Heat Transfer to Liquid Streams in a Packed Tube Containing Large Packings

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Wall-area heat transfer coefficients based on bulk-mean temperatures of the liquids flowing upward in a steam-jacketed packed tube (4 ft. long and 2.25-in. I.D.) were determined. The tube was randomly packed in each of the experiments with spherical glass packings of uniform size (with diameters between 3/4 and 5/32 in.). The liquids used were water, toluene, 45% aqueous glycerine, and nitrobenzene.

Analogous correlations were developed for the heat transfer coefficients and for pressure drop, the dimensionless groups in the above being the same as for open tubes. The two relationships are applicable for the range in D_T/D_P ratio from 14 to 3 and in N_{Re} from 40,000 to 300. The first is satisfactory within $\pm15\%$ for heating of liquids in the above packed tube, the second within $\pm10\%$ for most of the data of packed tubes reported so far.

CRITERIA OF FLOW IN PACKED BEDS

The packed beds containing small packings have received much attention; the flow and transfer processes in them have been studied with different methods of approach, for example empirical correlations, analysis based on differential equations, and analysis by means of statistical concepts for turbulent diffusion. As shown in the following brief discussion, the available information provides the basis for a conclusion that is important for the present study; this is that the packed columns may be conveniently divided into two classes: the packed beds with D_T/D_p ratios greater than 10 or 12 and the packed tubes with smaller D_T/D_p ratios. In the former, analogy among the three transfer processes is found by the use of the modified Reynolds number $[N'_{Re}; (D_p w_o \rho)/\mu]$ as the criterion of flow. In the latter it appears that the Reynolds number based on tube diameter $[N_{Re}; (D_T w_o \rho)/\mu]$ can be used advantageously for satisfactory empirical correlations. In the above as well as in the following account the term packed bed is used to specify the packed systems containing (nonconducting) smooth, spherical, randomly packed packings of uniform size with D_T/D_p ratios greater than 12. The term packed tube is used for the packed systems of same properties with smaller D_T/D_p ratios.

Data and different empirical correlations for heat transfer coefficients at the tube wall of packed columns have been reported by Colburn (*18*) and Leva and co-workers (*19, 20*). These correlations are based on the dimensionless groups N_{Nu} and N'_{Re} and a complex function of the D_P/D_T ratio. Schumacher (*10*) used the above data to show a single comprehensive correlation represented in a plot of log N_{Nu} vs. log N_{Re}. The significant part of this correlation, given as

$$N_{Nu} = 7.5(0.023)(N_{Re})^{0.75}$$

is applicable when N_{Re} is greater than 9,500 and also pertains mostly to the data of packed tubes with small D_T/D_P ratios. The suitability of this simple relationship, without any need for a complex correction factor based on D_P/D_T ratio, indicated that the tube-diameter–based Reynolds number is to be preferred for the correlation of the heat transfer data of the present investigation in packed tubes.

It is remarkable that none of the available correlations for pressure drop [including that of Leva and co-workers (*15, 16*)] is satisfactory for the case of packed tubes, as is evident from a recent report (*13*). On the other hand, for (spherical) packed beds the two apparently different correlations of Chilton and Colburn (*14*) and Ergun (*8*) are equally suitable. The first one uses the group $(D_P w_o \rho)/\mu$ to characterize the flow; the second uses for the same purpose the group $(4r'_H w \rho)/\mu$ [generally represented as $(D_P w_o \rho)/[\mu(1-\epsilon)]$ (*7*)]. However it is evident as indicated by Mott (*4*) that the values of the two groups are identical if the terms ϵ, w, and r'_H are given appropriate values (*9*); $\epsilon = 0.34 + 0.4\,D_P/D_T$ for $D_P/D_T < 0.08$, $w = w_o/\epsilon$, and $r'_H = D_P\epsilon/[6(1-\epsilon) + 4D_P/D_T]$. The above facts clearly show that the group $(D_P w_o \rho)/\mu$ or N'_{Re} is most satisfactory for correlations, as in the analogous field of heat transfer, only in the case of packed beds with D_T/D_P ratios > 12.

Recently Baron (*1*) and Wilhelm and co-workers (*2, 3*) used the approaches based on differential equations and also on statistical concepts to interpret the mechanism of turbulent diffusion in the packed bed by reference to the theory of random-walk flow. This theory is valid owing to inherent assumptions only for packed beds with D_T/D_P ratios > 10 and to $N'_{Re} > 200$. It predicts that the turbulent diffusivity for the lateral diffusion process is determined only by the product of w_o and D_P and that the modified Peclet number $[N'_{Pe}; (D_P w_o)/(E_T)]$ is constant and nearly equal to 10. References 2 and 3 present experimental data that are in accord with above predicted results, the former for lateral diffusion of mass in gas streams and water streams and the latter for the lateral diffusion of heat in gas streams. Thus these results show that the packed beds have unique characteristics different from those of the packed tubes. Besides in the former the mean fractional voids vary but slightly as the D_T/D_P ratios increase above 12 (*4*); the distribution of voids and velocity of flow across the cross section in the packed bed is nearly uniform. In all these properties the packed tubes show marked differences (*5*).

In the packed tube there is appreciable channeling of flow adjacent to the tube wall. Because of this the heat transfer process at the tube wall of the packed tube resembles that in open tubes, especially those provided with turbulence promoters. On the basis of this view Ranz (*6*) recommended the use of N_{Re} for correlation of heat transfer coefficients of packed tubes. This suggestion receives further support from the following observations of reference 3: heat transfer rates (as indicated from values of N'_{Pe}) are determined in the packed tubes, to an important degree, by the dimension D_T; their values are of the same order of magnitude as those of open tubes.

The temperature gradients in the packed bed, in its core as well as in the vicinity of the tube wall, have been studied to obtain a direct insight into the mechanism of heat flow. From the analysis of the temperature profiles in packed beds (with gas streams) Argo and Smith (*26*) noted that a constant value of N'_{Pe} is found only in the core

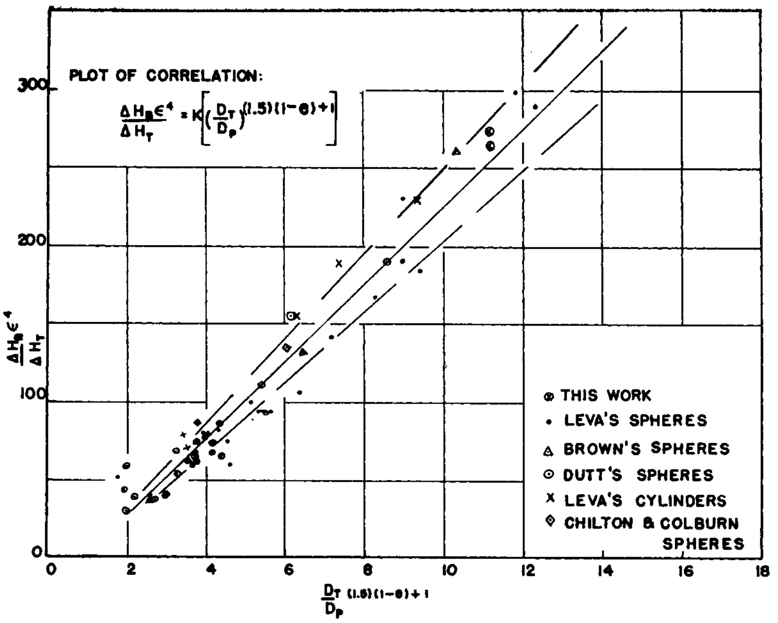

Fig. 1. Pressure drop in packed tubes.

of the bed. There is an appreciable temperature drop at the tube wall which indicates the presence of a convective type of boundary layer at the tube wall. Coberly and Marshall (22) and others (23, 24, 25) undertook special studies of this local resistance to heat flow at the tube wall. It is hence obvious that in packed tubes characterized by channeling of flow near the tube wall this boundary layer at the tube wall must assume a major role in controlling heat transfer as in the case of open tubes.

In summary the above cited results indicate that the choice of the criterion of flow, that is the selection of the length and velocity terms of the Reynolds group, is complicated for the case of the packed system. The lengths D_P, D_T and the ratios D_T/D_P and ϵ enter into the geometrical specification of the packed bed. But dimensional analysis can merely affirm that any characteristic length such as D_P, D_T, or $4r'_H$ (the equivalent diameter of the pores) must be a component of the Reynolds group. Similarly there is uncertainty as to the exact value of the velocity component. Under these circumstances the justification for the necessary choice of criterion of flow is a priori on the assumption of a plausible model of flow and a posteriori insofar as a simple and satisfactory correlation is obtained. It is interesting that the three models proposed so far for flow in packed beds all lead to the same criterion of flow: $(D_P w_o \rho)/\mu$. These models are (1) external flow past assembly of spheres, (2) internal flow through the assembly of capillaries within the packed bed, and (3) random-walk model. However it is evident that these models are satisfactory only for the case of uniform flow as in packed beds with D_T/D_P ratios greater than 12 and also that they are not consistent with the flow characteristics of packed tubes containing large packings. In the latter there is appreciable channeling of flow near the tube wall, and the pores are not comparable to capillaries since the pore system is more open in structure. Further, as found in the present experiments, the resistance to heat transfer is proportional to $1/w_o^{0.8}$ as in open pipes. Consequently it seems more appropriate to compare the flow to that in open tubes provided with turbulence promoters—which means that the criterion of flow would be the Reynolds number based on tube diameter. That this criterion is satisfactory is evidenced by the correlation of Schumacher for heat transfer to gases and the correlations presented in this paper for heat transfer to liquids and for pressure drop in packed tubes containing large packings.

PRESSURE-DROP CORRELATION

When one stipulates a similarity between the transfer processes in the packed tube and the open tube, a correlation for pressure drop in packed tubes can be expected which must be essentially a modified Fanning equation. Hence the following equations may be given:

$$\Delta H_T = f \cdot \frac{w_o^2}{2g} \cdot \frac{L}{r_H}$$

for the open tube

$$\Delta H_B = K \cdot f \cdot \frac{w_o^2}{\epsilon^2 \cdot 2g} \cdot \frac{L_B}{r'_H}$$

for the packed tube

In the above $r_H = D_T/4$ and $r'_H = D_T\epsilon/6(1-\epsilon)(D_T/D_P) + 4$, that is ratio of free volume and total frictional surface. Increased pressure drop in the packed tube is caused by the winding paths for the liquid in the core of the packed tube and by the consequent kinetic losses. The last mentioned effects would be prominent in tubes

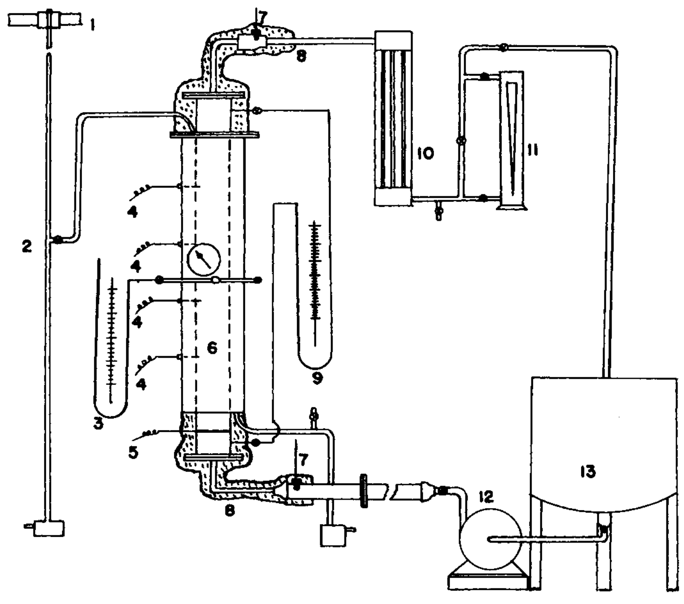

Fig. 2. Flow diagram: 1 and 2, steam main; 3 and 9, manometers; 4 and 5, thermocouples; 6, packed column; 7, thermometers; 8, insulation; 10, tubular cooler; 11, rotameter; 12, C.F. pump; 13, tank; 14, steam traps.

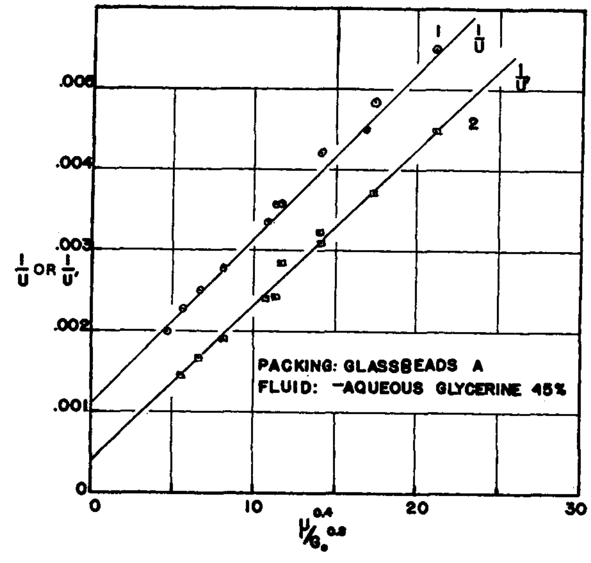

Fig. 3. Wilson plot for heating of liquid in packed tube.

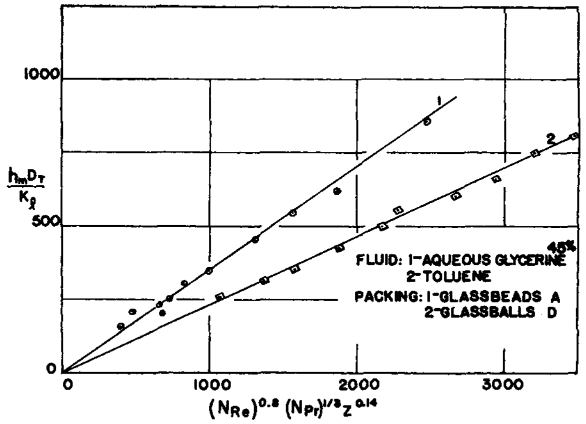

Fig. 4. Correlation of experimental heat transfer coefficients.

packed densely but would disappear as the voids approach that of the open tube. Hence it may be tentatively assumed that L_B may be replaced by L/ϵ in the above equation for the packed tube. When one introduces these assumptions the same can be given as

$$\Delta H_B = K \cdot \frac{2f}{g} \cdot \frac{w_o^2 L}{\epsilon^4} \cdot \frac{[(1.5)(1-\epsilon)(D_T/D_P)+1]}{D_T}$$

Comparison of this equation with that of Fanning gives with the introduction of an additive constant

$$\frac{\Delta H_B \epsilon^4}{\Delta H_T} = K[(1.5)(1-\epsilon)(D_T/D_P)+1]+b$$

or

$$\frac{\Delta H_B \epsilon^4}{\Delta H_T} = K\left[\frac{r_H \epsilon}{r'_H}\right] + b$$

This relationship (12) for packed tubes, a plot of which is given in Figure 1, is found to be satisfactory within ± 10% for the available data (11 to 17) of pressure drop in packed tubes with D_T/D_P ratios in the range between 14 and 3 and for a range in N_{Re} from 300 to 40,000. It may be noted that the constant K is a relative shape factor which might be justified by the complex geometry of packed tube. The constant b as also the lower limit of D_T/D_P ratio of 3 might be attributed to the behavior of ϵ which reaches a maximum at D_T/D_P ratio of approximately 2.

HEAT TRANSFER EXPERIMENTS IN PACKED TUBES

Only one tube size, a 2.25-in. I.D., was employed owing to limited equipment and because priority was given to the objective of getting the data for heating of different liquids with varying Prandtl numbers. However the analogous correlations of Schumacher for heating of gases and that of this paper for pressure drop cover the data of different tube sizes in the range usually feasible in laboratory work. In view of the above and of the observations noted earlier in the discussion on criteria of flow, it is believed that the use of N_{Re} for correlation of heat transfer coefficients, determined in this single packed tube, is appropriate. The inference that the transfer process in the packed tube is similar to that in the open tube is of basic importance to this work. It has enabled the application of simple procedures, as in open tubes, for the experiments and for the treatment of the data, for example the resolution of over-all coefficients into liquid-film coefficients by means of Wilson's plot. Further, this method of correlation is of practical advantage since it permits the direct comparison of heat transfer and pressure-drop characteristics of packed tubes with those of open tubes. However it is recognized that further experiments for other tube sizes are necessary. Such an extension of this work is also in progress.

The packed tube employed was a steam-jacketed copper tube of inside and outside diameters 2.25 and 2.5 in. respectively, of packed length 5 ft. 6 in. (L/D_T = 29.4), and steam-jacketed length 4 ft. (L/D_T = 21.4). It was mounted vertically in a closed-circuit flow system consisting of a glass-lined tank, a centrifugal pump, an orifice meter, a rotameter for visual inspection for presence of air, and tubular cooler of ample capacity (Figure 2). The liquids flowed upward through the packed tube heater. The steam jacket was provided with an air vent. Liquid temperatures were measured, at thermometer wells containing mercury, with certified and calibrated thermometers reading to 0.1°F. For measuring the temperature of the wall of the packed tube four copper-constantin thermocouples were inserted on the outer surface of the packed tube by adopting a simplified standard design with the tube wall itself forming one of the leads. In all the experiments the tube was first filled with the liquid, and the packings were then added a few at a time to ensure random packing and also the exclusion of air from the unit. The measurements for each experiment were liquid flow rate, inlet and outlet temperatures, saturated steam temperature, and tube wall temperature. In the heating experiments with liquids steady state conditions were reached by about 10 min. after setting the inlet valves for steam, for cooling water, and the discharge valve of the pump. Readings were then taken every 5 min. till three or four were in agreement. In most cases it took about 30 min. to complete an experiment. In a few orientating experiments the heat balance of the system was verified by collecting the condensate.

The treatment of the data was as follows. The total resistance is the sum of individual ones as in

$$\frac{1}{U} = \frac{A_i}{h_s A_o} + \frac{X A_i}{k_m A_m} + \frac{1}{h_m} + \frac{1}{h_d}$$

For computing the values of h_m the method of Wilson (27) involving extrapolation of the straight-line plot of $1/U$ vs. $1/(\text{velocity})^{0.8}$ is satisfactory provided $1/h_m$ is the controlling factor. In this work the resistance on the steam side is appreciable and increases with the heat flux, causing the above plot to bend slightly upward near the Y axis. Beatty and Katz (28) indicated that this difficulty can be overcome by fixing the slope of the same plot on the basis of a narrow interval of points in the high velocity range, and this procedure was found to be suitable in this case. However plots were made of $1/U$

Table 1. Characteristics of Packings Used

Packing number	Shape	Diameter of sphere or nominal diameter (D_p)	Equivalent diameter (D_n)	Voids %	D_n/D_T
(A)	(Glass beads) sphere	0.257 in.	0.257 in.	41.1	0.1143
(B)	(Glass beads) sphere	5/32 in.	5/32 in.	40.8	0.0695
(C)	(Glass beads) sphere	5/16 in.	5/16 in.	—	0.1390
(D)	(Glass balls) sphere	0.671 in.	0.671 in.	48.4	0.2985
(E)	(Glass balls) sphere	0.585 in.	0.585 in.	45.2	0.2600
(F)	Berl saddles	1/4 in.	0.227 in.	61.1	0.1010
(G)	Raschig rings	0.230 in.	0.229 in.	43.5	0.1020
(H)	Raschig rings	1/4 in.	0.249 in.	52.3	0.1111
(I)	Raschig rings	3/8 in.	0.353 in.	58.8	0.1570

against $\mu^{0.4}/G_o^{0.8}$ to get comparable slopes with different liquids. A partial over-all heat transfer coefficient may be defined on the same lines as U by replacing the steam temperature by the tube wall temperature in the equation used for computing U. U' is independent of condensate film resistance. The intercept of the plot of $1/U'$ vs. $\mu^{0.4}/G_o^{0.8}$ is a measure of the dirt-factor resistance. The difference between the values of the two intercepts of the above two plots is indicative of the resistance of the condensate film. In this series of experiments the slopes of the two plots tallied (Figure 3). The values of the difference between the two intercepts were of the right order and were of the same magnitude at equal heat-flux rates. However the data of h_m were computed based on the former plots, since greater reliance can be placed on the value of T_s than on the averaged value of T_w.

RESULTS AND CORRELATION

The data relating to nearly 330 runs using the liquids water, distilled water, aqueous glycerine 45%, toluene, and nitrobenzene have been reported (*11*). Table 1 lists the packings used. Representative data are given in Tables 2 to 5*.

Trial plots on logarithmic coordinates for the data for any one liquid and one D_P/D_T ratio indicated rough correlation on the basis of the dimensionless groups

$$\frac{h_m D_T}{k_l} \Big/ \left(\frac{C_p \mu_l}{k_l}\right)^{0.4} \text{ and } \frac{D_T w_o \rho}{\mu_l}$$

A better fit and a slope of 0.8 was indicated by the use of the groups

$$\left(\frac{h_m D_T}{k_l}\right) \Big/ \left(\frac{C_p \mu_l}{k_l}\right)^{0.33} \left(\frac{\mu_l}{\mu_w}\right)^{0.14} \text{ and } \frac{D_T w_o \rho}{\mu_l}$$

To determine the effect of D_P/D_T ratio on the shape factor in the relation

$$N_{Nu} = C(N_{Re})^{0.8}(N_{Pr})^{0.33}(Z)^{0.14}$$

(where $Z = \mu_l/\mu_w$), plots were made on linear coordinates based on N_{Nu} vs. $(N_{Re})^{0.8}$ $(N_{Pr})^{0.33}$ $(Z)^{0.14}$. Representative graphs are given in Figures 4 and 5. These shape factors for each of the D_P/D_T ratios are given in Table 6*. A plot of the value of C vs. the D_P/D_T ratio indicated the simple linear relation

$$C = 0.41 - 0.5\, D_P/D_T$$

The maximum variation in the value of C, for the same D_P/D_T ratio and different liquids, is within 15%, but the difference between the averaged value of C and that for any one liquid is less than 10%. Considering the approximations involved in computing the value of h_m from the value of U one cannot readily expect greater accuracy than ± 15%. Hence the relationship for the heat transfer coefficients of present experiments is given as

$$N_{Nu} = (0.41 - 0.5(D_P/D_T)(N_{Re})^{0.8}(N_{Pr})^{0.33}(Z)^{0.14}$$

as indicated in Figures 4 and 5, to within ± 15% for the range in Reynolds numbers from 300 to 40,000 and D_P/D_T ratios from 0.07 to 0.299 for spheres. The same relation is also seen to hold for the few sizes (three) of Raschig rings and one size of Berl saddles when their nominal sizes are used.

The above results indicate that the heat transfer coefficients for heating liquids in the packed tube are greater than those in open tubes by a factor of 10 to 13. This may be compared with the results of Schumacher who found the coefficient to be constant at 7.5 for gas streams in the case of data of Colburn and Leva and co-workers but nearly 50% greater in the case of data of Kling (*29*). Chu and Storrow (*21*) also reported higher values than those of Colburn. Again Colburn's correlation indicates a maximum for h_m at a D_P/D_T ratio of 0.15. In the present experiments this maximum is not exhibited in the D_P/D_T range studied. Hence it appears that the effect of this ratio is different in the case of liquids from that of gas streams.

One of the significant results of this work is that the same heat transfer characteristics are found even at very low Reynolds number down to 300, the lowest of the experiments. Similar effects are shown in the case of pressure drop. This result, though unexpected,

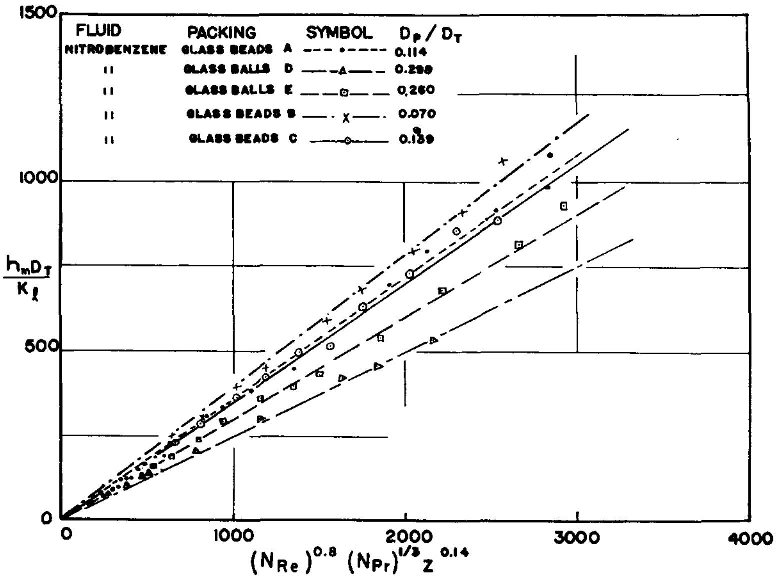

Fig. 5. Correlation of experimental heat transfer coefficients.

* Tabular material has been deposited as document No. 6269 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or 35-mm microfilm.

* See footnote to column 1.

seems to be in line with the observations of Satterfield and co-workers (30) that turbulence persisted even at the low N'_{Re} value of 10 in the packed beds studied by them.

The effect of L/D_T ratio to which reference has been made by Calderbank and Pogorski (31) could not be investigated with the present apparatus. Because of the similarity shown between the open tube and packed tube its effect might be small even as in the case of open tubes. However experimental data are needed for the case of downward flow of liquids, for cooling of liquids, for other tube sizes than the one used here, and for different L/D_T ratios.

CONCLUSION

Data on heat tranfer for heating liquids flowing upward in a single packed tube and for a range in D_T/D_P ratios from 14 to 3.35 have been presented. For packed tubes of this ratio from 14 to 3 a satisfactory correlation for pressure drop has been developed by the use of the Reynolds number based on tube diameter, the Fanning friction factor, and a simple rationally derived function of fractional voids. This relationship

$$\frac{\Delta H_B \epsilon^4}{\Delta H_T} = 24.8[(1.5)(1-\epsilon)(D_T/D_P) + 1] - 22.3$$

is applicable within ±10% for solid, nearly spherical packings in random-packed tubes. An analogous correlation has been found for heat transfer coefficients for the heating of liquids in a packed tube of L/D_T ratio 21.4. This is satisfactory within ±15% for the range in D_P/D_T ratio from 0.299 to 0.07, in N_{Re} from 40,000 to 300, and in N_{Pr} from 2.7 to 11.7 and is given as

$$\frac{h_m D_T}{k_l} = (0.4 - 0.5\, D_P/D_T) \left(\frac{D_T w_o \rho}{\mu_l}\right)^{0.8} \left(\frac{C_p \mu_l}{k_l}\right)^{0.33} \left(\frac{\mu_l}{\mu_w}\right)^{0.14}$$

ACKNOWLEDGMENT

The writer wishes to acknowledge his indebtedness to Professor G. S. Laddha, A. C. College of Technology, University of Madras for his valued interest and advice during this investigation. This paper forms a part of the Ph.D thesis submitted to the University of Madras (1956).

Notation

A_i = inside area of heat transfer surface of packed tube, sq. ft.
A_m = mean area for packed tube
A_o = outside area of heat transfer surface of packed tube, sq. ft.
C = shape factor
C_p = specific heat B.t.u./(lb.)(°F.)
D_n = diameter of the equivalent volume sphere, ft.
D_P = diameter of the packing, ft.
D_T = diameter of the packed tube, ft.
E_T = eddy diffusivity, sq. ft./sec.
f = Fanning friction factor
g = acceleration of gravity
G_o = mass velocity of fluid based on area of cross section of empty tube, lb./(sq. ft)(hr.)
h_d = dirt-factor coefficient
h_m = mean heat transfer coefficient of the packed tube based on the area of the wall of the tube, B.t.u./(hr.)(sq. ft.)(°F.)
h_s = condensing steam coefficient
ΔH_B = loss of head accompanying fluid flow in packed tube
ΔH_T = corresponding quantity in open tube
k_l = thermal conductivity of liquid at average bulk temperature, B.t.u./(hr.)(sq. ft.)(°F/ft.)
L = height of the packed bed, ft.
L_B = equivalent length of flow path in packed tube
N_{Nu} = Nusselt number, $h_m D_T/k_l$
N'_{Pe} = modified Peclet number, $D_P w_o/E_T$
N_{Pr} = Prandtl number, $C_p \mu_l/k_l$
N_{Re} = Reynolds number, $D_T w_o \rho/\mu_l$
N'_{Re} = modified Reynolds number, $D_P w_o \rho/\mu$
r_H = hydraulic radius of tube, ft.
r'_H = mean hydraulic radius of packed tube, ft.
t_l = average mean bulk temperature of liquid, °F.
t_1 = liquid inlet temperature °F.
t_2 = liquid outlet temperature °F.
T_s = temperature of saturated steam, °F.
T_w = tube wall temperature
U = over-all coefficient of heat transfer, B.t.u./(hr.)(sq. ft.)(°F.)
U' = over-all coefficient of heat transfer from metal wall to liquid, B.t.u./(hr.)(sq. ft.)(°F.)
w = velocity of the fluid, ft./sec.
w_o = velocity of fluid based on area of cross section of tube, ft./sec.
X = thickness of tube wall
Z = ratio of viscosities of liquid at bulk temperature and wall temperature, (μ_l/μ_w)
ϵ = mean fractional voids in packed bed
μ_l = viscosity at bulk temperature of liquid, lb./(hr.)(ft.)
μ_w = viscosity at wall temperature of liquid, lb./(hr.)(ft.)

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Manuscript received March 11, 1959; revision received August 3, 1959; paper accepted August 24, 1959. Paper presented at A.I.Ch.E. Atlantic City meeting.