288	0.00738
2416	0.00816	2280	0.00816	12400	0.00728	11703	0.00728
2416	0.00792	2280	0.00792	12760	0.00726	12043	0.00726
2540	0.00874	2397	0.00874	20200	0.00652	19065	0.00652

Table A.3

Carlson (1959)
Smooth triangular duct friction factor data

Duct 1: $h/b = 14.26$, $\alpha = 4.01^\circ$, $\psi_R = 1.512$, $\psi_I = 1.0$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
466	0.02540	705	0.02540	2170	0.00943	3282	0.00943
575	0.02140	870	0.02140	2410	0.00918	3644	0.00918
682	0.01820	1031	0.01820	2540	0.00903	3841	0.00903
794	0.01550	1201	0.01550	3140	0.00848	4748	0.00848
900	0.01400	1361	0.01400	3760	0.00803	5686	0.00803
1140	0.01090	1724	0.01090	4250	0.00788	6427	0.00788
1387	0.00883	2097	0.00883	4710	0.00768	7122	0.00768
1637	0.01040	2476	0.01040	5330	0.00740	8060	0.00740
1895	0.00995	2866	0.00995	5980	0.00740	9043	0.00740

Duct 2: $h/b = 7.21$, $\alpha = 7.96^\circ$, $\psi_R = 1.302$, $\psi_I = 1.0$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
563	0.02190	733	0.02190	3035	0.00880	3952	0.00880
664	0.01920	865	0.01920	3620	0.00840	4713	0.00840
772	0.01630	1005	0.01630	4259	0.00800	5545	0.00800
879	0.01470	1145	0.01470	4920	0.00780	6406	0.00780
1116	0.01140	1453	0.01140	5570	0.00753	7252	0.00753
1359	0.00935	1769	0.00935	6250	0.00740	8138	0.00740
1615	0.00820	2103	0.00820	6980	0.00713	9088	0.00713
1869	0.01000	2434	0.01000	7760	0.00700	10104	0.00700
2130	0.00960	2773	0.00960	8600	0.00680	11197	0.00680
2380	0.00930	3099	0.00930	9700	0.00660	12629	0.00660
2580	0.00930	3359	0.00930	10650	0.00650	13866	0.00650

Duct 3: $h/b = 4.75$, $\alpha = 12.0^\circ$, $\psi_R = 1.356$, $\psi_i = 1.0$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
440	0.02840	597	0.02840	16600	0.00598	22510	0.00598
546	0.02290	740	0.02290	24200	0.00548	32815	0.00548
643	0.02000	872	0.02000	2420	0.00980	3282	0.00980
748	0.01700	1014	0.01700	3020	0.00903	4095	0.00903
857	0.01480	1162	0.01480	3660	0.00863	4963	0.00863
1084	0.01220	1470	0.01220	4090	0.00848	5546	0.00848
1315	0.00980	1783	0.00980	4510	0.00833	6116	0.00833
1560	0.00848	2115	0.00848	6000	0.00780	8136	0.00780
1810	0.01040	2454	0.01040	7280	0.00723	9872	0.00723
2058	0.01020	2790	0.01020	8710	0.00070	11811	0.00070
2310	0.00988	3132	0.00988	9980	0.00685	13533	0.00685
2430	0.00930	3295	0.00930	11500	0.00650	15594	0.00650
4130	0.00835	5600	0.00835	12820	0.00640	17384	0.00640
7340	0.00715	9953	0.00715	16440	0.00600	22293	0.00600
11700	0.00640	15865	0.00640				

Duct 4: $h/b = 2.54$, $\alpha = 22.3^\circ$, $\psi_R = 1.512$, $\psi_i = 1.0$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
515	0.02500	665	0.02500	2260	0.00970	2918	0.00970
609	0.02070	786	0.02070	2810	0.00930	3628	0.00930
706	0.01790	912	0.01790	3390	0.00890	4377	0.00890
806	0.01620	1041	0.01620	3840	0.00883	4958	0.00883
1020	0.01290	1317	0.01290	4275	0.00875	5519	0.00875
1242	0.01060	1604	0.01060	5620	0.00835	7256	0.00835
1470	0.00915	1898	0.00915	6815	0.00805	8799	0.00805
1703	0.00820	2199	0.00820	8190	0.00748	10574	0.00748
1703	0.00945	2199	0.00945	9400	0.00728	12138	0.00728
2220	0.00980	2866	0.00980	10800	0.00690	13944	0.00690
2760	0.00870	3563	0.00870	12070	0.00680	15584	0.00680
3580	0.00880	4622	0.00880	15630	0.00628	20180	0.00628
6720	0.00788	8676	0.00788	19400	0.00605	25047	0.00605

Re	f	Re _m	f _m	Re	f	Re _m	f _m
8070	0.00750	10419	0.00750	23250	0.00578		
9250	0.00735	11943	0.00735	19300	0.00606	24918	0.00606
11900	0.00673	15364	0.00673	23200	0.00580	29953	0.00580
15420	0.00625	19909	0.00625	26200	0.00563	33827	0.00563
19080	0.00605	24608	0.00605	29100	0.00548	37571	0.00548
22900	0.00593	29566	0.00593	31600	0.00540	40799	0.00540
12030	0.00683	15532	0.00683	34100	0.00530	44027	0.00530
15560	0.00633	20090	0.00633				

Duct 5: $h/b = 1.42$, $\alpha = 38.8^\circ$, $\psi_R = 1.512$, $\psi_l = 1.0$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
535	0.02500	640	0.02500	8250	0.00790	9875	0.00790
623	0.02130	746	0.02130	7600	0.00780	9097	0.00780
712	0.01890	852	0.01890	8900	0.00760	10653	0.00760
900	0.01470	1077	0.01470	10500	0.00740	12569	0.00740
1090	0.01260	1305	0.01260	12560	0.00710	15034	0.00710
1304	0.00988	1561	0.00988	14800	0.00670	17716	0.00670
1500	0.00910	1796	0.00910	18150	0.00640	21726	0.00640
1770	0.00785	2119	0.00785	21800	0.00620	26095	0.00620
1923	0.00870	2302	0.00870	26800	0.00580	32080	0.00580
1990	0.01020	2382	0.01020	32650	0.00560	39082	0.00560
2470	0.00990	2957	0.00990	30925	0.00545	37017	0.00545
2980	0.00950	3567	0.00950	34500	0.00548	41297	0.00548
3350	0.00945	4010	0.00945	40900	0.00520	48957	0.00520
3770	0.00928	4513	0.00928	47500	0.00500	56858	0.00500
4950	0.00875	5925	0.00875	57200	0.00480	68468	0.00480
5000	0.00885	5985	0.00885	64000	0.00473	76608	0.00473
7350	0.00818	8798	0.00818				

Table A.4

Hartnett et al. (1962)
Smooth rectangular duct friction factor data

(a) Abrupt entrance

$$a_r = 1, \psi_R = 0.978, \psi_I = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
1199	0.01090	1173	0.01090	16722	0.00660	16356	0.00660
1742	0.00832	1704	0.00832	26902	0.00596	26313	0.00596
2585	0.00987	2528	0.00987	41952	0.00539	41034	0.00539
3131	0.00920	3062	0.00920	55663	0.00497	54444	0.00497
4642	0.00875	4540	0.00875	75361	0.00472	73711	0.00472
7094	0.00807	6939	0.00807	119922	0.00406	117297	0.00406
11635	0.00715	11380	0.00715	152815	0.00390	149470	0.00390

$$a_r = 5, \psi_R = 0.850, \psi_I = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
1020	0.01800	867	0.01800	11754	0.00767	9993	0.00767
1396	0.01340	1187	0.01340	15438	0.00720	13125	0.00720
1657	0.01140	1409	0.01140	24320	0.00650	20677	0.00650
2069	0.00875	1759	0.00875	27454	0.00620	23341	0.00620
2482	0.00791	2110	0.00791	30370	0.00610	25821	0.00610
2691	0.00902	2288	0.00902	36425	0.00580	30969	0.00580
3637	0.00968	3092	0.00968	50322	0.00539	42784	0.00539
4517	0.00948	3840	0.00948	56804	0.00517	48295	0.00517
5456	0.00911	4639	0.00911	81711	0.00477	69471	0.00477
7094	0.00857	6031	0.00857	111750	0.00427	95010	0.00427
9900	0.00783	8417	0.00783	198722	0.00352	168954	0.00352

$$a_t = 10, \psi_R = 0.842, \psi_f = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
1042	0.02020	877	0.02020	10952	0.00807	9218	0.00807
1262	0.01600	1082	0.01600	14236	0.00744	11982	0.00744
1691	0.01230	1423	0.01230	22529	0.00673	18962	0.00673
2175	0.00948	1831	0.00948	45032	0.00544	37903	0.00544
2531	0.00840	2130	0.00840	95507	0.00449	80387	0.00449
3227	0.00687	2716	0.00687	145308	0.00414	122303	0.00414
4736	0.00948	3986	0.00948	176046	0.00390	148175	0.00390
6677	0.00884	5620	0.00884				

(b) Critical Parameters for duct with smooth entrance

a_t	ψ_R	ψ_f
1	0.492	2.265
5	0.297	2.745
10	0.476	1.652

Table A.5

Jones (1976)
Smooth rectangular duct friction factor data

$$a_r = 13, \psi_R = 0.811, \psi_f = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
115	0.18900	93	0.18900	4267	0.00958	3459	0.00958
144	0.13800	117	0.13800	3480	0.00916	2821	0.00916
165	0.12900	134	0.12900	7025	0.00875	5695	0.00875
253	0.08170	205	0.08170	9220	0.00814	7475	0.00814
340	0.06000	276	0.06000	14055	0.00770	11394	0.00770
613	0.03400	497	0.03400	18470	0.00688	13352	0.00688
923	0.02170	748	0.02170	18869	0.00720	15297	0.00720
1037	0.01930	841	0.01930	27117	0.00658	21984	0.00658
1314	0.01540	1065	0.01540	27738	0.00601	22487	0.00601
2212	0.00980	1793	0.00980	35590	0.00610	28853	0.00610
2592	0.00836	2101	0.00836	53520	0.00570	43389	0.00570
3179	0.00958	2577	0.00958	76911	0.00536	62352	0.00536
3480	0.00916	2821	0.00916	80477	0.00510	65243	0.00510

$$a_r = 26, \psi_R = 0.724, \psi_f = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
141	0.15000	102	0.15000	4436	0.00923	3212	0.00923
206	0.10200	149	0.10200	4778	0.01040	3459	0.01040
283	0.07800	205	0.07800	4967	0.00995	3596	0.00995
340	0.06500	246	0.06500	5598	0.00929	4053	0.00929
436	0.05200	316	0.05200	6413	0.00908	4643	0.00908
522	0.04400	378	0.04400	7348	0.00887	5320	0.00887
717	0.03200	519	0.03200	10464	0.00836	7576	0.00836
880	0.02600	637	0.02600	14050	0.00790	10172	0.00790
1046	0.02200	757	0.02200	19738	0.00689	14290	0.00689
1253	0.01860	907	0.01860	24757	0.00673	17924	0.00673
1403	0.01590	1016	0.01590	35579	0.00614	25759	0.00614

Re	f	Re _m	f _m	Re	f	Re _m	f _m
1681	0.01580	1217	0.01580	40394	0.00614	29245	0.00614
2106	0.01130	1525	0.01130	58576	0.00547	42409	0.00547
2699	0.00818	2099	0.00818	76883	0.00522	55663	0.00522
3789	0.00985	2743	0.00985				

$$a_r = 31, \psi_R = 0.757, \psi_I = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
104	0.21500	79	0.21500	2772	0.00840	2099	0.00840
151	0.16400	114	0.16400	3399	0.00820	2574	0.00820
207	0.11400	157	0.11400	3477	0.01050	2633	0.01050
325	0.07500	246	0.07500	4884	0.00920	3699	0.00920
467	0.05000	354	0.05000	7020	0.00840	5316	0.00840
656	0.03400	497	0.03400	10460	0.00802	7921	0.00802
1046	0.02200	792	0.02200	14366	0.00730	10879	0.00730
1372	0.01700	1039	0.01700	23643	0.00690	17905	0.00690
1645	0.01400	1246	0.01400	37214	0.00611	28182	0.00611
2064	0.01100	1563	0.01100	48843	0.00560	36989	0.00560
2365	0.00960	1791	0.00960				

$$a_r = 31, \psi_R = 0.811, \psi_I = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
104	0.22200	84	0.22200	2590	0.00900	2100	0.00900
137	0.16600	111	0.16600	3478	0.00970	2820	0.00970
202	0.10300	164	0.10300	4463	0.00940	3619	0.00940
326	0.07000	264	0.07000	6561	0.00920	5320	0.00920
427	0.05030	346	0.05030	10369	0.00860	8407	0.00860
671	0.03500	544	0.03500	14371	0.00780	11652	0.00780
964	0.02300	782	0.02300	24202	0.00720	19623	0.00720
1314	0.01770	1065	0.01770	37229	0.00650	30185	0.00650
1647	0.01410	1335	0.01410	49983	0.00590	40526	0.00590
1973	0.01230	1600	0.01230				

Table A.6

Koch and Feind (1958)
Friction and heat transfer data for smooth annuli

(a) Friction factor data

$$\beta = 0.212, \psi_R = 0.731, \psi_t = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
590	0.03870	431	0.03870	8043	0.00900	4417	0.00900
792	0.02880	579	0.02880	8355	0.00810	6107	0.00810
1088	0.02160	795	0.02160	11024	0.00770	8058	0.00770
1757	0.01350	1284	0.01350	16484	0.00716	12049	0.00716
2006	0.01150	1466	0.01150	18878	0.00690	13799	0.00690
3014	0.00841	2203	0.00841	20780	0.00670	15189	0.00670
3482	0.00900	2545	0.00900	23762	0.00665	17369	0.00665
4069	0.00940	2974	0.00940	32227	0.00610	23556	0.00610
4642	0.00929	3393	0.00929	49979	0.00558	36532	0.00558
5426	0.00905	3966	0.00905				

$$\beta = 0.409, \psi_R = 0.697, \psi_t = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
953	0.02070	684	0.02070	6654	0.00940	4636	0.00940
1197	0.01950	834	0.01950	7323	0.00860	5102	0.00860
1487	0.01560	1036	0.01560	11439	0.00789	7970	0.00789
2130	0.01090	1484	0.01090	14776	0.00740	10295	0.00740
2773	0.00850	1932	0.00850	18627	0.00700	12978	0.00700
3163	0.00810	2204	0.00810	22837	0.00670	15772	0.00670
3525	0.00900	2456	0.00900	25260	0.00640	17600	0.00640
3697	0.00950	2576	0.00950	30703	0.00610	21392	0.00610
4119	0.00964	2870	0.00964	38703	0.00570	26968	0.00570
4756	0.00950	3314	0.00950	44256	0.00560	30835	0.00560
6192	0.00940	4314	0.00940	45348	0.00545	31596	0.00545

$$\beta = 0.6, \psi_R = 0.648, \psi_f = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
256	0.09340	166	0.09340	7780	0.00940	5031	0.00940
546	0.04600	354	0.04600	12990	0.00860	8422	0.00860
791	0.03100	513	0.03100	16169	0.00800	10483	0.00800
1575	0.01590	1021	0.01590	18287	0.00778	11856	0.00778
2203	0.01130	1426	0.01130	20967	0.00770	13594	0.00770
2735	0.00920	1773	0.00920	23392	0.00730	15166	0.00730
3157	0.00800	2047	0.00800	26483	0.00700	17170	0.00700
3517	0.00840	2280	0.00840	32544	0.00658	21100	0.00658
3603	0.00920	2336	0.00920	42107	0.00640	27300	0.00640
3918	0.00990	2540	0.00990	46271	0.00640	30000	0.00640

$$\beta = 0.698, \psi_R = 0.618, \psi_f = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
322	0.07730	199	0.07730	7285	0.00900	4502	0.00900
398	0.06630	246	0.06630	8026	0.00860	4960	0.00860
506	0.04800	313	0.04800	10741	0.00810	6638	0.00810
545	0.04340	337	0.04340	12754	0.00780	7882	0.00780
738	0.03270	456	0.03270	14071	0.00770	8696	0.00770
796	0.03030	492	0.03030	17548	0.00740	10845	0.00740
822	0.02770	508	0.02770	19352	0.00710	11960	0.00710
1023	0.02320	632	0.02320	21886	0.00690	13526	0.00690
1544	0.01490	954	0.01490	24144	0.00670	14921	0.00670
2275	0.01050	1406	0.01050	26634	0.00670	16460	0.00670
2830	0.00860	1749	0.00860	29744	0.00650	18382	0.00650
3157	0.00780	1951	0.00780	32813	0.00630	20279	0.00630
3563	0.00700	2202	0.00700	37556	0.00610	23210	0.00610
4171	0.00780	2576	0.00780	41941	0.00600	25920	0.00600
4595	0.00950	2840	0.00950	41941	0.00600	25920	0.00600

$$\beta = 0.793, \psi_R = 0.692, \psi_f = 1.0$$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
270	0.06680	187	0.06680	3037	0.00770	2100	0.00770
359	0.06480	248	0.06480	3342	0.00810	2311	0.00810
513	0.04600	355	0.04600	3679	0.00829	2544	0.00829
594	0.03970	411	0.03970	6237	0.00940	4313	0.00940
681	0.03540	471	0.03540	7203	0.00880	4981	0.00880
779	0.03030	539	0.03030	9156	0.00860	6331	0.00860
881	0.02670	609	0.02670	10330	0.00850	7143	0.00850
1109	0.02100	767	0.02100	12554	0.00810	8681	0.00810
1359	0.01720	940	0.01720	14181	0.00770	9806	0.00770
1628	0.01450	1126	0.01450	19654	0.00725	13590	0.00725
2223	0.01050	1537	0.01050	24247	0.00670	16766	0.00670
2538	0.00950	1755	0.00950				

(b) Heat transfer data (note: numbers in brackets refer to figure numbers)

Smooth tube data; $\psi_R(9) = 0.772, \psi_R(10) = 1$ (unscaled, $Re_m = Re$)

Re _m (10)	Nu	Re _m (9)	Nu _m	Re _m (10)	Nu	Re _m (9)	Nu _m
1005	10.58	776	10.58	10643	33.82	8220	33.82
1337	11.29	1033	11.29	11487	35.91	8872	35.91
1579	11.98	1219	11.98	13045	40.24	10075	40.24
2044	12.25	1579	12.25	15869	46.63	12256	46.63
2301	12.83	1777	12.83	18136	52.05	14007	52.05
2779	13.12	2146	13.12	19939	56.94	15400	56.94
3193	14.19	2466	14.19	21768	59.86	16813	59.86
3743	15.30	2891	15.30	24131	66.77	18638	66.77
4313	16.33	3331	16.33	27248	72.66	21045	72.66
4852	17.78	3747	17.78	30014	76.98	23181	76.98
5321	19.20	4109	19.20	36371	90.69	28091	90.69
5620	20.38	4340	20.38	39859	97.03	30785	97.03
6745	23.49	5210	23.49	44468	108.16	34344	108.16
7694	26.25	5943	26.25	48981	112.90	37830	112.90
8683	27.69	6706	27.69	52066	115.58	40212	115.58

Re_m (10)	Nu	Re_m (9)	Nu_m	Re_m (10)	Nu	Re_m (9)	Nu_m
9892	31.63	7640	31.63	58903	129.25	45494	129.25

$$\beta = 0.212, \psi_R(9) = 0.731, \psi_R(10) = 0.946$$

Re	Nu	Re_m (9)	Re_m (10)	Nu_m
1072	9.61	783	1014	9.61
1201	10.00	878	1137	10.00
1337	10.23	978	1266	10.23
1483	10.19	1084	1404	10.19
1649	10.39	1205	1560	10.39
1858	10.73	1358	1758	10.73
1960	11.03	1433	1855	11.03
2189	10.96	1600	2072	10.96
2490	11.06	1820	2356	11.06
2708	11.01	1979	2563	11.01
3021	11.34	2208	2859	11.34
3368	12.04	2462	3187	12.04
3760	13.11	2748	3558	13.11
4341	14.93	3173	4108	14.93
4889	16.55	3574	4627	16.55
5465	18.43	3994	5172	18.43
6089	20.00	4450	5762	20.00
6901	22.50	5045	6532	22.50
7559	24.50	5525	7153	24.50
8481	27.06	6199	8026	27.06
9235	28.75	6751	8740	28.75
10931	33.04	7990	10345	33.04
11919	35.77	8712	11280	35.77
13493	39.46	9862	12769	39.46
14957	42.58	10933	14155	42.58

Re	Nu	Re _m (9)	Re _m (10)	Nu _m
16528	47.49	12081	15642	47.49
20623	55.26	15074	19517	55.26
22876	59.43	16721	21649	59.43
25995	65.61	19001	24602	65.61
28799	70.47	21050	27255	70.47
30925	75.55	22605	29267	75.55
35729	83.66	26116	33814	83.66
38563	89.81	28187	36496	89.81
44581	99.98	32586	42191	99.98
50276	110.22	36749	47581	110.22

$$\beta = 0.409, \psi_R(9) = 0.697, \psi_R(10) = 0.902$$

Re	Nu	Re _m (9)	Re _m (10)	Nu _m
1062	8.01	740	958	8.01
1256	8.29	875	1133	8.29
1408	8.69	981	1270	8.69
1568	8.53	1092	1414	8.53
1661	8.70	1157	1499	8.70
1858	8.83	1295	1676	8.83
2039	8.92	1421	1839	8.92
2288	8.98	1594	2064	8.98
2598	9.15	1810	2344	9.15
2922	9.37	2036	2636	9.37
3205	10.96	2233	2891	10.96
3580	12.14	2494	3229	12.14
4216	14.11	2937	3803	14.11
4736	15.86	3300	4272	15.86
5207	16.99	3628	4697	16.99
5809	19.22	4047	5240	19.22

Re	Nu	Re _m (9)	Re _m (10)	Nu _m
6517	21.22	4541	5880	21.22
7197	23.64	5015	6493	23.64
8035	25.64	5598	7248	25.64
9055	27.78	6309	8169	27.78
10160	30.86	7079	9166	30.86
11575	34.44	8065	10442	34.44
12889	37.53	8980	11627	37.53
14206	39.48	9898	12816	39.48
15053	40.87	10488	13579	40.87
15638	43.76	10896	14107	43.76
17513	47.09	12202	15799	47.09
19438	51.38	13544	17536	51.38
20953	55.69	14599	18903	55.69
24627	60.92	17159	22217	60.92
27196	66.46	18949	24534	66.46
30072	70.79	20952	27128	70.79
32789	75.94	22846	29580	75.94
36071	81.41	25133	32541	81.41
40705	88.25	28361	36721	88.25

$$\beta = 0.6, \Psi_R(9) = 0.648, \Psi_R(10) = 0.839$$

Re	Nu	Re _m (9)	Re _m (10)	Nu _m
1328	6.40	861	1115	6.40
1658	6.74	1075	1392	6.74
2070	7.12	1342	1738	7.12
2499	7.34	1620	2098	7.34
2844	7.78	1844	2387	7.78
3116	8.38	2020	2616	8.38
3693	11.44	2394	3100	11.44

Re	Nu	Re _m (9)	Re _m (10)	Nu _m
4081	13.12	2646	3426	13.12
4715	15.06	3057	3958	15.06
5220	16.65	3384	4382	16.65
5876	18.19	3809	4932	18.19
6447	19.72	4180	5412	19.72
7106	21.55	4607	5965	21.55
8600	25.76	5576	7220	25.76
10057	28.97	6521	8443	28.97
12653	34.62	8204	10622	34.62
14053	38.35	9111	11797	38.35
15062	41.08	9765	12644	41.08
15838	42.41	10269	13296	42.41
18770	48.52	12169	15757	48.52
20156	52.08	13068	16920	52.08
21548	54.37	13971	18089	54.37
23781	57.53	15418	19963	57.53
25929	61.36	16811	21767	61.36
27720	64.51	17972	23270	64.51
29710	68.08	19263	24941	68.08
31762	72.51	20593	26663	72.51
33463	74.96	21696	28091	74.96

$$\beta = 0.698, \psi_R(9) = 0.618, \psi_R(10) = 0.800$$

Re	Nu	Re _m (9)	Re _m (10)	Nu _m
3317	8.10	2050	2654	8.10
3861	11.36	2386	3090	11.36
4447	13.58	2748	3558	13.58
4942	15.01	3054	3955	15.01
5327	16.20	3292	4263	16.20

Re	Nu	Re _m (9)	Re _m (10)	Nu _m
6058	18.21	3744	4847	18.21
6810	20.25	4209	5449	20.25
7853	23.02	4853	6284	23.02
8573	24.55	5298	6860	24.55
9674	27.42	5979	7741	27.42
10462	28.75	6465	8371	28.75
11716	31.71	7240	9375	31.71
13045	34.56	8062	10439	34.56
15091	38.55	9326	12075	38.55
16921	43.13	10458	13540	43.13

$$\beta = 0.793, \psi_R(9) = 0.692, \psi_R(10) = 0.895$$

Re	Nu	Re _m (9)	Re _m (10)	Nu _m
2528	6.21	1748	2263	6.21
2806	7.05	1940	2512	7.05
2937	7.63	2031	2630	7.63
3302	9.81	2283	2956	9.81
3729	11.05	2578	3338	11.05
4123	12.28	2851	3691	12.28
4769	14.13	3298	4270	14.13
5486	15.97	3793	4911	15.97
6505	18.61	4498	5824	18.61
6972	19.68	4821	6242	19.68
8106	22.41	5605	7258	22.41
9090	24.82	6285	8138	24.82
9880	26.51	6831	8845	26.51
11022	29.01	7621	9868	29.01
12856	32.85	8889	11510	32.85
13858	34.74	9582	12407	34.74

Table A.7

Koch (1960)

Friction and heat transfer data for smooth and rough tubes

(a) Smooth tube

Friction (smooth): $\psi_R = 0.713$, $\psi_f = 1.0$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
286	0.05080	204	0.05080	5081	0.00960	3624	0.00960
341	0.05187	243	0.05187	5414	0.00940	3861	0.00940
397	0.04026	283	0.04026	5862	0.00913	4181	0.00913
483	0.03199	345	0.03199	6340	0.00902	4522	0.00902
609	0.02554	434	0.02554	6763	0.00899	4824	0.00899
657	0.02183	468	0.02183	7489	0.00877	5341	0.00877
692	0.02107	493	0.02107	8149	0.00859	5813	0.00859
733	0.02236	523	0.02236	8715	0.00834	6216	0.00834
833	0.01893	594	0.01893	9285	0.00824	6623	0.00824
896	0.01690	639	0.01690	10243	0.00825	7306	0.00825
953	0.01646	680	0.01646	10887	0.00796	7765	0.00796
1060	0.01478	756	0.01478	11847	0.00792	8450	0.00792
1171	0.01373	835	0.01373	12638	0.00778	9014	0.00778
1269	0.01278	905	0.01278	13821	0.00758	9858	0.00758
1354	0.01227	966	0.01227	14744	0.00750	10517	0.00750
1475	0.01220	1052	0.01220	15554	0.00731	11094	0.00731
1552	0.01109	1107	0.01109	17635	0.00711	12578	0.00711
1643	0.01070	1172	0.01070	20702	0.00693	14766	0.00693
1717	0.01019	1224	0.01019	22781	0.00679	16249	0.00679
1829	0.00969	1305	0.00969	25352	0.00659	18083	0.00659
1946	0.00920	1388	0.00920	28565	0.00638	20375	0.00638
2097	0.00941	1496	0.00941	30434	0.00629	21708	0.00629
2177	0.00900	1553	0.00900	32547	0.00624	23215	0.00624
2396	0.00837	1711	0.00837	35243	0.00607	25138	0.00607
2623	0.00825	1871	0.00825	36947	0.00603	26354	0.00603
2794	0.00855	1993	0.00855	39562	0.00595	28218	0.00595
2944	0.00806	2100	0.00806	41579	0.00575	29657	0.00575

Re	f	Re _m	f _m	Re	f	Re _m	f _m
3030	0.00861	2161	0.00861	44854	0.00572	31993	0.00572
3180	0.00893	2268	0.00893	48088	0.00559	34300	0.00559
3285	0.00945	2343	0.00945	53646	0.00546	38265	0.00546
3392	0.00989	2420	0.00989	58161	0.00539	41485	0.00539
3456	0.01055	2465	0.01055	60698	0.00534	43437	0.00534
3614	0.01022	2578	0.01022	63844	0.00530	45538	0.00530
3841	0.01024	2740	0.01024	67182	0.00523	47919	0.00523
4175	0.01005	2978	0.01005	74762	0.00506	53326	0.00506
4769	0.00970	3402	0.00970	80452	0.00506	57384	0.00506

Heat transfer (smooth):

Re	Nu _m	Re	Nu _m
447	6.49	5703	21.29
526	7.69	5999	21.13
596	8.43	6670	23.77
678	9.19	7704	26.20
730	10.01	8566	28.06
787	9.81	9477	30.58
919	10.83	10146	32.05
989	11.12	10918	33.92
1112	11.42	11484	35.10
1181	11.71	11942	36.37
1235	12.11	12404	38.11
1356	12.06	13313	39.94
1548	12.45	14362	41.49
1704	12.53	16214	46.03
1813	12.51	18281	50.16
1949	12.85	19896	54.74
2039	12.88	23211	60.65
2203	12.82	26305	66.52
2308	13.00	29103	72.50

Re	Nu _m	Re	Nu _m
2388	13.30	32732	79.22
2487	13.46	34822	84.72
2592	13.84	38185	90.26
2689	13.76	40063	93.87
2776	14.29	42248	99.12
3002	14.62	45574	102.05
3317	15.40	48913	106.53
3735	15.97	50357	111.78
4034	16.70	53035	115.82
4368	17.52	56636	121.68
4624	17.95	59119	124.01
4882	19.00	61402	127.19
5064	19.66	63615	131.45
5260	19.88	66237	134.82
5422	20.84	68713	139.86

(b) transverse disc-shaped inserts with no clearance at the wall

Friction (e): $p/e = 3.92$, $e/D = 0.1$, $\psi_R = 2.061$, $\psi_I = 0.173$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
403	0.09876	830	0.01713	4257	0.16004	8773	0.02775
494	0.07901	1018	0.01370	5221	0.15427	10760	0.02675
573	0.06819	1181	0.01183	6171	0.15138	12718	0.02625
703	0.05868	1448	0.01018	8002	0.14850	16493	0.02575
800	0.05450	1649	0.00945	9458	0.13985	19493	0.02425
911	0.04888	1878	0.00848	11388	0.13293	23471	0.02305
1019	0.04614	2100	0.00800	14231	0.13048	29329	0.02263
1182	0.09934	2436	0.01723	15908	0.13293	32786	0.02305
1423	0.13048	2933	0.02263	19513	0.13293	40216	0.02305
1713	0.16580	3531	0.02875	23494	0.13293	48422	0.02305
2102	0.17878	4332	0.03100	30470	0.13985	62798	0.02425

Re	f	Re _m	f _m	Re	f	Re _m	f _m
2626	0.17878	5413	0.03100	38282	0.14273	78899	0.02475
3047	0.17878	6280	0.03100	48471	0.14850	99899	0.02575
3343	0.16580	6890	0.02875	59456	0.14850	122539	0.02575

Heat transfer (e): $\psi_R = 2.889$

Re	Nu	Re _m	Nu _m	Re	Nu	Re _m	Nu _m
959	13.2	2772	13.2	9829	77	28399	77
1247	15.2	3603	15.2	13220	91.7	38198	91.7
1650	20.1	4767	20.1	17477	114.9	50495	114.9
2145	25.2	6198	25.2	22311	132	64462	132
2789	31.1	8057	31.1	27990	168.2	80871	168.2
3501	37	10115	37	32181	186.6	92981	186.6
4797	44.8	13859	44.8	43291	233.8	125080	233.8
5754	51.5	16625	51.5	56238	287.8	162487	287.8
7612	64.7	21994	64.7				

Stanton number ratios (e):

Re _m	f _m	e ⁺	e _m ⁺	St _t /St _b
1977	0.00779	14.38	12.34	1.20
2570	0.01991	29.88	25.64	1.25
3400	0.02745	46.42	39.83	1.60
4421	0.03098	64.12	55.02	1.97
5747	0.03128	83.76	71.87	2.16
7215	0.02788	99.27	85.18	2.36
9885	0.02739	134.82	115.68	2.41
11858	0.02634	158.59	136.08	2.42
15688	0.02598	208.39	178.81	2.48
20258	0.02392	258.16	221.51	2.46
27244	0.02259	337.47	289.56	2.30
36017	0.02319	452.00	387.83	2.37
45979	0.02298	574.35	492.81	2.23
57683	0.02381	733.47	629.34	2.39

Re_m	t_m	e^+	e_m^+	St/St_0
66321	0.02444	654.53	733.21	2.39
66216	0.02519	1166.88	1001.22	2.32
115896	0.02605	1541.59	1322.73	2.38

Friction (f): $p/e = 9.8$, $a/D = 0.1$, $\psi_R = 2.161$, $\psi_I = 0.217$

Re	f	Re_m	t_m	Re	f	Re_m	t_m
274	0.10627	592	0.02308	3936	0.15774	8504	0.03426
332	0.09030	717	0.01961	4421	0.15744	9552	0.03420
399	0.06987	861	0.01518	4828	0.15744	10647	0.03420
453	0.06743	979	0.01465	5578	0.15395	12052	0.03344
544	0.05740	1174	0.01247	5993	0.15598	12947	0.03388
631	0.05073	1363	0.01102	6705	0.15424	14487	0.03350
690	0.04760	1490	0.01034	7860	0.15194	16981	0.03300
823	0.04160	1778	0.00904	9484	0.15337	20491	0.03331
972	0.03683	2100	0.00800	10571	0.15194	22839	0.03300
1024	0.03896	2213	0.00846	11966	0.15081	25853	0.03276
1063	0.04841	2296	0.01051	13546	0.15166	28266	0.03294
1107	0.05708	2391	0.01240	15453	0.15109	33386	0.03282
1189	0.10607	2569	0.02304	17124	0.15308	36996	0.03325
1270	0.12766	2744	0.02773	19309	0.15081	41717	0.03276
1386	0.14311	2993	0.03108	22721	0.15598	49089	0.03388
1512	0.15366	3286	0.03337	27259	0.15863	58893	0.03445
1618	0.15863	3495	0.03445	28556	0.16163	61695	0.03510
1745	0.15863	3770	0.03445	31951	0.16223	69031	0.03524
1874	0.16254	4050	0.03530	36098	0.16468	77991	0.03577
1960	0.16406	4234	0.03563	38407	0.16623	82979	0.03610
2163	0.16468	4674	0.03577	41743	0.17128	90186	0.03720
2449	0.16499	5291	0.03584	45106	0.16937	97452	0.03679
2656	0.16437	5739	0.03570	52159	0.17225	112691	0.03741
2893	0.16163	6250	0.03510	58361	0.17485	126091	0.03798
3066	0.16193	6624	0.03517	65048	0.17815	140538	0.03869
3477	0.15863	7512	0.03445	70836	0.18118	153042	0.03935

Heat transfer (f): $\psi_R = 3.029$

Re	Nu	Re _m	Nu _m	Re	Nu	Re _m	Nu _m
408	5.90	1237	5.90	3628	44.20	10968	44.20
491	6.83	1486	6.83	4404	49.41	13340	49.41
561	8.01	1699	8.01	5036	55.34	15254	55.34
637	9.14	1929	9.14	5514	58.16	16701	58.16
765	10.51	2316	10.51	6169	63.43	18687	63.43
870	11.54	2634	11.54	7145	69.55	21642	69.55
932	11.79	2822	11.79	8611	79.57	26084	79.57
939	12.43	2843	12.43	10492	93.66	31781	93.66
1028	13.73	3112	13.73	11890	100.36	36014	100.36
1123	15.03	3402	15.03	13971	115.63	42318	115.63
1188	16.02	3598	16.02	16536	129.97	50086	129.97
1238	17.01	3751	17.01	19642	150.82	59497	150.82
1303	18.20	3947	18.20	23460	171.94	71061	171.94
1401	19.29	4243	19.29	27219	190.88	82446	190.88
1579	21.76	4782	21.76	28844	199.88	87369	199.88
1732	23.73	5246	23.73	32568	218.78	98649	218.78
1903	25.21	5764	25.21	36441	239.46	110380	239.46
2184	29.51	6615	29.51	38898	253.87	117822	253.87
2548	32.82	7717	32.82	42356	269.15	128298	269.15
2734	35.42	8282	35.42	49680	303.07	150482	303.07
3110	39.11	9419	39.11	60861	344.90	184349	344.90

Stanton number ratios (f):

Re _m	t _m	e ⁺	e _m ⁺	St _f /St _e
883	0.01493	7.57	7.62	1.01
1060	0.01397	8.80	8.86	0.95
1212	0.01207	9.35	9.42	0.99
1376	0.01095	10.11	10.18	1.05
1652	0.00956	11.34	11.42	1.06
1879	0.00868	12.30	12.38	1.12
2013	0.00826	12.85	12.94	1.08

Re_m	f_m	e^+	e_m^+	St/St_0
2028	0.00822	12.91	13.00	1.13
2220	0.00861	14.46	14.56	1.22
2426	0.01398	20.14	20.28	1.31
2566	0.02292	27.29	27.47	1.36
2676	0.02664	30.67	30.88	1.40
2815	0.02875	33.52	33.75	1.50
3027	0.03144	37.69	37.85	1.60
3411	0.03419	44.30	44.60	1.74
3742	0.03444	48.76	49.10	1.90
4111	0.03545	54.36	54.74	1.98
4718	0.03577	62.67	63.10	2.30
5504	0.03583	73.17	73.68	2.39
5907	0.03549	78.15	78.69	2.53
6719	0.03516	88.47	89.08	2.64
7838	0.03429	101.92	102.63	2.79
9515	0.03420	123.57	124.42	2.81
10680	0.03407	141.04	142.02	2.82
11912	0.03344	152.99	154.04	2.74
13329	0.03394	172.44	173.63	2.95
15437	0.03317	187.42	196.79	2.75
18605	0.03316	237.90	239.54	2.82
22668	0.03303	289.32	291.31	2.85
25688	0.03275	326.48	328.73	2.77
30184	0.03292	384.58	387.23	2.83
35725	0.03313	456.68	459.83	2.78
42438	0.03275	539.36	543.06	2.79
50686	0.03403	656.62	661.15	2.82
58807	0.03444	766.37	771.66	2.78
62318	0.03521	821.17	826.84	2.78
70364	0.03525	927.76	934.16	2.78
78732	0.03581	1046.29	1053.51	2.73
84040	0.03626	1123.75	1131.51	2.78
91512	0.03723	1240.05	1248.61	2.71

Re_m	t_m	e^+	e_m^+	St_t/St_s
107335	0.03699	1449.80	1459.81	2.77
131491	0.03821	1805.04	1817.50	2.73

Friction (g): $p/e = 65$, $e/D = 0.1$, $\psi_R = 2.813$, $\psi_t = 0.215$

Re	f	Re_m	t_m	Re	f	Re_m	t_m
500	0.04525	1405	0.00978	2428	0.05027	6829	0.01087
556	0.04176	1564	0.00903	3110	0.05015	8748	0.01084
637	0.04063	1791	0.00878	3799	0.04973	10687	0.01075
747	0.03719	2100	0.00804	5064	0.05161	14245	0.01116
819	0.04127	2302	0.00892	6486	0.05137	18246	0.01111
944	0.04657	2657	0.01007	8656	0.05242	24351	0.01133
1054	0.04891	2964	0.01057	11452	0.05242	32216	0.01133
1165	0.04967	3278	0.01074	14834	0.05223	41729	0.01129
1268	0.05027	3568	0.01087	19625	0.05267	55207	0.01139
1403	0.05088	3946	0.01100	26191	0.05318	73677	0.01150
1480	0.05069	4163	0.01096	35347	0.05545	99433	0.01199
1921	0.05045	5405	0.01091	47114	0.05652	132534	0.01222

Heat transfer (g): $\psi_R = 3.944$

Re	Nu	Re_m	Nu_m	Re	Nu	Re_m	Nu_m
1205	12.80	4751	12.80	7440	46.99	29344	46.99
1511	15.31	5959	15.31	10108	61.00	39865	61.00
2193	18.76	8647	18.76	13071	73.98	51550	73.98
2476	20.49	9765	20.49	17161	91.21	67679	91.21
2740	22.58	10806	22.58	22616	112.87	89194	112.87
3222	25.55	12707	25.55	29843	139.68	117696	139.68
4433	33.01	17483	33.01	39380	172.85	155308	172.85
5653	39.93	22294	39.93				

Stanton number ratios (g):

Re_m	f_m	e^+	e_m^+	St/St_0
3389	0.01073	19.02	24.82	1.08
4251	0.01089	24.03	31.36	1.24
6168	0.01084	34.80	45.41	1.46
6965	0.01081	39.25	51.20	1.53
7707	0.01080	43.42	56.65	1.61
9063	0.01077	50.98	66.52	1.69
12470	0.01087	70.46	91.93	1.87
15902	0.01114	90.95	118.67	1.87
20930	0.01109	119.48	155.89	1.82
28435	0.01133	164.04	214.03	1.91
36769	0.01123	211.22	275.58	1.87
48274	0.01128	277.84	362.50	1.90
63620	0.01137	367.72	479.78	1.89
83950	0.01160	490.03	639.35	1.89
110777	0.01214	661.44	863.00	1.87

Friction (l): $p/e = 3.92$, $e/D = 0.2$, $\psi_R = 9.276$, $\psi_l = 0.0169$

Re	f	Re_m	f_m	Re	f	Re_m	f_m
148	0.64497	1370	0.01090	3047	0.77515	26264	0.01310
192	0.51775	1781	0.00875	3952	0.74704	36655	0.01263
226	0.47337	2100	0.00800	5125	0.72041	47538	0.01218
294	0.53846	2723	0.00910	5837	0.72041	54137	0.01218
403	0.74704	3734	0.01263	7159	0.69379	66405	0.01173
522	0.89645	4843	0.01515	9817	0.69379	91054	0.01173
690	1.00000	6398	0.01690	12497	0.69379	115914	0.01173
800	1.00000	7423	0.01690	14770	0.72041	136998	0.01218
878	1.00000	8145	0.01690	18117	0.74704	168045	0.01263
1000	1.00000	9276	0.01690	23409	0.74704	217128	0.01263
1450	0.84911	13448	0.01435	28820	0.77515	267324	0.01310
1846	0.86391	17120	0.01460	32821	0.77515	304432	0.01310
2306	0.84911	21393	0.01435				

Stanton number ratios (θ):

Re_m	f_m	e^+	e_m^+	St_e/St_e
4124	0.01370	56.60	68.26	1.21
5467	0.01610	81.34	96.10	1.19
6675	0.01696	104.99	126.62	1.25
8799	0.01694	134.28	161.94	1.48
11436	0.01567	167.87	202.44	1.72
14100	0.01419	196.97	237.54	2.15
19985	0.01458	282.96	341.24	2.65
24212	0.01380	333.56	402.26	2.87
34924	0.01268	461.14	556.13	3.11
43056	0.01232	560.53	675.99	3.41
52163	0.01218	675.01	814.06	3.25
72155	0.01160	911.32	1099.04	3.42
92760	0.01173	1178.28	1420.99	3.38
116371	0.01173	1477.94	1782.38	3.42
131485	0.01204	1691.60	2040.06	3.56
176874	0.01265	2332.99	2813.56	3.21
206941	0.01261	2725.23	3286.59	3.42
262314	0.01305	3514.28	4238.18	3.60

Friction (k): $p/e = 9.8$, $e/D = 0.2$, $\psi_R = 8.616$, $\psi_I = 0.0277$

Re	f	Re_m	f_m	Re	f	Re_m	f_m
113	0.42226	970	0.01170	1896	0.88787	16338	0.02460
147	0.37110	1264	0.01028	2041	0.85845	17586	0.02378
167	0.32249	1442	0.00893	2210	0.86490	19039	0.02396
204	0.33291	1757	0.00922	2397	0.84253	20653	0.02334
230	0.29312	1982	0.00812	2585	0.85204	22274	0.02361
244	0.28876	2100	0.00800	2949	0.84886	25410	0.02352
254	0.29588	2187	0.00820	3306	0.85684	28486	0.02374
262	0.31888	2256	0.00883	3913	0.86167	33715	0.02387
278	0.32370	2391	0.00897	4413	0.87631	38018	0.02428
292	0.40296	2515	0.01116	4928	0.86977	42456	0.02410

Re	f	Re _m	f _m	Re	f	Re _m	f _m
307	0.80284	2845	0.01670	5304	0.87467	45699	0.02423
328	0.89738	2825	0.01932	6229	0.88787	53670	0.02460
340	0.73905	2931	0.02047	7024	0.88124	60519	0.02441
384	0.80551	3305	0.02232	8378	0.91315	72185	0.02530
423	0.83468	3648	0.02312	9338	0.93215	80456	0.02582
475	0.86490	4090	0.02396	11117	0.92174	95780	0.02554
550	0.85045	4738	0.02356	11874	0.91829	102301	0.02544
645	0.85045	5554	0.02356	13678	0.94444	117840	0.02617
747	0.87631	6435	0.02428	16505	0.92174	142199	0.02554
852	0.87795	7341	0.02432	20385	0.94444	175629	0.02617
983	0.87467	8472	0.02423	23527	0.97864	202698	0.02711
1085	0.87467	9352	0.02423	27846	0.99527	239906	0.02757
1177	0.87631	10145	0.02428	31338	0.99713	269997	0.02763
1275	0.86977	10983	0.02410	35681	1.03130	307415	0.02857
1383	0.87959	11914	0.02437	42149	1.04491	363141	0.02895
1571	0.87631	13539	0.02428	48835	1.07466	420738	0.02977
1718	0.86652	14801	0.02401				

Friction (n): $p/e = 26$, $e/D = 0.25$, $\psi_R = 11.589$, $\psi_f = 0.0138$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
114	0.71945	1320	0.00995	2937	0.89660	34034	0.01240
145	0.69414	1681	0.00960	4102	0.91287	47539	0.01263
165	0.60015	1912	0.00830	5838	0.91287	67651	0.01263
181	0.57845	2100	0.00800	6648	0.92914	77040	0.01285
218	0.66884	2529	0.00925	9460	0.92914	109637	0.01285
294	0.80441	3408	0.01113	10190	0.92914	118088	0.01285
375	0.80441	4347	0.01113	11434	0.92914	132508	0.01285
485	0.81887	5622	0.01133	14497	0.91287	168009	0.01263
606	0.81887	7025	0.01133	18121	0.92914	210000	0.01285
862	0.80441	9992	0.01113	22644	0.92914	262420	0.01285
1038	0.80441	12032	0.01113	26271	0.91287	304452	0.01263
1397	0.84780	16194	0.01173	29917	0.91287	346705	0.01263

Re	f	Re _m	f _m	Re	f	Re _m	f _m
1916	0.84780	22199	0.01173	32224	0.92914	373448	0.01285
2627	0.89660	30441	0.01240				

Stanton number ratios (n):

Re _m	f _m	e ⁺	e _m ⁺	St _f /St _e
5727	0.01134	79.12	107.82	1.12
8010	0.01124	110.18	150.15	1.17
10995	0.01110	150.24	204.75	1.34
14291	0.01144	198.25	270.17	1.60
18892	0.01180	266.22	362.81	1.84
25413	0.01194	360.18	490.86	2.36
30257	0.01239	436.91	595.42	2.54
45193	0.01258	657.45	895.98	2.95
57694	0.01263	840.98	1146.09	2.95
73653	0.01276	1079.34	1470.83	2.96
94027	0.01295	1388.00	1891.58	3.01
182245	0.01272	2812.30	3832.64	3.02
277298	0.01277	4064.72	5539.44	3.02
318825	0.01258	4639.40	6322.62	2.89

(c) Transverse ring inserts with clearance for flow near the wall

Friction (e = 2.25mm): p/e = 9.8, e/D = 0.045, $\psi_R = 1.795$, $\psi_l = 0.254$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
453	0.06112	813	0.01550	5266	0.08251	9453	0.02093
569	0.05363	1022	0.01360	6730	0.08251	12081	0.02093
716	0.04535	1285	0.01150	8325	0.08123	14944	0.02060
900	0.03845	1616	0.00975	10467	0.07857	18788	0.01993
993	0.03431	1783	0.00870	13598	0.07857	24408	0.01993
1170	0.03155	2100	0.00800	14517	0.07857	26058	0.01993
1249	0.04535	2242	0.01150	20804	0.07729	37343	0.01960
1378	0.06989	2473	0.01773	26157	0.08350	46951	0.02118

Re	f	Re _m	f _m	Re	f	Re _m	f _m
1471	0.07857	2840	0.01993	33980	0.08251	60994	0.02093
1910	0.09424	3429	0.02390	41348	0.08123	74220	0.02060
2482	0.09119	4455	0.02313	53715	0.08251	96419	0.02093
3225	0.09119	5788	0.02313	67537	0.08389	121228	0.02128
4054	0.08537	7277	0.02165				

Heat transfer (e = 2.25mm): $\psi_R = 2.516$

Re	Nu	Re _m	Nu _m	Re	Nu	Re _m	Nu _m
503	7.5	1286	7.5	6739	51.8	16958	51.8
733	10.7	1844	10.7	9211	64.1	23179	64.1
1086	13.9	2732	13.9	12590	82.1	31682	82.1
1509	18.4	3797	18.4	15337	90.6	38594	90.6
2202	24.7	5542	24.7	21311	117.5	53626	117.5
2683	28.7	6752	28.7	26829	152.2	67513	152.2
3162	31.1	7958	31.1	41145	184.8	103537	184.8
4850	40.5	12204	40.5	58119	247.1	146250	247.1

Stanton number ratios (e = 2.25mm)

Re _m	f _m	e ⁺	e _m ⁺	St _t /St _s
903	0.01468	3.85	3.48	1.02
1315	0.01131	4.92	4.45	1.07
1949	0.00737	5.89	5.32	1.22
2708	0.02054	13.66	12.35	1.49
3953	0.02379	21.47	19.40	1.93
4816	0.02295	25.69	23.22	2.09
5676	0.02314	30.40	27.47	2.08
8705	0.02094	44.35	40.09	2.15
12096	0.02092	61.60	55.68	2.15
16533	0.02030	82.92	74.95	2.15
22598	0.01987	112.13	101.35	2.12
27528	0.01987	136.63	123.49	2.07
38250	0.01969	188.97	170.80	2.03

Re_m	f_m	e^+	e_m^+	St/St_e
48155	0.02130	247.42	223.62	2.25
73850	0.02060	373.17	337.28	1.91
104316	0.02109	533.40	482.09	2.01

Friction ($e = 3.75\text{mm}$): $p/e = 9.8$, $e/D = 0.075$, $\psi_R = 2.992$, $\psi_f = 0.113$

Re	f	Re_m	f_m	Re	f	Re_m	f_m
304	0.13556	909	0.01525	5532	0.13333	16551	0.01500
369	0.11311	1103	0.01273	6850	0.13111	20496	0.01475
485	0.08978	1450	0.01010	8912	0.13111	26666	0.01475
579	0.07467	1731	0.00840	10560	0.13111	31594	0.01475
702	0.07111	2100	0.00800	13010	0.13111	38927	0.01475
851	0.10067	2547	0.01133	15336	0.13333	45886	0.01500
1033	0.12289	3092	0.01383	19307	0.13556	57767	0.01525
1218	0.13778	3645	0.01550	22758	0.13778	68093	0.01550
1534	0.15000	4589	0.01688	27724	0.14000	82950	0.01575
1808	0.15000	5409	0.01688	33773	0.14000	101049	0.01575
2202	0.14756	6589	0.01660	40471	0.14000	121089	0.01575
2596	0.14511	7767	0.01633	53527	0.14511	160152	0.01633
3162	0.13556	9462	0.01525	65206	0.14756	195095	0.01660
3852	0.13111	11526	0.01475				

Heat transfer ($e = 3.75\text{mm}$): $\psi_R = 4.194$

Re	Nu	Re_m	Nu_m	Re	Nu	Re_m	Nu_m
441	6.6	1851	6.6	6852	57.2	28735	57.2
632	9.2	2653	9.2	7688	59.1	32242	59.1
809	11.4	3391	11.4	9839	75.6	41263	75.6
1034	13.7	4335	13.7	12184	90.6	51100	90.6
1345	17.5	5640	17.5	14842	101.6	62248	101.6
1749	20.6	7337	20.6	18081	122.1	75831	122.1
2276	26.8	9546	26.8	22763	144.2	95465	144.2
2773	30.6	11630	30.6	28189	170.4	118224	170.4

Re	Nu	Re _m	Nu _m	Re	Nu	Re _m	Nu _m
3060	32.7	12835	32.7	38077	206	151304	206
3790	38.5	15896	38.5	43948	237.6	184316	237.6
4694	44.7	19685	44.7	53537	280.7	224531	280.7
5909	52.7	24782	52.7				

Stanton number ratios ($e = 3.75\text{mm}$):

Re _m	t_m	e^+	e_m^+	St_r/St_s
1320	0.01095	7.30	7.32	1.03
1892	0.00784	8.85	8.88	1.06
2419	0.01028	12.96	13.00	1.16
3082	0.01383	19.21	19.28	1.22
4023	0.01629	27.14	27.23	1.45
5233	0.01691	35.97	36.09	1.65
6809	0.01654	46.28	46.44	2.08
8295	0.01633	56.02	56.21	2.14
9155	0.01637	61.90	62.11	2.23
11338	0.01535	74.25	74.50	2.40
14041	0.01475	90.13	90.44	2.46
17676	0.01500	114.42	114.82	2.50
20496	0.01475	131.56	132.01	2.34
22997	0.01467	147.19	147.70	2.26
29432	0.01477	189.05	189.70	2.41
36448	0.01472	233.73	234.54	2.43
44400	0.01494	286.85	287.84	2.39
51320	0.01519	352.28	353.50	2.16
68093	0.01550	448.05	449.59	2.40
84326	0.01576	559.47	561.40	2.41
107921	0.01575	715.75	718.22	2.39
131468	0.01575	871.99	875.00	2.35
160152	0.01632	1081.46	1085.19	2.41

(d) Koch (1960): Enhancement factors

e/D	p/e	ψ_R	ψ_f	ψ_f^+	$\psi_{h,max}$
0.1	65	3.941	0.217	2.25	2.01
0.1	9.8	3.029	0.219	6.81	2.98
0.2	9.8	12.066	0.028	4.86	4.09
0.1	3.92	2.889	0.175	4.56	2.61
0.045	9.8	2.516	0.255	4.18	2.33
0.075	9.8	4.194	0.113	2.97	2.58
smooth		1	1	1	1

+ Based on $Re_m = 50,000$.

Table A.8

Nunner (1956)
Friction and heat transfer data for smooth and rough tubes

(a) Smooth tube

Friction (smooth): $D = 50.06 \text{ mm}$, $\psi_R = 0.837$, $\psi_i = 0.970$

Re	f	Re _m	f _m	Re	f	Re _m	f _m
928	0.01746	776	0.01693	6292	0.00927	5264	0.00899
965	0.01681	808	0.01630	6583	0.00914	5508	0.00886
1004	0.01617	840	0.01568	6977	0.00904	5837	0.00877
1038	0.01563	868	0.01516	7419	0.00891	6207	0.00864
1076	0.01514	900	0.01468	7836	0.00877	6556	0.00850
1124	0.01462	940	0.01417	8340	0.00863	6978	0.00836
1173	0.01414	981	0.01371	8824	0.00852	7382	0.00826
1216	0.01381	1017	0.01339	9439	0.00838	7898	0.00813
1262	0.01343	1056	0.01302	10116	0.00825	8463	0.00800
1303	0.01317	1090	0.01277	10730	0.00811	8977	0.00787
1344	0.01284	1125	0.01246	11498	0.00797	9620	0.00773
1389	0.01254	1162	0.01216	12332	0.00786	10318	0.00762
1443	0.01217	1207	0.01181	13081	0.00774	10944	0.00751
1510	0.01180	1263	0.01144	13887	0.00763	11619	0.00740
1588	0.01143	1329	0.01109	14667	0.00753	12271	0.00731
1654	0.01102	1384	0.01069	15557	0.00740	13016	0.00717
1731	0.01068	1448	0.01036	16515	0.00730	13818	0.00708
1785	0.01039	1494	0.01008	17488	0.00715	14632	0.00693
1861	0.01012	1557	0.00982	18392	0.00708	15388	0.00687
1931	0.00988	1616	0.00958	19276	0.00703	16128	0.00681
2029	0.00956	1698	0.00927	20499	0.00691	17151	0.00671
2121	0.00923	1775	0.00895	21688	0.00684	18145	0.00663
2218	0.00902	1855	0.00874	23480	0.00665	19645	0.00645
2316	0.00879	1938	0.00852	25313	0.00655	21179	0.00636
2399	0.00866	2007	0.00839	27057	0.00644	22638	0.00624
2476	0.00860	2072	0.00834	28773	0.00635	24073	0.00616

Re	f	Re _m	f _m	Re	f	Re _m	f _m
2547	0.00885	2131	0.00839	30966	0.00624	25908	0.00605
2815	0.00876	2188	0.00849	33240	0.00612	27811	0.00593
2708	0.00894	2266	0.00867	35835	0.00600	29982	0.00582
2741	0.00915	2293	0.00887	38434	0.00590	32157	0.00572
2836	0.00953	2373	0.00924	40977	0.00581	34284	0.00564
2930	0.00981	2451	0.00951	43279	0.00572	36210	0.00554
3008	0.01009	2517	0.00978	46142	0.00563	38606	0.00546
3089	0.01034	2584	0.01003	49786	0.00554	41654	0.00537
3235	0.01052	2706	0.01020	53034	0.00545	44372	0.00529
3367	0.01062	2817	0.01030	55918	0.00535	46785	0.00519
3446	0.01059	2883	0.01027	59617	0.00527	49880	0.00511
3556	0.01048	2975	0.01016	61847	0.00524	51745	0.00508
3730	0.01037	3121	0.01006	66902	0.00514	55975	0.00498
3917	0.01024	3277	0.00993	70963	0.00506	59373	0.00490
4147	0.01017	3470	0.00986	74249	0.00501	62122	0.00486
4391	0.01010	3674	0.00979	78622	0.00495	65781	0.00480
4599	0.00997	3848	0.00967	81772	0.00488	68416	0.00473
4849	0.00988	4057	0.00958	85412	0.00482	71462	0.00467
5065	0.00976	4237	0.00946	91062	0.00476	76189	0.00462
5437	0.00959	4549	0.00930	93986	0.00474	78635	0.00460
5718	0.00942	4784	0.00913				

Heat transfer (smooth):

Re	Nu _m	Re	Nu _m	Re	Nu _m	Re	Nu _m
552	7.32	3763	14.92	12311	35.82	36548	84.61
584	7.64	3957	15.26	12810	36.80	39096	88.59
635	8.18	4128	15.56	13377	38.18	40999	91.96
679	8.63	4343	16.04	14117	39.80	43239	95.77
750	9.15	4515	16.50	14868	41.41	45343	100.21
815	9.50	4776	17.10	15781	43.46	48642	105.38
893	10.04	5055	17.81	16869	45.83	51010	109.41
974	10.40	5312	18.53	17478	47.28	53911	115.05
1050	10.79	5551	19.35	17993	48.16	56938	120.29

Re	Nu _m	Re	Nu _m	Re	Nu _m	Re	Nu _m
1128	11.06	5821	20.13	19003	50.53	59624	124.72
1233	11.25	5959	20.63	19957	52.43	63106	129.67
1333	11.41	6156	21.15	20721	54.20	65570	134.53
1441	11.51	6406	21.88	21167	55.25	68082	138.01
1578	11.64	6916	22.96	21792	56.71	70340	141.67
1674	11.72	7135	23.74	22787	58.51	73398	146.96
1843	11.86	7361	24.37	23477	60.02	76481	151.85
1980	11.93	7698	25.07	24324	61.65	78738	155.77
2147	12.14	8124	25.94	25149	63.07	81523	159.56
2305	12.36	8520	26.87	25928	65.06	84886	164.50
2510	12.66	9023	27.90	26655	66.32	87515	168.15
2760	13.15	9369	28.88	27853	68.66	90354	172.49
2976	13.45	9874	30.01	29334	71.84	92757	175.57
3127	13.75	10267	31.24	30587	74.12	96790	180.87
3284	13.97	10782	32.39	32236	77.61	98942	184.10
3444	14.32	11243	33.61	34605	81.55	98731	184.75
3609	14.58	11840	34.97				

(b) Rough tube data

(m) denotes extracted value of Re or f based on smooth tube mean diameter d_m

(l) denotes recomputed value of Re or f based on maximum internal tube diameter D

Friction (A20, data set (4)): rectangular, $p/e = 20$, $e/D = 0.04$, $d_m = 49.82$ mm

ψ_R (m) = 1.053, ψ_i (m) = 0.615, ψ_R (l) = 1.056, ψ_i (l) = 0.612

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
993	0.02178	968	0.02189	1044	0.01339
1028	0.02066	1023	0.02076	1061	0.01270
1069	0.01994	1064	0.02003	1124	0.01226
1120	0.01914	1114	0.01923	1177	0.01177
1154	0.01847	1148	0.01856	1213	0.01136
1192	0.01776	1186	0.01785	1253	0.01092
1226	0.01717	1220	0.01725	1289	0.01055
1289	0.01655	1283	0.01663	1355	0.01017

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
1330	0.01593	1323	0.01601	1398	0.00979
1373	0.01547	1367	0.01555	1444	0.00951
1456	0.01473	1449	0.01480	1530	0.00906
1502	0.01430	1495	0.01437	1579	0.00879
1573	0.01369	1566	0.01376	1654	0.00842
1633	0.01333	1626	0.01340	1717	0.00820
1727	0.01313	1718	0.01319	1815	0.00807
1824	0.01310	1815	0.01316	1917	0.00805
1933	0.01311	1923	0.01317	2032	0.00806
2017	0.01337	2007	0.01343	2120	0.00822
2068	0.01367	2058	0.01373	2173	0.00840
2130	0.01400	2120	0.01406	2239	0.00861
2189	0.01453	2179	0.01460	2301	0.00893
2237	0.01510	2226	0.01517	2351	0.00928
2312	0.01619	2301	0.01627	2431	0.00995
2356	0.01746	2345	0.01755	2477	0.01074
2380	0.01866	2369	0.01875	2502	0.01147
2374	0.01957	2363	0.01966	2496	0.01203
2403	0.02084	2391	0.02094	2526	0.01281
2411	0.02165	2400	0.02176	2535	0.01331
2430	0.02261	2418	0.02272	2554	0.01390
2453	0.02380	2441	0.02391	2578	0.01463
2525	0.02515	2513	0.02527	2654	0.01546
2573	0.02642	2561	0.02655	2705	0.01624
2633	0.02764	2620	0.02777	2768	0.01699
2720	0.02872	2707	0.02886	2859	0.01766
2834	0.02987	2820	0.03001	2979	0.01836
2970	0.03087	2956	0.03102	3122	0.01898
3131	0.03173	3116	0.03188	3292	0.01950
3338	0.03268	3322	0.03284	3509	0.02009
3538	0.03333	3521	0.03349	3719	0.02049
3759	0.03350	3741	0.03366	3952	0.02080
4032	0.03390	4013	0.03406	4238	0.02084

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
4365	0.03460	4344	0.03477	4569	0.02127
4763	0.03490	4740	0.03506	5006	0.02145
5254	0.03565	5229	0.03582	5523	0.02192
5713	0.03601	5685	0.03619	6005	0.02214
6164	0.03644	6134	0.03662	6479	0.02241
6742	0.03707	6710	0.03725	7067	0.02279
7238	0.03723	7203	0.03741	7606	0.02289
7769	0.03754	7732	0.03773	8167	0.02306
8682	0.03790	8640	0.03808	9126	0.02330
9415	0.03812	9370	0.03831	9897	0.02344
10012	0.03835	9964	0.03854	10525	0.02358
10730	0.03832	10678	0.03850	11279	0.02356
11391	0.03878	11336	0.03896	11973	0.02384
12332	0.03878	12273	0.03896	12963	0.02384
13478	0.03875	13413	0.03893	14167	0.02382
14468	0.03868	14398	0.03887	15208	0.02378
15267	0.03881	15194	0.03900	16049	0.02386
16445	0.03875	16366	0.03893	17287	0.02382
17805	0.03855	17719	0.03873	18716	0.02370
19375	0.03858	19283	0.03877	20367	0.02372
20622	0.03852	20523	0.03870	21677	0.02368
21986	0.03832	21881	0.03850	23111	0.02356
24484	0.03803	24366	0.03821	25737	0.02338
27242	0.03770	27112	0.03789	28636	0.02318
29900	0.03748	29757	0.03766	31430	0.02304
32151	0.03761	31997	0.03779	33797	0.02312
35560	0.03767	35390	0.03785	37380	0.02316
38731	0.03783	38545	0.03802	40713	0.02326
42948	0.03780	42742	0.03798	45145	0.02324
46977	0.03809	46752	0.03828	49381	0.02342
50904	0.03845	50660	0.03863	53508	0.02364
54178	0.03888	53919	0.03906	56951	0.02390
57812	0.03924	57534	0.03943	60770	0.02413

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
63020	0.03954	62718	0.03973	66244	0.02431
67881	0.04012	67555	0.04031	71354	0.02467
75981	0.04057	75617	0.04076	79869	0.02494
78689	0.04095	78311	0.04114	82715	0.02517

Heat transfer (A20, data set (4)): $\psi_R (m) = 2.04$, $\psi_R (l) = 2.05$

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
554	7.52	551	7.55	1129
572	7.72	569	7.76	1167
593	7.96	590	7.99	1209
620	8.26	617	8.30	1265
652	8.63	649	8.67	1330
693	8.94	690	8.98	1414
729	9.23	725	9.28	1487
759	9.45	755	9.50	1549
792	9.70	788	9.75	1616
835	10.00	831	10.05	1703
892	10.40	888	10.45	1820
941	10.69	936	10.74	1920
996	10.92	991	10.97	2032
1065	11.14	1059	11.19	2172
1127	11.33	1121	11.38	2299
1185	11.50	1179	11.55	2418
1275	11.67	1269	11.73	2601
1362	11.82	1355	11.88	2778
1442	12.00	1435	12.06	2943
1563	12.30	1555	12.36	3188
1673	12.62	1665	12.68	3413
1789	13.11	1781	13.17	3651
1874	13.53	1865	13.60	3823
1943	13.93	1933	14.00	3984
2019	14.39	2009	14.46	4119

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
2103	14.67	2063	14.94	4292
2147	15.21	2137	15.28	4381
2223	15.79	2212	15.86	4536
2311	16.59	2300	16.67	4716
2410	17.27	2399	17.36	4918
2499	18.07	2487	18.16	5099
2606	18.91	2593	19.00	5317
2776	20.13	2762	20.23	5663
2911	21.15	2897	21.25	5939
3050	22.13	3036	22.24	6223
3194	23.31	3179	23.42	6517
3383	24.82	3367	24.94	6903
3591	26.05	3574	26.17	7326
3803	27.49	3785	27.62	7760
3941	28.70	3922	28.84	8040
4106	30.01	4086	30.15	8377
4300	31.60	4279	31.75	8773
4532	33.28	4510	33.44	9246
4662	34.06	4640	34.23	9512
4854	35.37	4831	35.54	9904
5094	37.01	5070	37.18	10394
5357	38.86	5332	39.04	10930
5662	40.98	5635	41.17	11552
5954	43.06	5926	43.27	12149
6227	44.83	6197	45.05	12704
6590	47.04	6559	47.27	13446
6886	49.05	6853	49.29	14050
7268	51.29	7233	51.54	14829
7660	54.09	7623	54.35	15628
8032	56.35	7994	56.62	16388
8388	58.34	8347	58.62	17113
8903	60.87	8860	61.17	18164
9422	63.83	9377	64.14	19224

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
9930	67.12	9883	67.45	20260
10421	70.43	10371	70.77	21262
11251	74.80	11197	75.16	22954
12043	78.21	11986	78.59	24572
12846	82.54	12785	82.94	26210
13684	87.84	13618	88.27	27918
14555	92.11	14485	92.56	29695
15536	97.34	15462	97.81	31698
16478	101.21	16399	101.70	33620
17955	108.02	17869	108.54	36633
19248	113.59	19155	114.14	39270
20256	118.27	20159	118.84	41328
21978	126.05	21872	126.66	44841
22950	130.96	22840	131.59	46824
24101	137.03	23985	137.69	49172
26075	145.02	25950	145.72	53200
28191	151.42	28056	152.15	57518
29922	159.22	29778	159.99	61049
31782	167.79	31629	168.60	64843
34021	176.56	33858	177.42	69413
36887	186.19	36710	187.09	75259
39458	195.24	39269	196.18	80505
42149	204.00	41946	204.98	85995
44326	212.25	44113	213.27	90437
48230	225.26	47998	226.34	98402
51922	238.39	51673	239.53	105935
54449	249.08	54188	250.28	111082
57710	262.85	57434	264.12	117745
61253	274.46	60960	275.78	124974
65014	286.37	64702	287.75	132647
68034	295.64	67707	297.06	138807
71345	304.99	71003	306.46	145563
72879	308.69	72530	310.17	148694

(c) transverse ring inserts with no clearance for flow near the wall

Friction (B20, data set (5)): semicircular (radius = 2 mm), $p/e = 20$, $e/D = 0.04$, $d_m = 49.82$ mm
 $\psi_R (m) = 1.053$, $\psi_I (m) = 0.615$, $\psi_R (l) = 1.056$, $\psi_I (l) = 0.612$

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
834	0.02556	830	0.02568	877	0.01571
862	0.02481	857	0.02493	906	0.01525
895	0.02396	890	0.02410	940	0.01474
927	0.02318	923	0.02329	975	0.01425
957	0.02233	952	0.02243	1006	0.01373
982	0.02153	967	0.02163	1043	0.01323
1034	0.02072	1029	0.02082	1087	0.01274
1062	0.02018	1057	0.02027	1116	0.01241
1089	0.01974	1083	0.01983	1144	0.01213
1121	0.01887	1115	0.01896	1178	0.01160
1158	0.01845	1152	0.01854	1217	0.01135
1198	0.01788	1192	0.01797	1259	0.01099
1230	0.01724	1224	0.01732	1293	0.01060
1270	0.01679	1264	0.01687	1335	0.01032
1321	0.01617	1314	0.01625	1388	0.00994
1368	0.01555	1361	0.01563	1438	0.00956
1428	0.01492	1422	0.01499	1502	0.00917
1486	0.01441	1479	0.01448	1562	0.00886
1540	0.01396	1533	0.01403	1619	0.00858
1606	0.01346	1598	0.01352	1688	0.00827
1689	0.01317	1681	0.01323	1775	0.00809
1778	0.01302	1769	0.01308	1868	0.00800
1855	0.01303	1846	0.01309	1950	0.00801
1948	0.01320	1938	0.01326	2047	0.00811
2064	0.01345	2054	0.01351	2170	0.00827
2154	0.01385	2144	0.01392	2264	0.00852
2180	0.01451	2170	0.01458	2292	0.00892
2279	0.01540	2268	0.01547	2396	0.00947
2334	0.01663	2323	0.01671	2454	0.01023

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
2391	0.01814	2379	0.01823	2513	0.01115
2424	0.01839	2412	0.01948	2548	0.01192
2467	0.02091	2456	0.02101	2594	0.01286
2555	0.02261	2543	0.02272	2686	0.01390
2655	0.02394	2643	0.02406	2791	0.01472
2797	0.02504	2784	0.02516	2941	0.01540
2970	0.02618	2956	0.02630	3122	0.01609
3153	0.02681	3138	0.02694	3314	0.01648
3419	0.02774	3403	0.02787	3594	0.01705
3696	0.02833	3678	0.02847	3885	0.01742
4115	0.02889	4096	0.02903	4326	0.01776
4399	0.02926	4378	0.02940	4624	0.01799
4783	0.02964	4760	0.02978	5028	0.01822
5161	0.02992	5136	0.03006	5425	0.01839
5573	0.03022	5546	0.03037	5858	0.01858
6148	0.03046	6119	0.03060	6463	0.01872
6626	0.03046	6596	0.03060	6967	0.01872
7281	0.03046	7246	0.03060	7653	0.01872
7782	0.03046	7745	0.03060	8181	0.01872
8397	0.03043	8357	0.03058	8827	0.01871
9375	0.03043	9330	0.03058	9855	0.01871
10255	0.03043	10206	0.03058	10779	0.01871
11159	0.03069	11106	0.03084	11730	0.01887
12144	0.03043	12086	0.03058	12765	0.01871
13710	0.03015	13644	0.03029	14411	0.01853
14592	0.03015	14522	0.03029	15338	0.01853
15744	0.03002	15669	0.03016	16550	0.01846
16786	0.02976	16705	0.02991	17645	0.01830
18220	0.02999	18132	0.03014	19152	0.01844
20169	0.02982	20072	0.02996	21201	0.01833
21743	0.02981	21639	0.02976	22856	0.01821
24028	0.02939	23913	0.02953	25258	0.01807
26804	0.02946	26675	0.02960	28175	0.01811

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
29773	0.02956	29630	0.02970	31296	0.01818
33411	0.02961	33251	0.02976	35121	0.01821
37303	0.02949	37124	0.02963	39211	0.01813
40524	0.02966	40330	0.02981	42598	0.01824
43799	0.02966	43589	0.02981	46041	0.01824
48692	0.02971	48459	0.02986	51184	0.01827
52898	0.02989	52644	0.03004	55605	0.01838
56253	0.03033	55983	0.03047	59131	0.01864
59770	0.03033	59483	0.03047	62828	0.01864
65043	0.03028	64731	0.03042	68371	0.01861
69642	0.03059	69308	0.03073	73206	0.01880
72681	0.03085	72332	0.03100	76399	0.01896
74630	0.03103	74273	0.03118	78449	0.01908

Heat transfer (B20, data set (5)): ψ_R (m) = 1.899, ψ_R (l) = 1.908

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
1886	12.43	1877	12.49	3581
1994	12.99	1985	13.05	3788
2114	13.75	2104	13.82	4014
2215	14.46	2205	14.53	4207
2338	15.15	2327	15.23	4440
2441	15.98	2430	16.06	4636
2587	16.98	2575	17.06	4914
2710	18.14	2697	18.23	5146
2872	19.25	2858	19.34	5454
3083	20.60	3068	20.70	5855
3219	21.61	3204	21.71	6114
3424	22.99	3408	23.11	6503
3604	24.18	3586	24.30	6844
3784	25.48	3766	25.60	7187
4000	26.70	3980	26.83	7596
4165	28.14	4145	28.27	7909

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
4324	29.34	4304	29.48	8212
4480	30.54	4459	30.69	8509
4782	32.21	4739	32.37	9044
5019	33.75	4995	33.91	9531
5244	35.27	5219	35.44	9960
5457	36.54	5431	36.71	10363
5850	39.02	5822	39.21	11109
6022	40.34	5994	40.54	11437
6392	42.48	6362	42.69	12139
6737	44.86	6704	45.08	12794
7150	46.94	7116	47.17	13579
7504	49.09	7468	49.32	14250
8021	51.76	7983	52.01	15233
8605	54.59	8563	54.85	16341
8947	56.91	8904	57.19	16991
9237	58.80	9193	59.08	17542
9707	61.44	9661	61.73	18435
10209	64.51	10160	64.82	19387
10820	67.89	10768	68.21	20548
11517	71.03	11462	71.38	21872
12452	75.98	12392	76.34	23647
13301	79.61	13237	79.99	25260
14057	83.77	13990	84.18	26696
14878	87.16	14807	87.58	28255
15789	91.72	15694	92.16	29947
16761	96.18	16681	96.64	31831
17930	102.22	17844	102.71	34050
19057	106.65	18966	107.17	36192
20156	110.89	20059	111.42	38278
21515	117.02	21412	117.58	40859
22546	122.18	22438	122.77	42817
23863	127.57	23748	128.19	45317
25220	132.45	25099	133.09	47895

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
26523	137.71	26396	138.38	50369
28052	142.96	27917	143.67	53272
29795	149.39	29652	150.11	56583
31378	156.21	31228	156.96	59590
33447	164.38	33286	165.17	63519
35526	172.73	35355	173.56	67466
38245	180.36	38062	181.22	72631
40593	187.78	40399	188.69	77091
42812	194.83	42606	195.76	81303
45893	203.57	45673	204.55	87156
48367	213.76	48135	214.79	91853
51263	222.56	51018	223.64	97354
53530	231.40	53274	232.52	101659
57547	242.82	57271	243.99	109287
60262	254.61	59973	255.84	114444
62972	262.85	62670	264.12	119589
66933	274.65	66612	275.97	127111
71143	285.96	70802	287.34	135107
74500	297.11	74143	298.54	141482
78916	305.21	78547	306.68	146071
79693	313.09	79311	314.80	151345

Friction (B80, data set (7)): semicircular (radius = 2 mm), $p/e = 80$, $e/D = 0.04$, $d_m = 49.95$ mm
 $\psi_R (m) = 0.826$, $\psi_l (m) = 0.842$, $\psi_R (l) = 0.828$, $\psi_l (l) = 0.839$

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
500	0.04215	499	0.04224	413	0.03548
520	0.04057	519	0.04066	429	0.03415
546	0.03878	544	0.03886	451	0.03264
562	0.03777	560	0.03785	464	0.03179
577	0.03682	576	0.03690	477	0.03099
595	0.03589	594	0.03597	492	0.03021
621	0.03445	620	0.03453	513	0.02900
638	0.03333	637	0.03340	527	0.02805

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
657	0.03286	655	0.03273	542	0.02749
668	0.03200	667	0.03207	552	0.02693
682	0.03127	680	0.03134	563	0.02632
695	0.03066	694	0.03073	574	0.02581
715	0.02989	714	0.02996	591	0.02516
738	0.02897	736	0.02903	609	0.02438
766	0.02762	765	0.02768	633	0.02325
794	0.02678	793	0.02684	656	0.02255
820	0.02593	818	0.02599	677	0.02183
844	0.02517	842	0.02523	697	0.02119
863	0.02456	861	0.02461	730	0.02067
915	0.02348	913	0.02353	756	0.01976
944	0.02275	942	0.02280	780	0.01915
975	0.02216	973	0.02221	805	0.01865
1023	0.02096	1021	0.02101	845	0.01765
1080	0.01969	1078	0.01973	892	0.01657
1124	0.01896	1121	0.01900	928	0.01596
1163	0.01841	1160	0.01845	960	0.01549
1225	0.01739	1222	0.01743	1012	0.01464
1264	0.01693	1261	0.01697	1044	0.01425
1307	0.01640	1304	0.01643	1080	0.01380
1323	0.01611	1320	0.01614	1093	0.01356
1357	0.01583	1354	0.01587	1121	0.01333
1397	0.01533	1394	0.01536	1154	0.01290
1433	0.01499	1430	0.01503	1184	0.01262
1509	0.01448	1505	0.01451	1246	0.01219
1569	0.01376	1566	0.01379	1296	0.01158
1647	0.01333	1644	0.01336	1361	0.01122
1728	0.01286	1724	0.01288	1427	0.01082
1799	0.01231	1795	0.01234	1486	0.01036
1908	0.01193	1904	0.01195	1576	0.01004
1973	0.01151	1968	0.01153	1630	0.00969
2055	0.01111	2051	0.01113	1698	0.00935

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
2152	0.01085	2148	0.01088	1778	0.00914
2233	0.01080	2228	0.01082	1844	0.00892
2340	0.01039	2335	0.01042	1933	0.00875
2449	0.01030	2443	0.01032	2023	0.00867
2540	0.01038	2535	0.01041	2098	0.00874
2608	0.01069	2603	0.01071	2155	0.00900
2699	0.01123	2693	0.01125	2229	0.00945
2760	0.01189	2753	0.01191	2279	0.01001
2851	0.01245	2844	0.01247	2355	0.01048
2887	0.01294	2881	0.01297	2385	0.01089
2937	0.01371	2931	0.01374	2426	0.01154
3047	0.01420	3040	0.01423	2517	0.01195
3139	0.01453	3132	0.01456	2593	0.01223
3268	0.01499	3261	0.01503	2699	0.01262
3437	0.01503	3429	0.01507	2839	0.01265
3683	0.01519	3675	0.01522	3042	0.01278
3893	0.01523	3885	0.01526	3216	0.01282
4151	0.01525	4142	0.01529	3429	0.01284
4544	0.01527	4534	0.01530	3754	0.01285
4899	0.01529	4888	0.01532	4047	0.01287
5254	0.01527	5243	0.01530	4340	0.01285
5684	0.01527	5671	0.01530	4695	0.01285
6117	0.01524	6103	0.01527	5053	0.01283
6538	0.01511	6524	0.01514	5401	0.01272
7060	0.01501	7045	0.01504	5832	0.01263
7743	0.01505	7728	0.01508	6396	0.01266
8390	0.01496	8372	0.01499	6930	0.01259
9303	0.01484	9283	0.01488	7685	0.01249
10168	0.01475	10145	0.01479	8399	0.01242
10970	0.01459	10946	0.01462	9062	0.01228
11938	0.01453	11912	0.01456	9861	0.01223
12663	0.01442	12635	0.01445	10460	0.01214
13432	0.01436	13402	0.01439	11095	0.01209

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
14431	0.01425	14399	0.01428	11920	0.01199
15359	0.01406	15325	0.01409	12687	0.01183
16686	0.01384	16649	0.01387	13783	0.01165
18173	0.01373	18133	0.01376	15012	0.01155
19743	0.01360	19700	0.01363	16308	0.01145
21618	0.01351	21770	0.01354	18022	0.01137
24380	0.01332	24326	0.01335	20138	0.01121
26967	0.01312	26927	0.01315	22292	0.01104
29748	0.01309	29682	0.01312	24572	0.01102
32125	0.01304	32055	0.01307	26536	0.01098
35196	0.01302	35119	0.01305	29073	0.01096
37976	0.01293	37892	0.01296	31369	0.01089
41221	0.01287	41130	0.01289	34050	0.01083
44632	0.01284	44534	0.01287	36867	0.01081
48732	0.01288	48625	0.01291	40254	0.01084
54176	0.01286	54057	0.01288	44751	0.01082
58560	0.01275	58431	0.01277	48372	0.01073
62806	0.01278	62668	0.01281	51879	0.01076
68638	0.01275	68487	0.01277	56697	0.01073
73116	0.01263	72955	0.01266	60396	0.01063
78692	0.01262	78519	0.01264	65002	0.01062

Heat transfer (B80, data set (7)): $\psi_R (m) = 1.639$, $\psi_R (l) = 1.643$

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
4191	20.40	4182	20.45	6871
4398	21.41	4389	21.45	7211
4688	22.75	4678	22.80	7686
4983	23.99	4972	24.05	8170
5373	25.53	5361	25.59	8808
5788	27.33	5775	27.39	9489
6161	28.99	6147	29.05	10100
6548	30.57	6534	30.63	10735

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
6940	31.94	6925	32.01	11378
7361	33.54	7345	33.61	12068
7666	35.37	7668	35.44	12928
8328	36.93	8310	37.01	13654
8752	38.45	8733	38.53	14349
9126	40.09	9106	40.18	14962
9652	42.18	9631	42.26	15824
9902	43.06	9880	43.15	16234
10303	44.48	10281	44.56	16891
10782	46.19	10758	46.29	17676
11331	48.02	11306	48.13	18576
11773	49.75	11747	49.86	19301
12585	53.14	12557	53.25	20632
13254	54.90	13225	55.02	21728
13889	57.03	13858	57.16	22770
14868	59.93	14835	60.06	24374
15547	62.31	15513	62.45	25488
16572	65.76	16536	65.90	27169
17814	69.00	17576	69.15	28877
18643	72.25	18602	72.41	30564
19564	74.80	19521	74.97	32074
20546	77.61	20501	77.78	33683
21500	80.23	21453	80.41	35247
22197	82.30	22148	82.49	36390
22999	84.85	22948	85.04	37704
23812	87.16	23760	87.35	39038
24812	89.98	24758	90.18	40677
25526	92.44	25470	92.64	41848
26448	94.09	26390	94.30	43359
27853	98.31	27792	98.53	45663
29292	101.71	29228	101.93	48022
30739	105.60	30672	105.83	50395
31804	109.25	31734	109.49	52140

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
32999	112.63	32927	112.88	54099
34778	116.44	34701	116.69	57015
37096	122.01	37015	122.26	60617
39654	125.43	39570	125.70	63371
39626	128.30	39539	128.58	64964
41057	131.43	40967	131.71	67309
42690	134.91	42596	135.21	69967
44673	138.89	44575	139.19	73238
46715	142.98	46612	143.29	76585
49232	147.71	49124	148.04	80712
51409	152.49	51296	152.83	84281
54759	160.47	54639	160.82	89773
57302	165.31	57177	165.68	93943
60777	171.88	60644	172.26	99640
62793	176.56	62655	176.95	102945
65523	180.48	65379	180.88	107420
68469	186.19	68319	186.60	112250
70490	191.68	70335	192.10	115562
72673	195.38	72513	195.81	119141
74606	200.00	74442	200.44	122310
76318	202.56	76151	203.01	125118
77905	204.87	77733	205.32	127718

Friction (D2, data set (6)): semicircular (radius = 4 mm), $p/e = 2$, $a/D = 0.08$, $d_m = 43.85$ mm
 $\psi_R (m) = 0.737$, $\psi_I (m) = 0.8$, $\psi_R (l) = 0.841$, $\psi_I (l) = 0.702$

$Re (m)$	$f (m)$	$Re (l)$	$f (l)$	Re_m	f_m
1202	0.01766	1053	0.02016	886	0.01414
1258	0.01711	1102	0.01953	927	0.01371
1301	0.01641	1140	0.01873	959	0.01315
1348	0.01585	1181	0.01809	993	0.01270
1376	0.01550	1205	0.01770	1014	0.01242
1438	0.01478	1260	0.01687	1060	0.01184
1510	0.01422	1323	0.01624	1112	0.01140
1562	0.01380	1369	0.01575	1151	0.01105
1629	0.01335	1427	0.01524	1200	0.01069
1687	0.01300	1478	0.01484	1243	0.01041
1765	0.01254	1546	0.01432	1301	0.01005
1838	0.01210	1610	0.01382	1354	0.00970
1916	0.01170	1679	0.01335	1412	0.00937
1991	0.01131	1744	0.01291	1467	0.00906
2087	0.01100	1828	0.01256	1538	0.00881
2193	0.01065	1921	0.01216	1616	0.00853
2262	0.01040	1981	0.01187	1666	0.00833
2344	0.01029	2053	0.01174	1727	0.00824
2436	0.01020	2134	0.01164	1795	0.00817
2564	0.01016	2246	0.01159	1889	0.00814
2671	0.01015	2340	0.01159	1968	0.00813
2743	0.01014	2403	0.01158	2021	0.00812
2817	0.01023	2467	0.01167	2075	0.00819
2965	0.01036	2597	0.01182	2184	0.00830
3013	0.01065	2639	0.01216	2220	0.00853
3078	0.01100	2696	0.01256	2268	0.00881
3147	0.01142	2757	0.01304	2319	0.00915
3180	0.01192	2785	0.01361	2343	0.00955
3260	0.01262	2855	0.01440	2401	0.01011
3290	0.01330	2882	0.01518	2424	0.01066
3370	0.01381	2952	0.01576	2483	0.01106
3443	0.01438	3016	0.01642	2536	0.01152

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
3484	0.01497	3052	0.01709	2567	0.01199
3569	0.01567	3153	0.01789	2651	0.01256
3689	0.01641	3232	0.01873	2718	0.01315
3837	0.01701	3361	0.01942	2827	0.01362
3984	0.01751	3472	0.01998	2920	0.01402
4144	0.01784	3630	0.02036	3053	0.01429
4306	0.01813	3772	0.02069	3172	0.01452
4479	0.01836	3923	0.02096	3299	0.01471
4738	0.01849	4150	0.02110	3491	0.01481
4949	0.01842	4335	0.02103	3646	0.01476
5178	0.01834	4536	0.02094	3815	0.01470
5488	0.01828	4807	0.02087	4043	0.01465
5876	0.01822	5147	0.02080	4329	0.01460
6276	0.01813	5497	0.02069	4623	0.01452
6754	0.01807	5916	0.02062	4976	0.01447
7182	0.01816	6291	0.02073	5291	0.01455
7547	0.01813	6811	0.02069	5560	0.01452
8157	0.01805	7145	0.02061	6009	0.01446
8907	0.01822	7802	0.02080	6562	0.01460
9660	0.01817	8461	0.02075	7116	0.01456
10396	0.01830	9106	0.02089	7659	0.01466
11074	0.01833	9700	0.02092	8158	0.01468
11989	0.01841	10502	0.02101	8833	0.01475
12892	0.01856	11293	0.02119	9498	0.01487
13698	0.01858	11999	0.02121	10092	0.01488
14780	0.01858	12946	0.02121	10889	0.01488
16139	0.01863	14137	0.02126	11890	0.01492
17881	0.01871	15663	0.02136	13173	0.01499
19129	0.01893	16756	0.02161	14092	0.01517
20063	0.01896	17592	0.02165	14795	0.01519
21031	0.01906	18422	0.02176	15494	0.01527
22672	0.01906	19660	0.02176	16703	0.01527
24991	0.01919	21891	0.02191	18411	0.01537

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
26485	0.01937	23200	0.02211	18512	0.01522
27973	0.01962	24503	0.02240	20606	0.01572
30311	0.01970	26551	0.02249	22331	0.01578
33755	0.01984	29568	0.02265	24868	0.01589
36235	0.02002	31740	0.02286	26695	0.01604
38665	0.02007	33868	0.02292	28485	0.01608
42655	0.02026	37384	0.02313	31424	0.01623
45749	0.02047	40074	0.02337	33704	0.01640
51165	0.02075	44818	0.02369	37694	0.01663
55490	0.02104	48606	0.02402	40680	0.01685
60334	0.02127	52849	0.02428	44448	0.01704
64655	0.02162	56635	0.02468	47632	0.01732
70360	0.02197	61631	0.02508	51835	0.01760
76111	0.02238	66669	0.02555	56072	0.01793
81076	0.02308	71019	0.02635	59730	0.01849
84686	0.02342	74180	0.02673	62389	0.01876
89215	0.02374	78147	0.02710	65725	0.01902

Heat transfer (D2, data set (6)): $\psi_R (m) = 1.510$, $\psi_R (l) = 1.724$

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
620	6.39	543	7.30	936
642	6.66	562	7.60	970
679	6.97	585	7.96	1025
719	7.33	630	8.37	1086
762	7.71	667	8.80	1150
801	8.07	702	9.21	1210
858	8.53	752	9.74	1296
897	8.80	788	10.04	1355
967	9.22	847	10.53	1461
1025	9.53	898	10.88	1548
1074	9.80	940	11.18	1622
1148	10.17	1005	11.61	1733

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
1215	10.38	1064	11.84	1835
1309	10.57	1146	12.08	1976
1391	10.61	1218	12.12	2101
1472	10.79	1290	12.32	2223
1534	10.70	1344	12.22	2317
1618	10.84	1417	12.38	2443
1747	11.03	1530	12.60	2638
1872	11.13	1640	12.70	2828
1983	11.25	1737	12.84	2995
2149	11.42	1882	13.04	3245
2271	11.49	1989	13.12	3430
2459	11.60	2154	13.24	3713
2610	11.63	2286	13.27	3941
2727	11.63	2389	13.27	4118
2797	11.61	2450	13.26	4225
2831	11.64	2480	13.28	4276
2874	12.01	2517	13.71	4340
2950	12.79	2584	14.61	4456
3007	13.41	2634	15.31	4542
3085	14.04	2702	16.03	4659
3134	14.52	2745	16.58	4733
3242	15.22	2840	17.37	4896
3390	16.05	2970	18.32	5120
3490	16.83	3057	19.21	5271
3647	17.80	3195	20.32	5508
3798	18.63	3327	21.27	5736
3988	19.65	3494	22.43	6023
4191	20.63	3671	23.56	6330
4349	21.45	3809	24.49	6568
4551	22.61	3986	25.81	6873
4739	23.41	4151	26.72	7156
4945	24.32	4331	27.76	7468
5098	24.80	4465	28.32	7699

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
5415	26.14	4743	29.84	8177
5559	26.98	4869	30.81	8395
5804	28.34	5084	32.35	8766
6014	29.36	5268	33.51	9082
6205	30.31	5435	34.60	9370
6567	32.05	5752	36.59	9918
6789	32.95	5947	37.61	10254
7090	34.33	6210	39.19	10707
7377	35.39	6462	40.40	11141
7720	36.80	6762	42.01	11658
8021	38.18	7026	43.58	12114
8495	40.17	7442	45.86	12830
8840	41.80	7743	47.72	13350
9276	43.52	8126	49.68	14010
9632	45.44	8437	51.87	14546
10101	47.41	8848	54.13	15255
10577	49.61	9265	56.63	15974
11069	51.98	9695	59.34	16716
11525	53.59	10096	61.18	17406
12155	56.03	10647	63.97	18357
12692	58.51	11118	66.79	19169
13169	60.53	11536	69.10	19889
13481	61.79	11809	70.54	20360
14208	65.20	12445	74.44	21457
14878	67.65	13033	77.23	22470
15736	71.34	13784	81.44	23765
16643	74.80	14578	85.39	25135
17614	77.99	15429	89.04	26602
18669	81.84	16353	93.43	28195
19872	86.36	17407	98.59	30011
21002	91.20	18397	104.12	31719
22197	95.09	19444	108.56	33523
23278	99.36	20390	113.43	35155

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
24445	104.56	21413	119.37	36918
25653	106.79	22471	124.19	38742
26731	113.11	23415	129.13	40370
28271	118.10	24764	134.82	42696
29085	121.41	25477	138.60	43925
30114	125.25	26378	142.98	45479
31267	129.39	27389	147.72	47221
33518	136.74	29360	156.11	50620
34458	140.77	30184	160.70	52040
35601	143.59	31185	163.92	53766
36626	146.96	32082	167.80	55314
38709	151.85	33907	173.35	58460
40022	156.54	35057	178.71	60442
41673	161.95	36503	184.89	62936
43423	168.15	38036	191.96	65579
45343	174.08	39718	198.74	68479
46914	178.83	41094	204.16	70851
49267	186.33	43155	212.71	74405
51336	193.04	44968	220.38	77530
53606	200.14	46956	228.48	80958
56136	210.01	49172	239.75	84778
58369	216.96	51128	247.69	88151
61558	224.78	53922	256.61	92968
63781	232.06	55869	264.92	96324
65616	237.88	57477	271.57	99097
67457	244.19	59069	278.78	101876
69942	252.10	61266	287.80	105629
72384	259.53	63387	296.28	109287
74659	266.60	65397	304.36	112752
77905	276.99	68240	316.22	117654
79524	280.55	69659	320.28	120100
80374	283.54	70404	323.70	121384

Friction (D5, data set (2)): semicircular (radius = 4 mm), $p/e = 5$, $a/D = 0.08$, $d_m = 47.78$ mm
 $\psi_R (m) = 0.995$, $\psi_l (m) = 0.508$, $\psi_R (l) = 0.998$, $\psi_l (l) = 0.485$

$Re (m)$	$f (m)$	$Re (l)$	$f (l)$	Re_m	f_m
1646	0.01974	1571	0.02068	1638	0.01003
1722	0.01924	1644	0.02016	1714	0.00977
1767	0.01883	1686	0.01973	1758	0.00957
1817	0.01819	1735	0.01906	1808	0.00924
1879	0.01773	1793	0.01858	1870	0.00901
1939	0.01724	1851	0.01806	1930	0.00876
1985	0.01676	1894	0.01756	1975	0.00852
2036	0.01649	1943	0.01728	2026	0.00838
2087	0.01659	1992	0.01738	2077	0.00843
2130	0.01702	2033	0.01783	2120	0.00865
2145	0.01758	2047	0.01842	2134	0.00893
2167	0.01834	2068	0.01922	2156	0.00932
2182	0.01975	2083	0.02070	2171	0.01003
2176	0.02151	2077	0.02253	2166	0.01093
2201	0.02326	2100	0.02437	2190	0.01181
2225	0.02550	2124	0.02671	2214	0.01295
2262	0.02845	2159	0.02981	2250	0.01445
2287	0.03130	2183	0.03279	2276	0.01590
2314	0.03419	2209	0.03582	2303	0.01737
2380	0.03710	2272	0.03887	2369	0.01885
2407	0.04067	2297	0.04261	2395	0.02066
2459	0.04383	2347	0.04592	2447	0.02227
2551	0.04668	2435	0.04891	2538	0.02371
2640	0.04963	2519	0.05199	2627	0.02521
2771	0.05156	2645	0.05402	2758	0.02619
2965	0.05344	2830	0.05599	2950	0.02715
3150	0.05459	3007	0.05719	3135	0.02773
3460	0.05628	3303	0.05897	3443	0.02859
3870	0.05808	3694	0.06086	3851	0.02951
4317	0.05858	4120	0.06138	4296	0.02976
4857	0.06015	4636	0.06302	4833	0.03055
5263	0.06015	5023	0.06302	5237	0.03055

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
5942	0.06061	5671	0.06372	5912	0.03069
6702	0.06066	6397	0.06355	6669	0.03061
7343	0.06051	7009	0.06339	7307	0.03074
8262	0.06066	7886	0.06355	8221	0.03061
9115	0.06009	8699	0.06296	9070	0.03053
9910	0.05959	9459	0.06243	9861	0.03027
10859	0.05928	10364	0.06211	10805	0.03011
11857	0.05878	11317	0.06159	11799	0.02986
12914	0.05838	12326	0.06117	12850	0.02966
13982	0.05784	13345	0.06060	13913	0.02938
14932	0.05769	14252	0.06044	14859	0.02931
15866	0.05749	15143	0.06024	15787	0.02921
16901	0.05711	16131	0.05983	16817	0.02901
18127	0.05691	17301	0.05963	18037	0.02891
19492	0.05672	18604	0.05942	19395	0.02881
21558	0.05624	20576	0.05892	21452	0.02857
23440	0.05657	22373	0.05927	23325	0.02874
25904	0.05657	24724	0.05927	25776	0.02874
28431	0.05691	27136	0.05963	28290	0.02891
31769	0.05740	30322	0.06014	31612	0.02916
36111	0.05774	34467	0.06049	35933	0.02933
40455	0.05948	38613	0.06232	40256	0.03022
44213	0.06076	42199	0.06366	43995	0.03087
48984	0.06149	46753	0.06443	48743	0.03124
53170	0.06384	50748	0.06688	52907	0.03243
58158	0.06560	55509	0.06873	57871	0.03332
61794	0.06701	58979	0.07020	61489	0.03404
66163	0.06856	63150	0.07184	65837	0.03483
71389	0.07022	68137	0.07357	71036	0.03567
76633	0.07228	73142	0.07573	76254	0.03672
80731	0.07472	77054	0.07828	80332	0.03795
84831	0.07619	80967	0.07983	84412	0.03870
86735	0.07671	82785	0.08037	86307	0.03897

Heat transfer (D5, data set (2)): $\psi_R (l) = 1.765$, $\psi_R (m) = 1.684$

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
1416	14.86	1351	15.56	2385
1490	15.30	1422	16.03	2510
1579	15.79	1507	16.54	2660
1675	16.24	1599	17.02	2821
1782	16.73	1681	17.53	2967
1849	17.21	1764	18.03	3114
1943	17.90	1854	18.75	3272
2059	18.58	1965	19.47	3468
2193	19.36	2093	20.28	3694
2330	20.11	2224	21.07	3924
2452	21.06	2340	22.07	4129
2526	21.71	2411	22.75	4254
2615	22.37	2496	23.44	4405
2744	23.22	2619	24.33	4622
2868	24.20	2737	25.35	4830
2942	24.73	2808	25.91	4955
3070	25.63	2930	26.85	5170
3247	26.68	3099	27.95	5468
3538	28.88	3377	30.26	5958
3736	30.70	3566	32.16	6293
3946	32.46	3766	34.01	6646
4188	34.09	3998	35.71	7054
4424	36.15	4222	37.88	7450
4759	38.45	4542	40.28	8015
5030	40.86	4800	42.81	8471
5350	43.03	5106	45.08	9010
5638	44.96	5381	47.10	9496
5933	47.34	5663	49.60	9993
6370	50.50	6079	52.90	10728
6761	52.84	6453	55.36	11387
7171	55.56	6844	58.21	12077

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
7566	58.18	7223	60.95	12746
8055	60.53	7688	63.42	13567
8405	62.49	8023	65.47	14157
8960	65.43	8552	68.56	15060
9449	68.47	9019	71.73	15915
9825	71.08	9378	74.48	16548
10347	74.17	9876	77.71	17427
11045	78.21	10542	81.85	18603
11731	81.67	11197	85.56	19759
12320	84.31	11759	88.33	20750
13188	88.53	12587	92.76	22212
13978	92.90	13341	97.33	23542
14878	97.27	14201	101.92	25059
15492	101.35	14787	106.19	26093
16143	103.53	15408	108.47	27188
16969	108.48	16215	113.66	28613
17981	113.51	17162	118.92	30284
18842	117.85	17984	123.47	31735
19914	122.79	19007	128.65	33541
21530	129.94	20550	136.15	36263
22868	135.87	21827	142.36	38516
24324	141.87	23216	148.64	40968
26168	149.39	24976	156.52	44073
27794	155.88	26528	163.32	46812
29668	167.08	28317	175.05	49969
31312	174.21	29886	182.52	52737
32952	181.25	31452	189.90	55500
34852	189.52	33264	198.56	58699
36730	196.91	35057	206.30	61862
38572	204.87	36816	214.65	64966
40911	214.37	39048	224.60	68905
44012	227.18	42008	238.02	74128
46681	241.27	44555	252.79	78623

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
48607	250.14	46394	262.08	81867
50327	257.88	48035	270.18	84763
52366	268.12	49981	280.91	88198
54527	278.76	52043	292.07	91837
56415	286.77	53846	300.46	95017
59751	300.49	57030	314.83	100637
63645	315.98	60747	331.06	107195
67649	332.51	64568	348.38	113938
69300	343.76	66144	360.17	116719
72006	354.89	68726	371.83	121276
75083	368.72	71664	386.32	128459
76753	375.31	73257	393.22	129271
78126	382.01	74568	400.24	131584

Friction (D10, data set (1)): $p/e = 10$, $e/D = 0.08$, $d_m = 48.92$ mm
 ψ_R (m) = 1.241, ψ_l (m) = 0.427, ψ_R (l) = 1.270, ψ_l (m) = 0.417

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
593	0.04963	579	0.05078	736	0.02119
623	0.04760	609	0.04871	774	0.02032
651	0.04554	636	0.04660	808	0.01944
689	0.04302	674	0.04402	856	0.01837
720	0.04084	704	0.04180	894	0.01744
753	0.03941	736	0.04033	935	0.01683
784	0.03806	766	0.03895	973	0.01625
814	0.03675	796	0.03761	1011	0.01569
845	0.03571	826	0.03654	1049	0.01524
873	0.03466	853	0.03547	1083	0.01480
907	0.03327	886	0.03405	1126	0.01421
945	0.03200	923	0.03274	1173	0.01366
979	0.03103	957	0.03175	1216	0.01325
1010	0.03007	987	0.03077	1254	0.01284
1038	0.02919	1014	0.02987	1288	0.01246

Re (m)	f (m)	Re (l)	f (l)	Re _m	t _m
1102	0.02766	1077	0.02831	1368	0.01181
1135	0.02692	1109	0.02755	1409	0.01149
1163	0.02636	1136	0.02697	1443	0.01125
1199	0.02556	1172	0.02616	1488	0.01091
1240	0.02487	1211	0.02545	1539	0.01062
1294	0.02398	1264	0.02454	1606	0.01024
1339	0.02320	1308	0.02374	1662	0.00990
1416	0.02206	1384	0.02258	1758	0.00942
1483	0.02113	1449	0.02162	1841	0.00902
1544	0.02026	1509	0.02074	1917	0.00865
1600	0.01974	1564	0.02020	1987	0.00843
1653	0.01975	1615	0.02021	2052	0.00843
1699	0.01999	1660	0.02046	2109	0.00853
1727	0.02073	1687	0.02122	2143	0.00885
1738	0.02165	1699	0.02216	2158	0.00924
1741	0.02267	1702	0.02320	2162	0.00968
1774	0.02354	1734	0.02408	2203	0.01005
1787	0.02500	1746	0.02558	2218	0.01067
1799	0.02727	1758	0.02790	2233	0.01164
1814	0.03043	1773	0.03114	2252	0.01299
1842	0.03373	1800	0.03451	2287	0.01440
1868	0.03685	1825	0.03771	2319	0.01573
1890	0.04033	1847	0.04127	2347	0.01722
1918	0.04447	1874	0.04551	2381	0.01899
1943	0.04858	1898	0.04972	2412	0.02074
1978	0.05335	1933	0.05459	2455	0.02278
2002	0.05784	1956	0.05919	2485	0.02469
2005	0.06035	1959	0.06176	2489	0.02577
2034	0.06411	1988	0.06560	2525	0.02737
2112	0.06962	2064	0.07124	2622	0.02972
2162	0.07364	2112	0.07536	2683	0.03144
2279	0.07619	2227	0.07797	2829	0.03253
2417	0.07816	2362	0.07998	3001	0.03337

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
2577	0.07709	2519	0.07971	3199	0.03326
2809	0.07816	2745	0.07998	3488	0.03337
3052	0.07816	2983	0.07998	3789	0.03337
3285	0.07796	3191	0.07978	4053	0.03328
3481	0.07803	3402	0.07985	4322	0.03331
3624	0.07783	3541	0.07964	4499	0.03323
3772	0.07743	3686	0.07924	4683	0.03306
4101	0.07763	4008	0.07944	5082	0.03314
4437	0.07750	4336	0.07930	5503	0.03309
4694	0.07783	4587	0.07964	5827	0.03323
5086	0.07750	4971	0.07930	6314	0.03309
5143	0.07743	5026	0.07924	6385	0.03306
5414	0.07717	5290	0.07897	6720	0.03295
5737	0.07704	5607	0.07883	7122	0.03289
6054	0.07652	5917	0.07830	7516	0.03267
6449	0.07665	6303	0.07843	8006	0.03272
6847	0.07645	6691	0.07823	8500	0.03264
7293	0.07632	7127	0.07810	9054	0.03258
7723	0.07555	7547	0.07731	9587	0.03225
8297	0.07542	8108	0.07718	10300	0.03220
8937	0.07516	8734	0.07691	11095	0.03209
9693	0.07491	9472	0.07665	12033	0.03198
10176	0.07472	9944	0.07646	12633	0.03190
10657	0.07415	10414	0.07587	13229	0.03186
11449	0.07421	11188	0.07594	14213	0.03168
12652	0.07427	12384	0.07600	15707	0.03171
13535	0.07384	13227	0.07536	16803	0.03144
14369	0.07358	14042	0.07529	17838	0.03141
15372	0.07427	15022	0.07600	19083	0.03171
16057	0.07389	15691	0.07562	19933	0.03155
17163	0.07389	16772	0.07562	21306	0.03155
18645	0.07472	18220	0.07646	23146	0.03190
19709	0.07465	19260	0.07639	24467	0.03187

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
21595	0.07446	21103	0.07620	26808	0.03179
23420	0.07478	22887	0.07652	29074	0.03193
25465	0.07465	24885	0.07639	31612	0.03187
27594	0.07516	26965	0.07691	34255	0.03209
29219	0.07548	28553	0.07724	36272	0.03223
31661	0.07600	30940	0.07777	39304	0.03245
33967	0.07606	33213	0.07783	42182	0.03247
38010	0.07806	37144	0.07783	47186	0.03247
40214	0.07891	39298	0.07870	49922	0.03283
43168	0.07710	42185	0.07890	53589	0.03292
46181	0.07737	45130	0.07917	57330	0.03303
49701	0.07750	48569	0.07930	61699	0.03309
53626	0.07829	52405	0.08012	66572	0.03343
57027	0.07849	55728	0.08032	70794	0.03351
60799	0.07943	59415	0.08129	75477	0.03391
66447	0.07991	64933	0.08177	82488	0.03412
71817	0.08059	70181	0.08247	89154	0.03441
78554	0.08011	76766	0.08198	97518	0.03420
83252	0.08052	81356	0.08240	103349	0.03438

Heat transfer (D10, data set (1)): $\psi_R (l) = 2.668$, $\psi_R (m) = 2.607$

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
508	7.30	497	7.47	1325
529	7.61	517	7.79	1380
561	8.00	549	8.18	1464
596	8.48	582	8.68	1553
647	9.07	632	9.28	1685
694	9.62	678	9.84	1809
752	10.29	735	10.53	1960
810	10.87	792	11.12	2112
867	11.38	847	11.64	2259
922	11.88	901	12.15	2405

Re (m)	Nu (m)	Re (l)	Nu (l)	Fie _m
978	12.31	955	12.59	2549
1038	12.79	1014	13.09	2705
1097	13.24	1072	13.55	2859
1150	13.53	1124	13.85	2998
1220	13.99	1192	14.31	3180
1301	14.52	1272	14.86	3392
1380	15.05	1349	15.40	3598
1451	15.56	1418	15.92	3784
1517	16.06	1482	16.46	3954
1620	17.07	1583	17.47	4223
1699	17.85	1660	18.26	4429
1775	18.78	1735	19.22	4628
1850	19.66	1808	20.12	4822
1936	20.44	1892	20.92	5046
2029	21.51	1982	22.02	5288
2124	22.38	2076	22.91	5538
2256	23.79	2205	24.34	5882
2353	24.82	2299	25.40	6133
2504	26.14	2447	26.75	6528
2647	27.53	2587	28.17	6900
2825	29.07	2761	29.74	7365
2999	30.94	2931	31.66	7817
3254	32.90	3180	33.67	8482
3525	35.22	3445	36.04	9190
3739	37.24	3654	38.11	9747
3969	38.94	3878	39.85	10345
4159	40.60	4064	41.55	10841
4439	43.30	4338	44.31	11572
4793	46.42	4684	47.50	12494
5182	49.61	5064	50.77	13507
5369	51.29	5246	52.48	13995
5702	53.82	5572	55.07	14865
6161	57.40	6020	58.74	16060

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
6632	60.74	6481	62.16	17289
7145	63.82	6983	65.41	18626
7665	67.36	7490	68.93	19981
8246	71.64	8058	73.31	21496
8934	75.76	8731	77.53	23290
9571	79.78	9353	81.64	24949
10167	83.71	9955	85.67	26556
10866	88.09	10619	90.15	28326
11411	91.72	11151	93.86	29747
12294	96.65	12014	98.91	32047
13310	103.38	13007	105.79	34697
14360	110.42	14033	112.99	37433
15394	115.86	15043	118.56	40128
16525	122.62	16149	125.47	43078
17841	129.39	17435	132.41	46507
19454	137.13	19011	140.32	50711
21182	146.36	20700	149.77	55217
22435	152.93	21824	156.49	58482
23914	161.95	23369	165.73	62338
25400	169.10	24821	173.04	66212
26769	176.07	26159	180.17	69780
28392	182.93	27745	187.19	74012
29668	191.14	28993	195.59	77339
29480	191.00	28808	195.45	76847
31245	198.16	30534	202.78	81450
32766	204.72	32020	209.50	85414
33328	209.42	32569	214.30	86881
36110	221.15	35288	226.30	94131
36110	222.72	35288	227.91	94131
38137	234.54	37269	240.00	99416
40421	245.58	39501	251.31	105370
43208	257.70	42224	263.70	112635
46122	271.17	45072	277.49	120230

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
48746	285.76	47635	292.42	127070
51263	296.69	50096	303.60	133634
53682	307.81	52460	314.99	139939
55818	316.88	54547	324.26	145506
58245	329.23	56919	336.90	151833
61997	343.76	60585	351.77	161613
65570	359.19	64077	367.56	170927
68372	372.92	66815	381.61	178233
71042	385.00	69424	393.97	185192
73659	395.21	71982	404.42	192014
74711	400.28	73010	409.61	194758

Friction (D20, data set (3)): $p/e = 20$, $e/D = 0.08$, $d_m = 49.50$ mm
 $\psi_R (m) = 2.032$, $\psi_l (m) = 0.241$, $\psi_R (l) = 2.055$, $\psi_l (l) = 0.238$

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
628	0.05501	621	0.05563	1276	0.01324
656	0.05294	648	0.05354	1332	0.01274
682	0.05044	675	0.05101	1387	0.01214
705	0.04912	697	0.04968	1432	0.01182
731	0.04672	723	0.04725	1486	0.01124
755	0.04531	747	0.04582	1535	0.01090
782	0.04391	773	0.04440	1588	0.01056
820	0.04215	811	0.04263	1666	0.01014
858	0.04015	848	0.04061	1743	0.00966
876	0.03934	867	0.03979	1781	0.00947
903	0.03816	893	0.03859	1835	0.00918
932	0.03710	922	0.03752	1894	0.00893
958	0.03595	947	0.03636	1946	0.00865
990	0.03478	979	0.03517	2012	0.00837
1018	0.03460	1006	0.03499	2068	0.00833
1044	0.03454	1032	0.03493	2122	0.00831
1076	0.03525	1064	0.03565	2186	0.00848
1114	0.03666	1102	0.03708	2264	0.00882

Re (m)	f (m)	Re (l)	f (l)	Re _m	f _m
1153	0.03812	1140	0.03856	2343	0.00917
1195	0.04019	1182	0.04064	2428	0.00967
1245	0.04295	1231	0.04343	2530	0.01033
1290	0.04512	1276	0.04563	2622	0.01086
1342	0.04862	1327	0.04917	2727	0.01170
1416	0.05152	1400	0.05210	2878	0.01240
1486	0.05385	1469	0.05446	3019	0.01296
1593	0.05653	1576	0.05716	3238	0.01360
1699	0.05804	1680	0.05869	3452	0.01396
1833	0.05888	1813	0.05955	3725	0.01417
1983	0.05928	1961	0.05995	4029	0.01426
2178	0.05918	2154	0.05985	4426	0.01424
2399	0.05898	2372	0.05965	4875	0.01419
2681	0.05918	2651	0.05985	5447	0.01424
2945	0.05878	2912	0.05945	5983	0.01414
3218	0.05813	3182	0.05879	6539	0.01399
3307	0.05813	3270	0.05879	6720	0.01399
3499	0.05789	3460	0.05854	7110	0.01393
3827	0.05779	3784	0.05844	7777	0.01390
4067	0.05813	4042	0.05879	8306	0.01399
4440	0.05759	4391	0.05824	9023	0.01386
4832	0.05735	4778	0.05800	9819	0.01380
5281	0.05686	5222	0.05751	10731	0.01368
5932	0.05667	5865	0.05731	12053	0.01364
6499	0.05653	6426	0.05716	13206	0.01360
7012	0.05633	6934	0.05697	14249	0.01355
7540	0.05628	7456	0.05692	15322	0.01354
8248	0.05581	8156	0.05644	16760	0.01343
9115	0.05581	9013	0.05644	18521	0.01343
9944	0.05562	9833	0.05625	20207	0.01338
10989	0.05557	10866	0.05620	22330	0.01337
12031	0.05543	11896	0.05606	24446	0.01334
13329	0.05543	13180	0.05606	27084	0.01334

Re (m)	f (m)	Re (l)	f (l)	Re_m	f_m
14394	0.05557	14233	0.05620	29248	0.01337
15333	0.05562	15161	0.05625	31156	0.01338
16208	0.05581	16027	0.05644	32935	0.01343
17017	0.05571	16826	0.05634	34578	0.01341
18376	0.05562	18171	0.05625	37340	0.01338
19359	0.05581	19142	0.05644	39337	0.01343
20657	0.05624	20428	0.05687	41975	0.01353
22327	0.05624	22077	0.05687	45368	0.01353
23865	0.05628	23598	0.05692	48493	0.01354
25443	0.05628	25159	0.05692	51701	0.01354
26965	0.05614	26663	0.05678	54792	0.01351
29621	0.05638	29289	0.05702	60189	0.01357
31932	0.05677	31575	0.05741	64887	0.01366
34750	0.05730	34361	0.05795	70612	0.01379
37816	0.05730	37393	0.05795	76842	0.01379
40698	0.05706	40242	0.05770	82698	0.01373
43949	0.05677	43458	0.05741	89305	0.01366
47178	0.05725	46650	0.05790	95866	0.01378
50991	0.05725	50420	0.05790	103613	0.01378
56061	0.05779	55434	0.05844	113917	0.01390
59211	0.05779	58548	0.05844	120316	0.01390
62644	0.05789	61943	0.05854	127293	0.01393
66107	0.05789	65367	0.05854	134330	0.01393
70963	0.05808	70169	0.05874	144198	0.01398
74249	0.05804	73418	0.05869	150875	0.01396
76961	0.05804	76100	0.05869	156385	0.01396
79499	0.05853	78610	0.05919	161543	0.01408

Heat transfer (D20, data set (3)): $\psi_R (m) = 2.607$, $\psi_R (l) = 2.668$

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
908	10.84	897	10.76	2394
984	11.11	953	11.23	2543
1010	11.49	999	11.62	2664
1050	11.84	1039	11.97	2770
1104	12.22	1091	12.36	2912
1150	12.70	1137	12.85	3034
1206	13.12	1193	13.27	3181
1264	13.64	1250	13.79	3334
1322	14.14	1307	14.30	3486
1389	14.69	1373	14.85	3664
1477	15.46	1461	15.63	3897
1555	16.08	1537	16.26	4101
1670	17.15	1652	17.35	4406
1775	18.14	1756	18.34	4683
1774	18.15	1754	18.36	4680
1845	18.85	1824	19.06	4866
2017	20.53	1995	20.76	5321
2231	22.37	2206	22.62	5885
2392	23.86	2365	24.13	6308
2547	25.12	2519	25.41	6719
2756	26.95	2725	27.25	7270
3037	29.07	3003	29.40	8012
3247	30.74	3210	31.09	8564
3481	32.51	3442	32.88	9181
3742	34.33	3700	34.72	9869
3907	35.34	3863	35.74	10306
4060	36.72	4014	37.13	10708
4209	37.72	4162	38.15	11103
4442	39.97	4393	40.43	11718
4692	41.44	4639	41.91	12376
4966	43.74	4910	44.23	13098
5301	45.76	5241	46.28	13981

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
5594	47.92	5532	48.46	14756
5917	50.64	5850	51.21	15606
6451	54.12	6379	54.74	17017
6921	57.56	6843	58.21	18255
7435	60.27	7352	60.96	19611
8061	63.74	7971	64.46	21263
8777	67.89	8679	68.65	23152
9191	70.63	9089	71.43	24244
9469	72.10	9363	72.91	24977
9790	74.17	9681	75.01	25824
45666	229.77	45155	232.37	120454
48504	239.06	47962	241.77	127940
51300	251.03	50726	253.87	135314
53988	262.48	53384	265.45	142404
57710	276.80	57065	279.93	152223
62085	292.51	61390	295.82	163761
67123	308.69	66372	312.18	177050
71802	324.83	70999	328.51	189393
75618	340.85	74772	344.71	199458
79130	350.40	78245	354.36	208721

Heat transfer (C80, data set (8)): $p/e = 80$, $e/D = 0.04$, $d_m = 49.82$ mm, $\psi_R (m) = 1.306$, $\psi_R (l) = 1.312$
semicircular, flattened (radius = 18 mm)

Re (m)	Nu (m)	Re _l	Nu _l	Re _m
2002	12.00	1992	12.05	2614
2120	12.20	2110	12.26	2769
2247	12.57	2236	12.63	2935
2371	12.71	2360	12.77	3087
2506	13.11	2494	13.17	3273
2621	13.48	2608	13.55	3423
2723	13.77	2710	13.84	3557
2874	14.15	2860	14.22	3754
3035	14.61	3021	14.68	3964

Re (m)	Nu (m)	Re_i	Nu_i	Re_m
3176	14.97	3161	15.04	4148
3340	15.42	3324	15.50	4363
3495	15.99	3479	16.07	4565
3632	16.39	3614	16.47	4744
3787	16.92	3769	17.00	4946
3982	17.38	3964	17.47	5071
4000	17.78	3980	17.87	5224
4115	18.22	4095	18.30	5374
4188	18.46	4148	18.55	5443
4352	19.16	4331	19.25	5684
4522	20.06	4500	20.15	5906
4705	20.82	4683	20.92	6145
4982	21.91	4938	22.02	6481
5120	22.64	5095	22.75	6687
5399	23.67	5373	23.79	7052
5642	24.61	5615	24.73	7369
5879	25.55	5851	25.68	7679
6135	26.59	6105	26.71	8013
6484	27.92	6452	28.05	8468
6775	28.99	6743	29.12	8849
7171	30.39	7136	30.54	9366
7445	31.44	7410	31.60	9725
7819	32.62	7781	32.78	10212
8211	33.97	8172	34.13	10725
8562	35.02	8521	35.19	11183
8915	36.10	8872	36.27	11644
9165	36.80	9121	36.97	11971
9483	38.01	9437	38.20	12386
9874	39.50	9827	39.69	12897
10238	40.98	10189	41.17	13372
10660	42.33	10609	42.54	13924
11108	44.14	11055	44.35	14508
11715	45.76	11659	45.98	15301

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
12390	47.95	12331	48.18	16183
13113	50.25	13051	50.49	17128
13830	52.65	13764	52.90	18064
14380	54.55	14311	54.81	18782
15209	56.75	15136	57.03	19865
15859	58.92	15783	59.21	20714
16773	61.18	16693	61.47	21908
17677	63.43	17592	63.73	23088
18643	66.46	18554	66.78	24350
19788	69.54	19693	69.88	25845
20928	72.82	20628	73.17	27335
22197	75.55	22091	75.91	28992
23344	79.50	23232	79.88	30490
24497	82.01	24380	82.41	31997
26075	85.63	25950	86.05	34057
28012	90.43	27877	90.87	36587
29459	94.42	29317	94.88	38477
30980	97.96	30832	98.44	40464
32650	102.22	32493	102.71	42645
34852	106.95	34685	107.47	45521
36834	112.15	36658	112.69	48110
38709	115.86	38524	116.42	50559
40392	120.04	40199	120.62	52758
43300	125.34	43093	125.94	56556
45375	130.41	45158	131.03	59266
47449	134.53	47222	135.18	61975
49829	138.79	49590	139.46	65084
52627	143.49	52374	144.18	68737
54837	147.82	54574	148.53	71624
57221	152.60	56947	153.34	74738
60262	157.99	59973	158.75	78710
62749	162.99	62448	163.77	81958
65850	168.15	65534	168.96	86008

Re (m)	Nu (m)	Re (l)	Nu (l)	Re _m
68275	173.22	67948	174.06	89176
70790	178.07	70451	178.83	92461
72983	181.12	72633	182.00	95325
75030	184.36	74670	185.25	97999

Nunner (1956): Enhancement factors

e/D	p/e (set)	ψ_R^*	ψ_i^*	ϕ_i^+	$\phi_{h,max}$
0.08	10 (1)	1.518	0.43	7.48	2.8
0.08	5 (2)	1.246	0.5	8.48	2.6
0.08	20 (3)	2.456	0.245	3.06	2.5
0.04	20 (4)	1.262	0.631	5.48	2.2
0.04	20 (5)	1.262	0.631	4.15	2.1
0.08	20 (6)	1.005	0.724	4.24	2.4
0.04	80 (7)	0.989	0.866	2.31	1.4
smooth		1	1	1	1

+ Based on Re_m = 50,000

* Based on the data of Table 1

Table A.9

Nikuradse (1933)
Friction data for sand-grain roughened tubes

$$e/D = 0.033, \psi_R = 0.921, \psi_f = 1.031$$

$\log(Re)$	$\log(400f)$	Re	f	Re_m	f_m
2.739	1.056	549	0.02841	505	0.02930
2.884	0.911	766	0.02037	705	0.02101
3.016	0.793	1037	0.01554	955	0.01602
3.109	0.698	1285	0.01246	1184	0.01285
3.184	0.620	1528	0.01043	1407	0.01076
3.345	0.503	2211	0.00796	2036	0.00821
3.358	0.492	2281	0.00776	2100	0.00800
3.388	0.493	2443	0.00777	2249	0.00801
3.386	0.502	2430	0.00794	2237	0.00819
3.429	0.522	2688	0.00832	2475	0.00858
3.458	0.538	2870	0.00862	2643	0.00889
3.480	0.543	3022	0.00873	2782	0.00901
3.454	0.555	2843	0.00898	2617	0.00926
3.475	0.576	2986	0.00942	2750	0.00971
3.513	0.574	3261	0.00937	3003	0.00966
3.534	0.588	3423	0.00968	3151	0.00999
3.529	0.604	3379	0.01004	3111	0.01035
3.558	0.603	3612	0.01003	3325	0.01034
3.564	0.620	3666	0.01042	3376	0.01074
3.589	0.625	3881	0.01054	3573	0.01087
3.602	0.636	4004	0.01081	3686	0.01114
3.633	0.641	4293	0.01095	3953	0.01129
3.643	0.652	4396	0.01121	4047	0.01156
3.666	0.651	4638	0.01120	4271	0.01155
3.687	0.655	4863	0.01130	4477	0.01166

log(Re)	log(400f)	Re	f	Re _m	f _m
3.695	0.661	4958	0.01146	4565	0.01182
3.713	0.670	5164	0.01170	4755	0.01206
3.743	0.669	5538	0.01168	5098	0.01204
3.765	0.679	5818	0.01194	5357	0.01231
3.768	0.686	5862	0.01214	5397	0.01252
3.820	0.692	6611	0.01229	6087	0.01267
3.859	0.699	7227	0.01250	6654	0.01289
3.908	0.705	8090	0.01268	7448	0.01307
3.964	0.709	9212	0.01279	8482	0.01319
4.006	0.723	10136	0.01320	9333	0.01362
4.046	0.728	11105	0.01336	10225	0.01378
4.074	0.728	11870	0.01336	10929	0.01378
4.081	0.736	12050	0.01362	11094	0.01405
4.119	0.744	13145	0.01386	12102	0.01429
4.137	0.734	13707	0.01354	12620	0.01397
4.181	0.739	15179	0.01371	13975	0.01414
4.208	0.739	16137	0.01371	14857	0.01414
4.197	0.748	15743	0.01398	14495	0.01442
4.219	0.753	16576	0.01415	15262	0.01459
4.267	0.753	18495	0.01416	17028	0.01460
4.294	0.748	19683	0.01398	18123	0.01442
4.313	0.761	20547	0.01443	18918	0.01488
4.346	0.756	22199	0.01424	20439	0.01468
4.372	0.770	23524	0.01472	21659	0.01518
4.397	0.765	24929	0.01456	22952	0.01501
4.419	0.767	26219	0.01461	24140	0.01506
4.435	0.776	27253	0.01491	25092	0.01538
4.450	0.768	28175	0.01466	25941	0.01512
4.476	0.778	29921	0.01501	27549	0.01548

log(Re)	log(400f)	Re	f	Re _m	f _m
4.481	0.772	30277	0.01478	27876	0.01524
4.508	0.771	32223	0.01475	29668	0.01521
4.534	0.773	34220	0.01482	31506	0.01528
4.559	0.773	36224	0.01483	33352	0.01529
4.594	0.776	39262	0.01493	36149	0.01540
4.630	0.773	42692	0.01483	39307	0.01529
4.686	0.779	48512	0.01501	44665	0.01548
4.723	0.771	52864	0.01475	48672	0.01521
4.730	0.777	53722	0.01498	49462	0.01544
4.812	0.777	64898	0.01494	59752	0.01541
4.838	0.769	68847	0.01470	63388	0.01516
4.858	0.776	72100	0.01494	66383	0.01541
4.882	0.772	76241	0.01480	70196	0.01526
4.893	0.780	78231	0.01505	72028	0.01552
4.913	0.772	81841	0.01479	75351	0.01525
4.933	0.778	85616	0.01498	78827	0.01545
4.957	0.777	90630	0.01496	83444	0.01542
4.990	0.776	97706	0.01493	89958	0.01540
5.004	0.783	101013	0.01517	93003	0.01564
5.063	0.781	115524	0.01508	106364	0.01555
5.088	0.775	122421	0.01489	112714	0.01536
5.106	0.782	127657	0.01512	117534	0.01559
5.133	0.783	135715	0.01515	124954	0.01563
5.148	0.774	140460	0.01486	129322	0.01533
5.156	0.785	143355	0.01524	131988	0.01572
5.178	0.781	150614	0.01510	138671	0.01557
5.209	0.776	161676	0.01491	148856	0.01538
5.238	0.775	172992	0.01488	159275	0.01535
5.232	0.783	170411	0.01516	156898	0.01563

log(Re)	log(400f)	Re	f	Re _m	f _m
5.305	0.777	201705	0.01497	185711	0.01544
5.348	0.773	222650	0.01483	204995	0.01530
5.376	0.783	237723	0.01518	218873	0.01565
5.403	0.780	252729	0.01506	232689	0.01553
5.437	0.780	273631	0.01507	251934	0.01554
5.456	0.776	285948	0.01492	263274	0.01539
5.511	0.782	324229	0.01513	298519	0.01561
5.565	0.777	367635	0.01498	338484	0.01544
5.586	0.783	385837	0.01516	355242	0.01564
5.614	0.780	411515	0.01508	378884	0.01555
5.690	0.784	490234	0.01520	451361	0.01568
5.792	0.782	618878	0.01513	569804	0.01560
5.828	0.783	672227	0.01518	618923	0.01565
5.862	0.778	728607	0.01499	670832	0.01546
5.883	0.778	763859	0.01501	703289	0.01548
5.926	0.780	843178	0.01507	776318	0.01554
5.957	0.779	905106	0.01503	833336	0.01550
5.995	0.780	988420	0.01506	910044	0.01553
6.020	0.783	1046330	0.01516	963350	0.01564

$$e/D = 0.016, \psi_R = 0.890, \psi_t = 1.055$$

log(Re)	log(400f)	Re	f	Re _m	f _m
2.815	0.976	653	0.02366	581	0.02495
2.900	0.903	795	0.02002	707	0.02111
3.065	0.735	1162	0.01358	1034	0.01433
3.226	0.584	1681	0.00959	1496	0.01011
3.310	0.528	2042	0.00844	1817	0.00890
3.373	0.482	2361	0.00758	2100	0.00800

$\log(Re)$	$\log(400f)$	Re	f	Re_m	f_m
3.415	0.497	2603	0.00786	2316	0.00829
3.555	0.561	3592	0.00909	3196	0.00959
3.597	0.577	3953	0.00944	3516	0.00995
3.640	0.580	4363	0.00950	3881	0.01002
3.664	0.593	4614	0.00980	4104	0.01033
3.717	0.586	5214	0.00964	4639	0.01017
3.766	0.592	5830	0.00978	5187	0.01031
3.760	0.585	5750	0.00962	5115	0.01014
3.795	0.574	6232	0.00937	5544	0.00988
3.834	0.578	6820	0.00945	6067	0.00997
3.882	0.577	7618	0.00944	6777	0.00995
3.889	0.570	7742	0.00928	6887	0.00979
3.942	0.578	8750	0.00947	7784	0.00999
3.941	0.569	8722	0.00927	7759	0.00978
3.989	0.572	9742	0.00933	8666	0.00984
4.017	0.580	10390	0.00951	9243	0.01003
4.057	0.577	11395	0.00944	10137	0.00996
4.084	0.587	12127	0.00965	10789	0.01018
4.137	0.582	13707	0.00956	12194	0.01008
4.136	0.590	13692	0.00973	12181	0.01026
4.196	0.610	15693	0.01018	13960	0.01073
4.198	0.594	15760	0.00982	14020	0.01036
4.267	0.605	18475	0.01006	16435	0.01061
4.296	0.615	19747	0.01031	17567	0.01087
4.311	0.607	20459	0.01011	18201	0.01067
4.337	0.624	21751	0.01052	19349	0.01109
4.395	0.628	24822	0.01060	22082	0.01119
4.427	0.635	26731	0.01078	23780	0.01137
4.451	0.627	28266	0.01058	25146	0.01116

log(Re)	log(400f)	Re	f	Re _m	f _m
4.504	0.642	31879	0.01097	28359	0.01157
4.566	0.634	36773	0.01077	32713	0.01136
4.612	0.640	40897	0.01092	36382	0.01152
4.635	0.648	43153	0.01113	38389	0.01173
4.672	0.645	47024	0.01104	41833	0.01165
4.739	0.652	54829	0.01122	48777	0.01184
4.797	0.646	62639	0.01107	55724	0.01168
4.829	0.658	67384	0.01136	59945	0.01199
4.856	0.658	71791	0.01137	63866	0.01199
4.901	0.655	79587	0.01129	70801	0.01191
4.933	0.656	85800	0.01132	76328	0.01194
4.962	0.661	91609	0.01145	81496	0.01208
4.990	0.665	97706	0.01155	86919	0.01218
5.034	0.656	108199	0.01133	96254	0.01195
5.063	0.656	115648	0.01133	102881	0.01195
5.069	0.666	117274	0.01158	104327	0.01221
5.103	0.663	126837	0.01150	112835	0.01213
5.134	0.660	136153	0.01144	121122	0.01206
5.169	0.665	147414	0.01157	131140	0.01220
5.167	0.656	146940	0.01133	130718	0.01195
5.180	0.645	151262	0.01105	134563	0.01166
5.238	0.665	172807	0.01156	153730	0.01219
5.228	0.656	168953	0.01132	150301	0.01194
5.259	0.652	181362	0.01123	161340	0.01184
5.268	0.665	185300	0.01157	164844	0.01220
5.314	0.663	205863	0.01151	183137	0.01214
5.317	0.653	207639	0.01126	184717	0.01187
5.344	0.655	220983	0.01130	196587	0.01192
5.341	0.663	219093	0.01151	194906	0.01214

$\log(Re)$	$\log(400f)$	Re	f	Re_m	f_m
5.396	0.662	248690	0.01147	221236	0.01210
5.424	0.665	265241	0.01157	235960	0.01220
5.452	0.661	282894	0.01145	251664	0.01207
5.475	0.661	298819	0.01144	265831	0.01207
5.519	0.667	330557	0.01162	294065	0.01226
5.543	0.661	349166	0.01146	310620	0.01209
5.599	0.665	396761	0.01156	352960	0.01219
5.662	0.662	459151	0.01148	408463	0.01211
5.723	0.662	527938	0.01148	469656	0.01211
5.811	0.666	646735	0.01159	575338	0.01222
5.865	0.668	732529	0.01163	651661	0.01226
5.915	0.665	822608	0.01155	731796	0.01218
5.964	0.665	919804	0.01156	818262	0.01219
6.012	0.669	1028480	0.01166	914943	0.01230

Table A.10

Blackwelder and Kreith (1970)
Heat transfer data for circular tube with twisted tape inserts

Smooth tube data

Re	Nu
2994	7.04
3751	7.86
3334	9.14
6103	16.27
6275	15.70
6575	16.70
11487	26.65
19586	41.01
24491	45.02
43233	65.96
47391	77.71
53132	91.54
53967	88.01
59672	87.58
65524	95.69

$$p/D = 3.54, \psi_R = 2.45$$

Re	Nu	Re _m	Nu _m
1035	5.36	2536	5.36
1102	5.57	2699	5.57
1547	10.54	3790	10.54
2035	13.28	4983	13.28
1928	13.68	4723	13.68
2017	14.51	4940	14.51
1932	15.24	4731	15.24
2662	18.37	6518	18.37
2722	21.96	6667	21.96
2989	22.22	7321	22.22
3392	27.22	8308	27.22
3579	27.36	8766	27.36
4898	33.91	11995	33.91
4906	32.28	12016	32.28
11000	55.17	26940	55.17
19928	89.32	48808	89.32
20992	91.24	51412	91.24
20992	96.95	51412	96.95
47556	149.68	116470	149.68
47391	157.22	116067	157.22
67366	192.65	164990	192.65
66324	184.01	162437	184.01

$$p/D = 8.5, \psi_R = 2.32$$

Re	Nu	Re _m	Nu _m
1127	5.35	2611	5.35
1451	7.23	3363	7.23
1434	7.76	3322	7.76
1824	9.43	4227	9.43
2238	11.53	5186	11.53
2760	15.54	6395	15.54
3288	20.81	7618	20.81
3586	19.39	8308	19.39
4293	21.36	9948	21.36
5936	29.84	13755	29.84
7170	30.58	16614	30.58
14844	47.29	34395	47.29
21396	66.94	49575	66.94
21845	72.77	50616	72.77
31432	96.31	72829	96.31
47638	118.80	110380	118.80
49575	138.13	114867	138.13
65072	155.43	150775	155.43
70470	168.15	163283	168.15

$$p/D = 22.0, \psi_R = 2.18$$

Re	Nu	Re _m	Nu _m
1202	4.85	2616	4.85
1843	7.35	4013	7.35
1847	7.82	4020	7.82
2571	10.22	5597	10.22
2699	10.96	5875	10.96
3985	13.41	8676	13.41
5645	20.14	12290	20.14
5895	19.45	12834	19.45
6199	20.14	13495	20.14
11871	35.50	25843	35.50
20524	55.17	44680	55.17
21211	60.47	46175	60.47
28974	63.10	63074	63.10
34335	76.07	74746	76.07
43158	89.47	93953	89.47
45225	93.51	98453	93.51
46416	90.06	101045	90.06
73082	121.75	159094	121.75
71578	129.36	155821	129.36

Table A.11

Knudsen and Katz (1950)
Heat transfer data for smooth and rough annuli

(a) smooth tube: $\psi_R = 1.692$

Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$
2615	33.27	4425	33.27	23281	98.14	39398	98.14
3224	34.46	5455	34.46	23740	101.11	40175	101.11
3763	35.27	6369	35.27	29653	126.83	50182	126.83
5264	37.63	8908	37.63	31034	126.67	52520	126.67
7940	40.94	13437	40.94	37379	147.21	63256	147.21
9739	50.30	16481	50.30	42904	170.42	72608	170.42
11310	55.57	19141	55.57	45847	169.75	77587	169.75
12898	60.14	21828	60.14	45907	183.47	77688	183.47
15295	69.80	25883	69.80	49119	183.47	83125	183.47
17647	84.45	29864	84.45	75550	254.96	127854	254.96

(b) Transverse-fin tubes

Tube 1: $\psi_R = 1.99$

Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$
1276	21.00	2539	21.00	17841	117.05	35501	117.05
1706	22.37	3394	22.37	21613	144.77	43006	144.77
2141	21.58	4260	21.58	27386	168.13	54495	168.13
2612	21.89	5197	21.89	31981	199.47	63637	199.47
3120	23.88	6207	23.88	37701	226.76	75020	226.76
3553	25.79	7071	25.79	45942	275.51	91419	275.51
4140	29.39	8237	29.39	49853	287.54	99201	287.54
6118	42.21	12175	42.21	56384	306.21	112198	306.21
9248	58.44	18403	58.44	61039	305.48	121459	305.48
10264	68.85	20424	68.85	63096	360.30	125553	360.30
11733	76.61	23347	76.61	68548	381.88	136401	381.88
15098	96.00	30043	96.00	76254	402.84	151736	402.84

Tube 2: $\psi_R = 2.252$

Re	$Nu/Pr^{0.4}$	Re _m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re _m	$Nu_m/Pr^{0.4}$
1010	19.37	3847	19.37	9231	85.65	35173	85.65
1102	17.82	4201	17.82	9946	84.64	37899	84.64
1167	20.62	4445	20.62	10475	95.98	39913	95.98
1386	22.57	5281	22.57	11058	95.87	42135	95.87
1578	25.38	6014	25.38	11800	122.12	44965	122.12
1666	26.24	6349	26.24	13072	112.52	49810	112.52
1784	28.28	6800	28.28	17898	141.14	68201	141.14
1893	31.20	7213	31.20	20631	159.30	78612	159.30
2049	29.23	7809	29.23	24953	190.78	95083	190.78
2112	31.54	8048	31.54	28384	207.31	108156	207.31
2479	33.94	9446	33.94	30695	226.60	116960	226.60
3105	35.55	11831	35.55	32994	234.81	125722	234.81
3489	38.81	13296	38.81	36461	258.81	138934	258.81
4670	42.73	17793	42.73	39859	275.61	151880	275.61
4636	46.10	17665	46.10	44850	298.76	170900	298.76
5312	51.30	20240	51.30	46668	371.66	177827	371.66
6242	57.01	23783	57.01	52576	334.81	200338	334.81
6766	59.64	25781	59.64	59303	352.75	225970	352.75
8076	72.19	30773	72.19	72684	393.91	276960	393.91
8702	70.84	33158	70.84				

Tube 3: $\psi_R = 1.616$

Re	$Nu/Pr^{0.4}$	Re _m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re _m	$Nu/Pr^{0.4}$
1018	12.18	2785	12.18	15159	81.68	41467	81.68
1406	16.68	3846	16.68	18335	94.96	50156	94.96
1650	18.10	4514	18.10	21389	111.19	58513	111.19
1795	19.53	4911	19.53	23694	129.74	64818	129.74
1984	21.60	5427	21.60	26758	130.05	73199	130.05
2464	26.81	6740	26.81	29357	151.38	80309	151.38
2888	29.61	7901	29.61	32131	165.86	87898	165.86

Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$
3254	29.97	8902	29.97	33920	181.29	92792	181.29
4145	33.39	11339	33.39	36859	186.97	100630	186.97
5744	42.33	15713	42.33	39287	193.29	107473	193.29
6758	46.65	18487	46.65	41275	208.05	112912	208.05
8333	52.22	22795	52.22	45339	213.30	124029	213.30
9898	60.93	26529	60.93	51017	195.37	139561	195.37
10939	67.23	29923	67.23	62755	264.08	171672	264.08
11786	72.45	32242	72.45	72772	260.97	199073	260.97

Tube 4: $\psi_R = 2.918$

Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$
1047	13.05	5170	13.05	15117	117.92	74646	117.92
1073	16.64	5299	16.64	17308	137.08	85467	137.08
1374	20.93	6786	20.93	19197	152.64	94795	152.64
1555	21.82	7678	21.82	20505	160.69	101254	160.69
1737	23.70	8577	23.70	23395	182.61	115525	182.61
2362	27.45	11662	27.45	25585	195.71	126337	195.71
2992	33.35	14775	33.35	27848	206.52	137512	206.52
3795	38.40	18741	38.40	30562	228.60	150914	228.60
5203	45.94	25693	45.94	33540	253.95	165622	253.95
6348	56.82	31348	56.82	36507	268.94	180271	268.94
7016	62.60	34647	62.60	39830	291.00	196679	291.00
8274	69.04	40855	69.04	42795	324.43	211322	324.43
9585	73.29	47331	73.29	44964	336.27	222033	336.27
10202	75.33	50379	75.33	56168	358.25	277359	358.25
10859	87.89	53622	87.89	62006	412.99	306188	412.99
11833	96.59	58434	96.59	70082	434.25	346065	434.25
13141	103.77	64888	103.77				

Tube 5: $\psi_R = 2.653$

Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$
1212	11.93	5440	11.93	9307	56.69	41787	56.69
1229	13.10	5517	13.10	10707	67.41	48071	67.41
1317	13.68	5914	13.68	11960	69.12	53696	69.12
1284	14.64	5675	14.64	13517	77.62	60689	77.62
1562	15.86	7014	15.86	15808	90.66	70975	90.66
1632	17.02	7327	17.02	18185	96.82	81648	96.82
1774	18.11	7965	18.11	19887	112.55	89289	112.55
1879	18.22	8438	18.22	22398	112.28	100562	112.28
2065	19.34	9272	19.34	25255	124.58	113392	124.58
2090	21.25	9381	21.25	27913	131.00	125325	131.00
2318	20.90	10405	20.90	30706	141.57	137863	141.57
2821	22.83	12666	22.83	37819	138.07	169800	138.07
3241	24.62	14553	24.62	33580	164.58	150766	164.58
4049	30.75	18180	30.75	40779	177.02	183087	177.02
5703	37.45	25607	37.45	45657	237.79	204993	237.79
7000	44.11	31428	44.11	59015	257.00	264966	257.00
8362	51.58	37542	51.58	67730	216.11	304093	216.11

Tube 6: $\psi_R = 3.29$

Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$
1212	11.84	6748	11.84	15779	137.54	87847	137.54
1443	15.79	8036	15.79	17048	153.41	94915	153.41
1569	18.53	8733	18.53	19808	185.34	110282	185.34
1829	19.39	10183	19.39	23259	233.87	129498	233.87
2064	23.05	11490	23.05	25818	233.04	143740	233.04
2315	22.75	12889	22.75	27960	212.90	155668	212.90
3144	21.89	17503	21.89	30818	286.89	171578	286.89
5060	58.08	28173	58.08	33888	314.78	188671	314.78
6428	62.32	35786	62.32	36743	324.16	204568	324.16
7654	70.26	42616	70.26	39053	379.41	217427	379.41
9553	68.06	53187	68.06	41801	405.20	232726	405.20

Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$	Re	$Nu/Pr^{0.4}$	Re_m	$Nu_m/Pr^{0.4}$
9180	77.36	51109	77.36	45058	440.44	250860	440.44
11538	94.01	64237	94.01	52846	403.30	294223	403.30
12393	110.16	68999	110.16	60545	474.26	337086	474.26
13219	125.35	73595	125.35	64653	445.64	359960	445.64
14315	121.30	79702	121.30				

Knudsen and Katz (1950): Enhancement factors

Tube	ψ_R	ψ_f	ϕ_i^+	$\phi_{h,max}$
1	1.99	0.533	1.082	1.54
2	2.252	0.433	1.703	1.80
3	1.616	0.619	1.682	1.26
4	2.918	0.333	1.822	1.90
5	2.653	0.371	2.37	1.20
6	3.29	0.296	2.385	2.40
smooth	1.692	0.615	1	1

+ Based on $Re_m = 50,000$.

Table A.12

Watkinson et al. (1974)

Enhancement factors for finned tubes

Tube	Ψ_R	Ψ_f	$\Psi_{h,max}$	Fin geometry
1	2.239	0.258	1.35	High Spiral Fins (HSF)
2	2.778	0.286	2.01	
3	2.126	0.250	1.90	
4	2.213	0.250	1.35	
5	3.030	0.286	1.24	
9	2.370	0.235	1.70	
18	2.817	0.070	-	
11	1.434	0.267	1.62	High Straight Fins (STF)
13	1.617	0.320	1.50	
14	1.888	0.308	1.60	
16	1.629	0.400	1.60	
20	1.416	0.320	1.13	
15	1.045	0.333	1.87	Low Spiral Fins (LSF)
17	1.620	0.444	1.83	
19	0.987	0.333	1.57	
21	1.417	0.421	2.03	
22	1.330	0.533	1.38	
23	1.421	0.521	-	
10 (smooth)	1.0	1.0	1.0	