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MODELING OF A FLUIDIZED BED COMBUSTOR WITH IMMERSED TUBES

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OBJECTIVE AND SCOPE OF WORK

A mathematical model of a fluidized-bed combustor will be developed which will include coal combustion phenomena and will incorporate basic mass transport relationships, bubble mechanics, heat transfer and configuration effects. A cold model test bed will be designed, constructed and operated to generate data in support of the effort in developing the mathematical model. In particular, experiments will provide data concerning heat transfer effects of tubes and tube bundles in fluidized beds, bubble formation, dispersion etc.

SUMMARY OF PROGRESS TO DATE

Experiments have been carried out to measure the total heat transfer coefficient between 12.7 mm diameter copper tubes with different surface roughness and glass beads of different sizes. The comparison of results for the rough and technically smooth tubes revealed that the heat transfer coefficient strongly depends on the ratio of pitch (P) to particle diameter ($\bar{d}_p$). By the proper choice of this ratio, $P/\bar{d}_p$, the total maximum heat transfer coefficient could be increased by as much as 40% over the value for a smooth tube with the same outside diameter. However, if $P/\bar{d}_p$ ratio is less than unity, the maximum heat transfer coefficient for rough tube is smaller as compared to the smooth tube. The design of the two end plates of the fluidized bed for mounting tube bundles of varying configuration and pitches has been completed and is currently under fabrication in the departmental workshop.

DETAILED DESCRIPTION OF TECHNICAL PROGRESS

Experiments have been carried out to measure total heat transfer coefficient for rough tubes and smooth tube immersed in a fluidized bed of glass beads. The tubes were mounted horizontally and 213 mm above the perforated plate distributor. The rough tubes consisted of v-thread tubes with pitches of 1/32", 1/64", 1/108", and a knurled tube of diameteral pitch equal to 32. For all the tubes under study, the outside diameter was 12.7 mm.

Table 1 lists the physical properties and minimum fluidizing velocities of glass beads. From the screen analysis of glass beads as obtained by a sonic sifter, the average diameter of the particles is computed from the following equation:

$$\bar{d}_p = \frac{1}{\sum_i \left(\frac{w}{d_p}\right)_i} \qquad (1)$$

The particle density of glass beads is determined by the displacement of methanol in a graduated cylinder. The minimum fluidizing velocity for a given bed of glass beads is determined in the conventional fashion [1] by measuring the bed pressure drop as a function of fluidizing velocity. The minimum fluidizing velocity is established by the intersection of the two linear plots describing the constant and decreasing pressure drop with decreasing fluidizing velocity.

Perforated plate distributor consists of two perforated steel plates with a coarse cloth sandwiched between them. 10.2 mm diameter holes are drilled in both the plates at a triangular pitch of 14 mm. The open area being 37.5%.

The heat transfer tubes are electrically heated by a calrod heater. Two iron-constantan thermocouples are silver soldered at the center of

TABLE 1

MINIMUM FLUIDIZATION VELOCITIES OF GLASS BEADS AT ROOM TEMPERATURE

MATERIAL	WEIGHTED AVERAGE DIA $\bar{d}_p$ μm	PARTICLE DENSITY ρ_s kg/m^3	MINIMUM FLUIDIZING VELOCITY U_{mf} cm/s	MINIMUM MASS FLUIDIZING VELOCITY G_{mf} kg/m^{2}s
Glass beads	265	2485	5.9	0.071
Glass beads	357	2495	10.6	0.127
Glass beads	427	2490	16.3	0.196

the tube at 90 apart. The ends of the tubes are provided with teflon supports to reduce axial heat loss. In all runs, one of the thermocouples is kept at the top side of the tube. The static bed height is kept at 35 cm.

The temperatures of the bed, the heat transfer surface, and of the fluidizing air are measured at a steady state along with the gas flow rate. The electrical current and voltage, and pressure drops in the vicinity of the heat transfer tube are recorded. The steady state is assumed to be established when the bed temperature variation is less than 0.4 k per hour. The temperatures at each of the other locations are recorded over a period of time and an average value is used. From these readings, the total heat transfer coefficient, is determined from the following relation:

$$h_w = \frac{Q}{A_w(T_w - T_b)} \qquad (2)$$

The total heat transfer coefficient for rough tube is based on the surface area of the smooth tube of the same outside diameter. In Tables 2 to 15 are tabulated the computed values of total heat transfer coefficient for rough and technically smooth tubes as a function of reduced mass fluidizing velocity.

The pressure loss in a fluidized bed is equal to the weight of the solid per unit cross-sectional area of the column i.e.

$$\Delta P = H(1 - \varepsilon)(\rho_s - \rho_f) \qquad (3)$$

Since ΔP, H, ρ_s and ρ_f are known for each experiment, the above relation has been used to compute the bed porosity ε. Tables 2 to 15 also list the calculated values of the bed porosity.

Figures 1 to 3 show the performance of various rough tubes as compared with the smooth tube for glass beads having average diameter 265, 357, and 427 μm respectively. It is clear that the heat transfer coefficient depends not only on the type of surface roughness but also pitch/particle diameter ratio. The heat transfer coefficient for the v-threaded tube (P = 1/32") is found to be larger than the heat transfer coefficient for the knurled tube for all the three particle sizes. This is probably because v-threads are less effective in hampering the solids motion in the bed close to tube surface than the knurled tube surface.

The influence of $P/\bar{d}_p$ ratio for v-threaded tubes on $h_{wb\ max}/h_{w\ max}$ is shown in Figure 4. For $P/\bar{d}_p \lessapprox 1$, the maximum heat transfer for v-thread tubes is smaller than for smooth tubes and is correlated by the following equation:

$$h_{wb\ max} = h_{w\ max}[1 - 0.159(P/\bar{d}_p)] \qquad (4)$$

$h_{wb\ max}$ is greater than $h_{w\ max}$ when $P/\bar{d}_p$ is greater than unity and is correlated by the following expression:

$$h_{wb\ max} = h_{w\ max}[1 + 0.40\ (1-(P/\bar{d}_p)^{-3})] \qquad (5)$$

for $1.1 < P/\bar{d}_p \leqslant 3$

The decrease of heat transfer coefficient for v-thread tubes when $(P/\bar{d}_p) < 1$ as compared to smooth tubes can be easily explained with the help of Figures 5a and 5b. It is evident that the resistance to heat flow is greater for the case of Figure 5b than for the case of Figure 5a because of longer heat conduction paths. As $(P/\bar{d}_p)$ decreases from 1 to 0 the heat conduction path decreases and therefore $h_{wb\ max}$ increases.

Figure 5c represents a typical case when $(P/\bar{d}_p)$ is greater than 1 but less than 2. In this case the solid particle has multiple contact with the heat transfer surface thus more surface area of the sphere is exposed to heat transfer from the heated tube surface. This should result in considerable enhancement in heat transfer. However, due to possible particle capture in threads, the increase in $h_{wb\ max}$ is about 33% when $P/\bar{d}_p = 1.8$. When the particle size is much smaller than the pitch, the particle capture is not a serious problem. As shown in Figure 5d, there is larger effective surface area of the rough tube participating in heat transfer and also there is only limited improvement in particle-surface contact area. The maximum heat transfer coefficient for rough tubes having $(P/\bar{d}_p) = 3$, the $h_{wb\ max}$ is about 40% greater than for smooth tubes.

Figure 6 illustrates the effect of $P/\bar{d}_p$ on maximum heat transfer for knurled tube. In this case the increase in $h_{wb\ max}$ is smaller than for v-threaded tubes. For example, when $P/\bar{d}_p = 4$, the maximum heat transfer coefficient is about 13% larger than for a smooth tube.

Hager and Thomson [2] studied bubble motion around the horizontal tubes with longitudinal and transverse fins. They [2] observed that bubbles do not penetrate into the space between fins and thus solids have a poor renewal rate. This situation is more serious with closely spaced fins, and much of the advantage in using large number fins is neutralized. Genetti et al. [3] observed a reduction in heat transfer in some cases for finned tubes and attributed this to particle hold up. This reduction is due to the inability of bubbles to penetrate the fin space and subsequently solids are defluidized in fin spacing. Due to the small height of the surface roughness in our experiments, the bubbles are able to renew the solids in the grooves. A practical economic advantage of the v-threaded rough tubes over the finned tubes is the ease of fabrication.

WORK FORECAST

Experiments will be performed with a bank of tubes to study the effect of tube gap on the total heat transfer coefficient between 12.7 mm diameter copper tubes immersed in a fluidized bed of glass beads of different sizes.

CONCLUSIONS

The analytical formulation will enable a more realistic treatment of the fluidized-bed combustion. The experimental work on development will provide a thorough base for resolving the mechanism of heat transfer in relation to an immersed array of horizontal tubes. This information will help in optimal design of fluidized-beds and their scale-up.

Nomenclature

A_w	Surface area of the heat transfer tube, m^2
d_p	Particle diameter, m
$\bar{d}_p$	Average particle diameter defined by eq. (1), m
G	Mass fluidizing velocity, kg/m^2s
G_{mf}	Minimum mass fluidizing velocity, kg/m^2s
H	Distance between pressure probes, m
h_w	Total heat transfer coefficient, W/m^2K
$h_{w\ max}$	Maximum total heat transfer coefficient, W/m^2K
$h_{wb\ max}$	Maximum total heat transfer coefficient for rough tubes based on smooth tube surface area, W/m^2K
P	Pitch, for v-threaded tubes: it is the distance between two identical points of the consecutive threads; for knurled tubes this distance is measured along the tube axis only, m
Q	Electrical power supplied to heater, W
T_b	Average fluidized bed temperature, K
T_w	Average surface temperature of the heat transfer tube, K
U	Fluidizing superficial velocity at 70 F and atmospheric pressure cm/s
U_{mf}	Minimum fluidizing superficial velocity at 70 F and atmospheric pressure, cm/s
w	Weight fraction of particles in a specified size range, dimensionless

Greek Letters

ε	Void fraction at fluidization conditions, dimensionless
$1 - \varepsilon$	Particle fraction, dimensionless
ρ_f	Fluid density, kg/m^3

ρ_s Density of solid particle, kg/m^3

ΔP Pressure drop across the bed, Pa

References

1. D. Kunii and O. Levenspiel, "Fluidization Engineering," John Wiley and Sons New York, 1969.

2. W. R. Hager and W. J. Thomson, AIChE Symp. Ser. No. 128, 69, pp. 68-77, 1951.

3. W. E. Genetti, R. A. Schall and E. S. Grimmett, AIChE Symp. Ser. No. 116, 67, pp. 90-96, 1971.

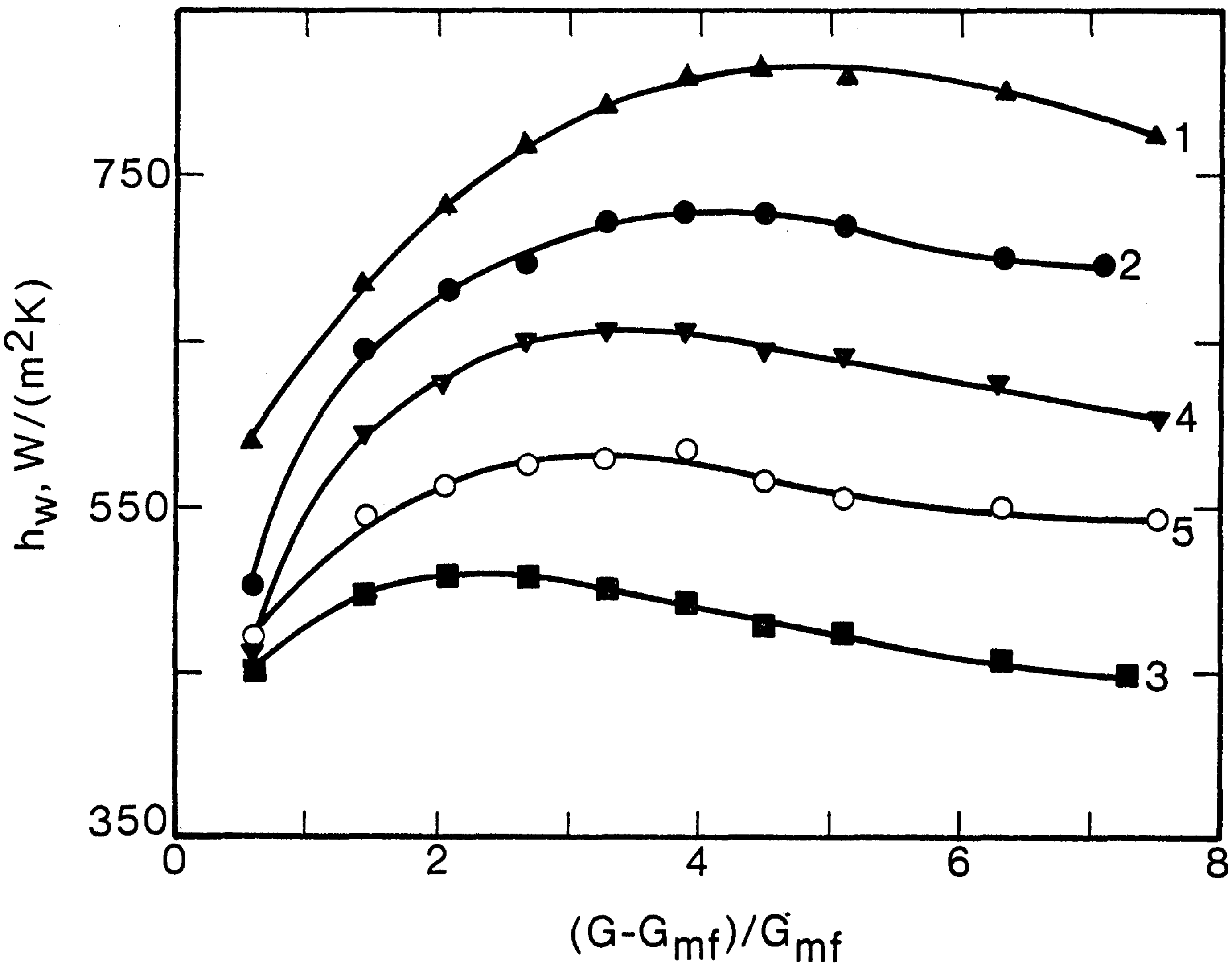

Figure 1. Variation of h_w with $(G - G_{mf})/G_{mf}$ for glass beads ($\bar{d}_p$ = 265 μm) and an electrically heated 12.7 mm copper tube with different surface roughness. Curves 1 through 3 refer to surface with v-threads of pitch 1/32", 1/64" and 1/108" respectively, curve 4 is for a knurled surface of diameteral pitch 32, and curve 5 is for a technically smooth surface.

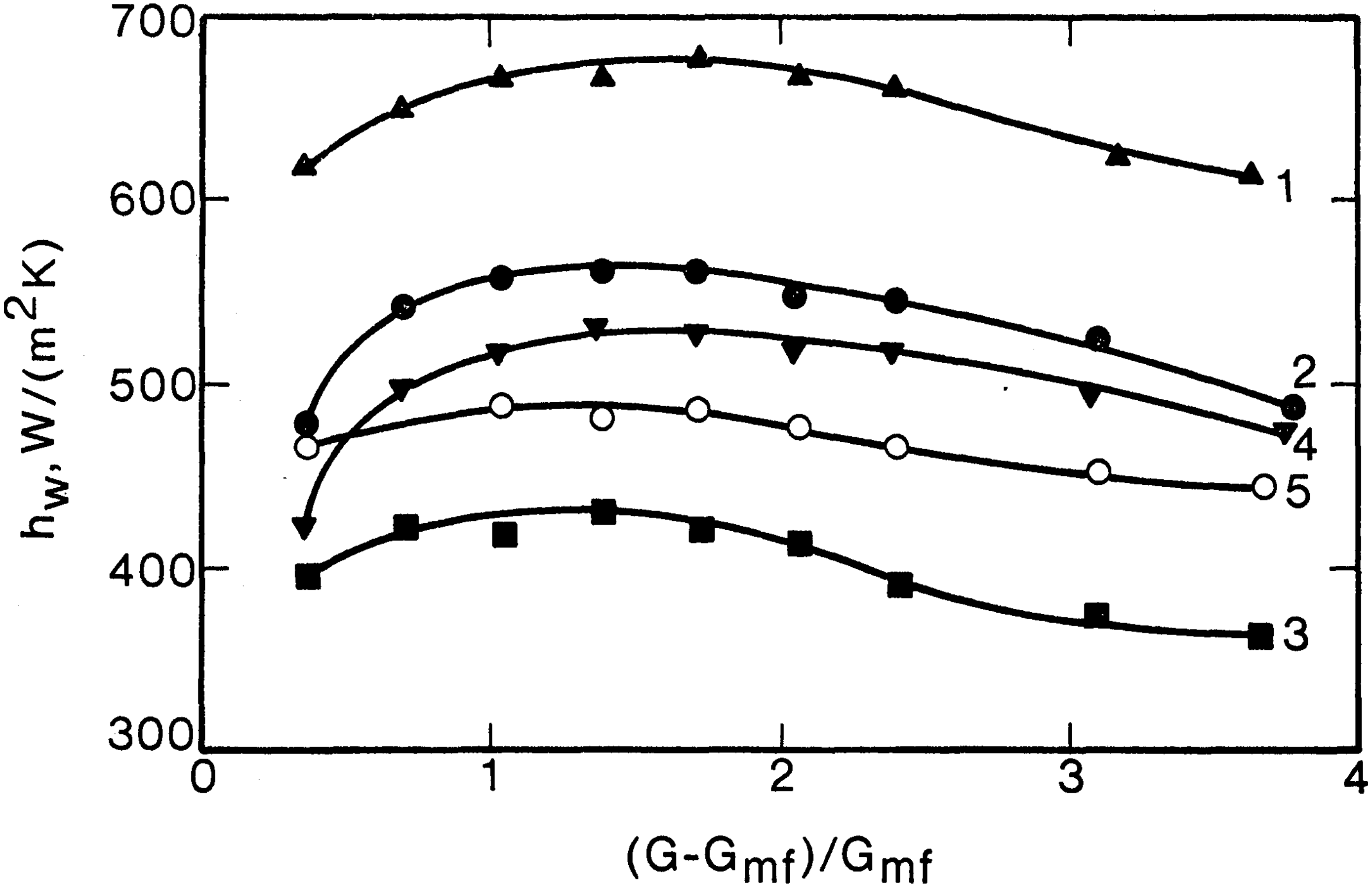

Figure 2. Variation of h_w with (G - G_{mf}/G_{mf}) for glass beads ($\bar{d}_p$ = 357 μm) and an an electrically heated 12.7 mm copper tube with different surface roughness. Curves 1 through 3 refer to surface with v-threads of pitch 1/32", 1/64", and 1/108" respectively, curve 4 is for a knurled surface of diametral pitch 32, and curve 5 is for a technically smooth surface.

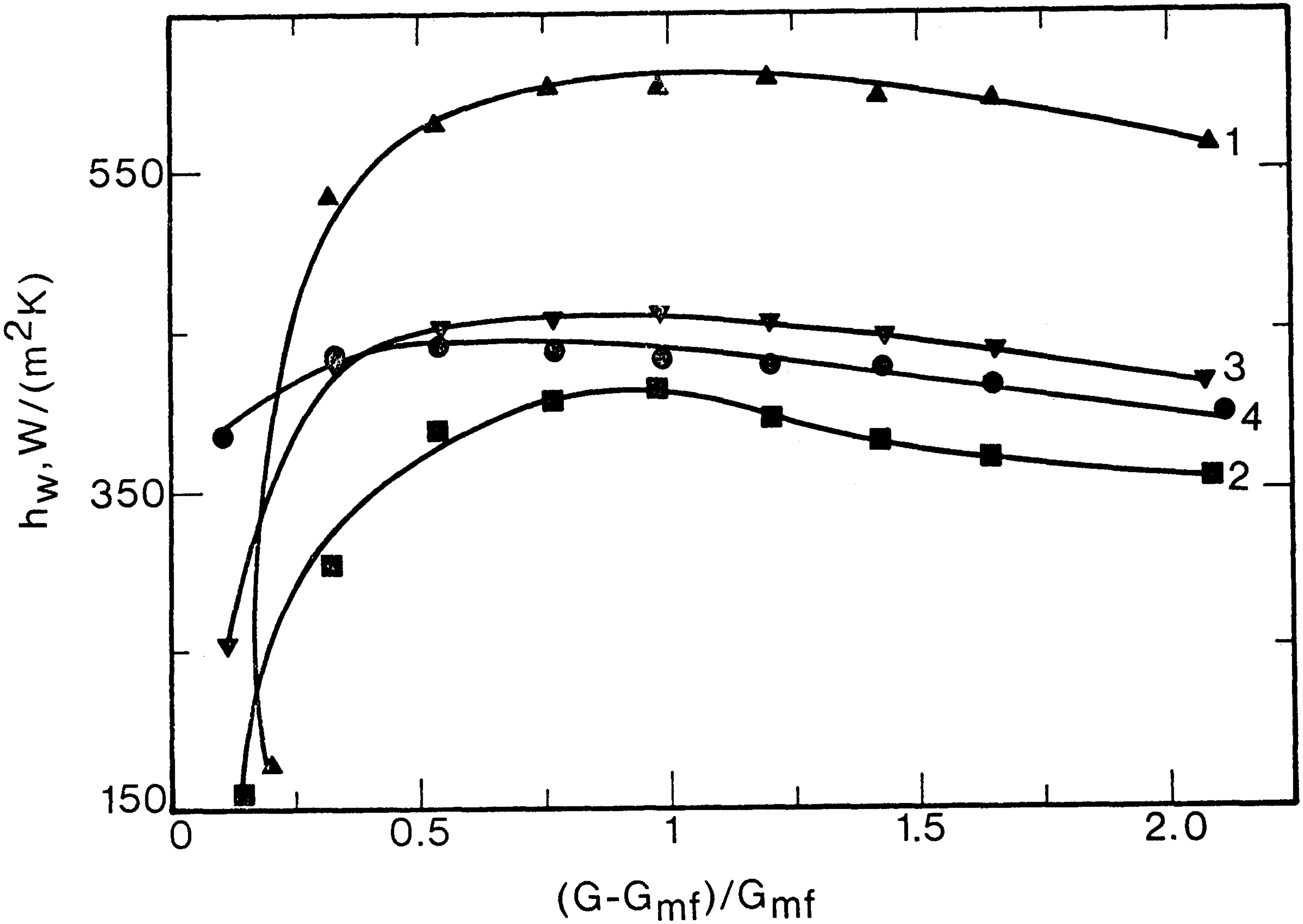

Figure 3. Variation of h_w with reduced fluidizing velocity for glass beads ($\bar{d}_p$ = 427 μm) and an electrically heated 12.7 mm copper tube with different surface roughness. Curves 1 and 2 refer to surface with v-threads of pitch 1/32" and 1/108" respectively, curve 3 is for a knurled surface of diametral pitch 32, and curve 4 is for a technically smooth surface.

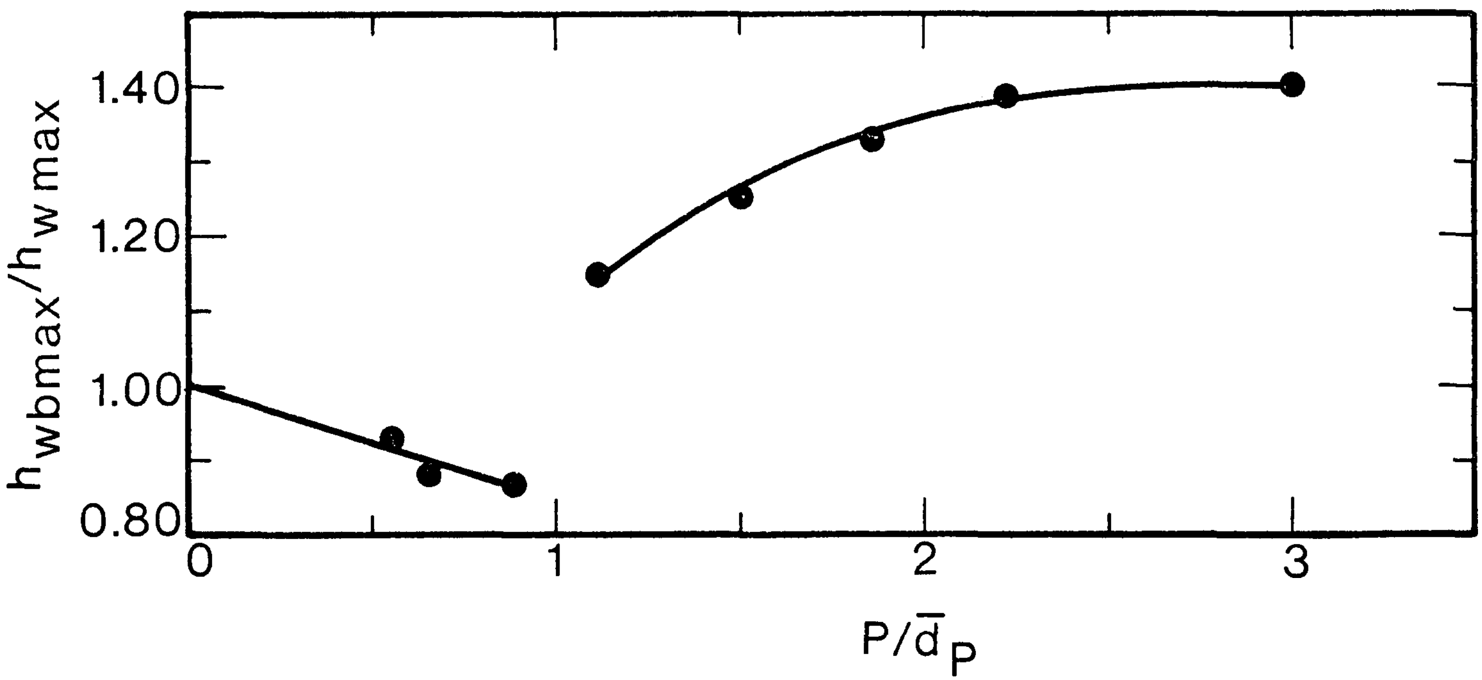

Figure 4. Variation of $h_{wb\ max}/h_{w\ max}$ with $P/\bar{d}_p$ for v-threaded tubes.

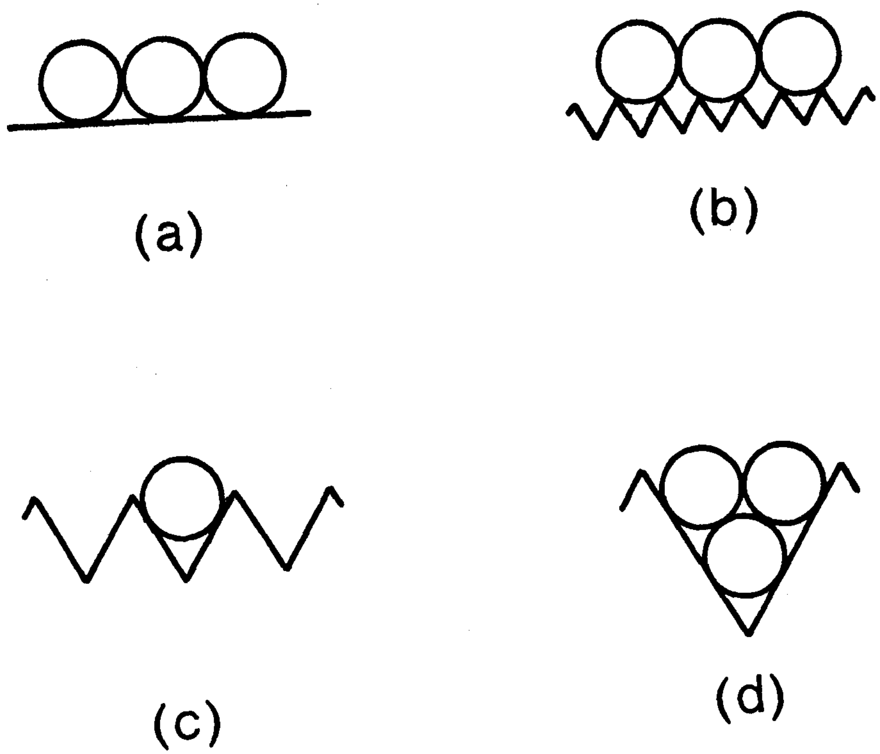

Figure 5. Particle and heat transfer surface contact for (a) smooth tube, (b) tube with fine roughness, $P/\bar{d}_p = 0.5$, (c) tube with matching roughness, $P/\bar{d}_p = 1.2$, and (d) tube with coarse roughness, $P/\bar{d}_p = 2.5$.

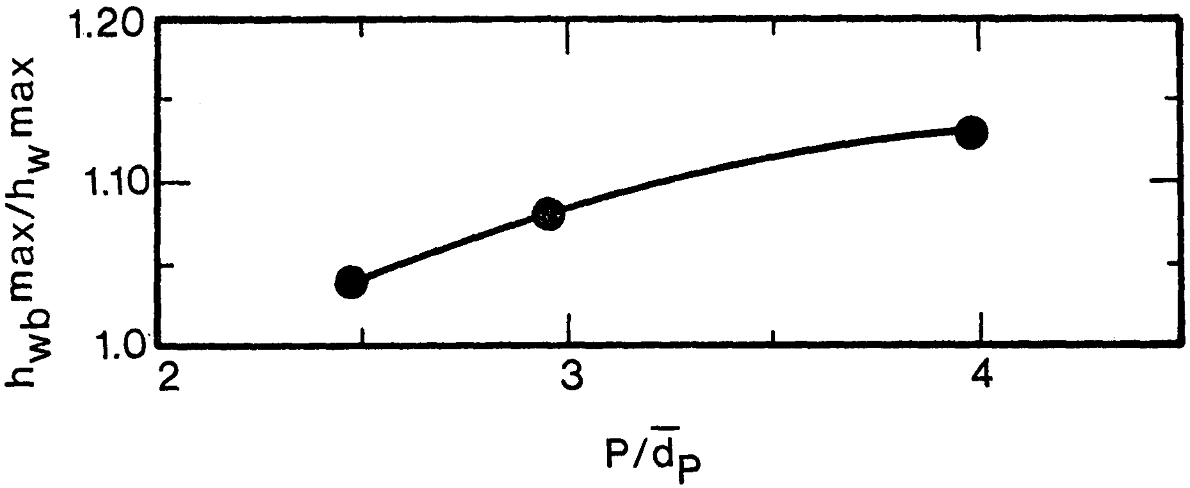

Figure 6. Variation of $h_{wb\ max}/h_{w\ max}$ with $P/\bar{d}_p$ for a knurled tube.

TABLE 2

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1035

Height of Bed: 35 cm

U_{mf}: 5.9 cm/s

Material: Glass Beads, $\bar{d}_p$ = 265 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: Smooth

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
9.37	0.112	1.59	37.4	0.434	338.5	310.15	28.35	162.0	470
14.4	0.173	2.44	36.6	0.446	331.2	306.65	24.55	162.0	543
18.0	0.216	3.05	36.0	0.455	329.15	305.45	23.7	162.0	562
21.6	0.259	3.67	35.6	0.461	327.55	304.3	23.25	162.0	574
25.2	0.302	4.26	35.2	0.467	326.5	303.5	23.0	162.0	579
28.9	0.347	4.90	35.1	0.469	325.45	302.6	22.85	162.0	583
32.4	0.389	5.49	34.9	0.472	325.55	302.0	23.55	162.0	565
36.0	0.432	6.11	34.9	0.472	325.2	301.15	24.05	162.0	554
43.2	0.518	7.32	34.7	0.475	324.6	300.45	24.15	162.0	551
50.1	0.601	8.50	34.7	0.475	324.5	299.9	24.6	162.0	541

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 3

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1035

Height of Bed: 35 cm

U_{mf}: 5.9 cm/s

Material: Glass Beads, $\bar{d}_p$ = 265 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: 32 V-THREAD PER INCH

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
9.35	0.112	1.585	37.4	0.434	329.6	307.2	22.4	160.6	590
14.4	0.173	2.44	36.6	0.446	323.1	303.75	19.35	160.6	683
18.05	0.217	3.06	36.0	0.445	320.75	302.7	18.05	160.6	731
21.7	0.260	3.68	35.6	0.461	318.85	301.65	17.2	160.6	767
25.25	0.303	4.28	35.2	0.467	317.55	300.9	16.65	160.6	792
28.9	0.347	4.90	35.2	0.467	317.1	300.75	16.35	160.6	809
32.3	0.387	5.47	35.0	0.470	316.5	300.3	16.2	160.6	814
36.1	0.433	6.12	34.8	0.473	316.1	299.7	16.4	160.9	807
43.4	0.521	7.36	34.5	0.478	315.6	299.05	16.55	160.9	799
50.2	0.602	8.51	34.5	0.478	315.6	298.5	17.1	161.2	775

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 4

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1035

Height of Bed: 35 cm

U_{mf}: 5.9

Material: Glass Beads, $\bar{d}_p$ = 265 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: 64 V-THREAD PER INCH

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
9.35	0.112	1.585	37.2	0.437	333.45	307.3	26.15	160.0	503
14.5	0.174	2.455	36.6	0.446	325.0	304.6	20.4	160.0	645
18.1	0.217	3.07	36.1	0.454	322.5	303.15	19.35	160.0	681
21.65	0.260	3.67	35.9	0.456	321.15	302.25	18.9	160.1	697
25.25	0.[illegible]3	4.28	35.6	0.461	319.7	301.5	18.2	160.3	723
28.8	[illegible]	4.88	35.4	0.464	318.5	300.45	18.15	160.3	726
32.5	0.[illegible]90	5.51	35.2	0.467	317.8	299.65	18.15	160.3	726
36.1	0.[illegible]33	6.12	35.2	0.467	317.95	299.6	18.35	160.4	719
43.3	0.[illegible]19	7.34	34.9	0.472	317.5	298.6	18.9	160.6	699
47.8	0.573	8.10	34.7	0.475	317.4	298.45	18.95	160.6	697

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 5

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1035

Height of Bed: 35 cm

U_{mf}: 5.9 cm/s

Material: Glass Beads, $\bar{d}_p$ = 265 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: 108 V-THREAD PER INCH

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
9.4	0.113	1.595	37.2	0.437	335.5	306.45	29.05	159.2	451
14.4	0.173	2.44	36.7	0.445	330.3	303.95	26.35	159.2	497
18.1	0.217	3.07	36.2	0.452	328.65	302.8	25.85	159.2	507
21.7	0.260	3.68	35.7	0.460	327.8	301.9	25.9	159.4	506
25.3	0.304	4.29	35.5	0.463	327.45	301.25	26.2	159.4	500
28.9	0.347	4.90	35.5	0.463	327.40	300.75	26.65	159.4	492
32.5	0.390	5.51	35.3	0.466	327.7	300.25	27.45	159.4	478
36.1	0.433	6.12	35.3	0.466	327.45	299.8	27.65	159.4	474
43.2	0.518	7.32	35.3	0.466	329.3	299.3	30.0	159.5	437
49.0	0.588	8.31	35.1	0.469	329.35	298.75	30.6	159.5	428

[a] It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b] The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 6

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1035

Height of Bed: 35 cm

U_{mf}: 5.9 cm/s

Material: Glass Beads, $\bar{d}_p$ = 265 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: Knurling

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
9.34	0.112	1.58	37.0	0.440	339.1	310.0	29.1	162.6	459
14.4	0.173	2.44	36.8	0.443	329.6	307.05	22.55	162.9	594
17.95	0.215	3.04	36.5	0.448	327.45	305.95	21.5	162.9	623
21.6	0.259	3.66	36.1	0.454	325.7	305.1	20.6	162.9	650
25.15	0.302	4.26	35.9	0.457	324.55	304.1	20.45	162.9	655
28.8	0.346	4.88	35.6	0.461	323.85	303.4	20.45	162.9	655
32.3	0.387	5.48	35.6	0.461	323.75	302.9	20.85	162.9	643
36.0	0.432	6.10	35.5	0.463	323.5	302.55	20.95	162.9	640
43.1	0.517	7.30	35.2	0.467	323.15	301.7	21.45	162.9	625
50.2	0.602	8.52	35.2	0.467	323.5	301.2	22.3	163.2	602

[a] It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b] The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 7

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1935

Height of Bed: 35 cm

U_{mf}: 10.6 cm/s

Material: Glass Beads, $\bar{d}_p$ = 357 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: Smooth

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
14.4	0.173	1.36	38.3	0.423	334.1	305.6	28.5	162.0	467
21.6	0.259	2.04	37.3	0.438	331.05	303.75	27.3	162.0	488
25.2	0.302	2.38	36.9	0.444	330.75	303.05	27.7	162.0	480
28.8	0.346	2.72	36.1	0.456	329.85	302.35	27.5	162.0	485
32.4	0.389	3.06	36.1	0.456	329.85	301.85	28.0	162.0	476
36.0	0.432	3.40	36.1	0.456	329.65	301.2	28.45	162.0	468
43.4	0.521	4.09	35.4	0.467	329.6	300.1	29.5	162.0	452
49.4	0.593	4.66	35.1	0.471	330.40	300.25	30.15	162.0	442

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 8

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1935

Height of Bed: 35 cm

U_{mf}: 10.6 cm/s

Material: Glass Beads, $\bar{d}_p$ = 357 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: 32 V-THREAD PER INCH

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
14.4	0.173	1.36	38.5	0.420	325.7	304.3	21.4	160.6	617
18.0	0.216	1.70	37.9	0.429	323.3	303.05	20.25	160.6	651
21.6	0.259	2.04	37.4	0.436	322.05	302.2	19.85	160.6	666
25.25	0.303	2.38	36.9	0.444	321.1	301.25	19.85	160.6	666
28.9	0.347	2.73	36.6	0.448	320.15	300.65	19.5	160.6	677
32.5	0.390	3.07	36.1	0.456	320.5	300.65	19.85	160.6	666
36.0	0.432	3.40	36.0	0.457	320.25	300.25	20.0	160.6	660
44.2	0.530	4.17	35.6	0.463	320.45	299.2	21.25	160.6	622
49.0	0.588	4.62	35.5	0.465	320.95	299.45	21.5	160.6	614

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 9

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1935

Height of Bed: 35 cm

U_{mf}: 10.6 cm/s

Material: Glass Beads, $\bar{d}_p$ = 357 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: 64 V-THREAD PER INCH

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
14.4	0.173	1.36	38.1	0.426	334.5	307.05	27.45	160.0	479
18.0	0.216	1.70	37.8	0.430	329.45	305.15	24.3	160.0	542
21.6	0.259	2.04	37.5	0.435	327.85	304.25	23.6	160.0	557
25.2	0.303	2.38	37.0	0.442	326.7	303.2	23.5	160.0	560
28.8	0.346	2.72	36.6	0.448	326.05	302.6	23.45	160.0	561
32.3	0.387	3.05	36.5	0.450	325.95	301.9	24.05	160.0	547
36.0	0.432	3.40	36.0	0.457	325.35	301.2	24.15	160.0	544
43.3	0.519	4.08	36.1	0.456	325.75	300.65	25.1	160.0	524
50.5	0.606	4.76	35.8	0.460	327.05	300.05	27.0	160.0	487

[a] It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b] The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 10

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1935

Height of Bed: 35 cm

U_{mf}: 10.6 cm/s

Material: Glass Beads, $\bar{d}_p$ = 357 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: 108 V-THREAD PER INCH

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity U cm/s	Superficial Fluidizing Velocity G kg/m^2s	Fluidization Number G/G_{mf}	Pressure Drop CM of H_2O	Porosity ε	Average Heater Surface Temp[a] T_w, K	Average Bed Temp[a] T_b, K	$\Delta T = T_w - T_b$ K	Power Supplied to Heater Q, W	Total Heat Transfer Coeff. h_w W/m^2K
14.5	0.174	1.37	38.0	0.427	336.15	303.15	33.0	159.5	397
18.15	0.218	1.71	37.7	0.432	333.0	302.0	31.0	159.5	423
21.7	0.260	2.05	37.5	0.435	332.5	301.1	31.4	159.6	418
25.3	0.304	2.39	36.6	0.448	330.8	300.3	30.5	159.9	431
28.9	0.347	2.73	36.3	0.453	331.35	300.15	31.2	160.0	421
32.5	0.390	3.07	36.0	0.457	331.35	294.45	31.9	160.0	413
36.1	0.433	3.41	36.0	0.457	332.2	298.55	33.65	160.0	391
43.4	0.521	4.09	35.6	0.463	334.15	299.0	35.15	160.0	374
49.3	0.591	4.65	35.4	0.466	334.65	298.3	36.35	160.1	362

[a] It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b] The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 11

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1935

Height of Bed: 35 cm

U_{mf}: 10.6 cm/s

Material: Glass Beads, $\bar{d}_p$ = 357 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: Knurling

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G $kg/m^2 s$	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w $W/m^2 K$
14.4	0.173	1.36	37.9	0.429	338.65	306.85	31.8	162.9	422
18.0	0.216	1.70	37.6	0.433	332.2	305.3	26.9	162.9	498
21.6	0.259	2.03	37.3	0.438	330.35	304.4	25.95	163.2	517
25.1	0.301	2.37	37.0	0.442	329.0	303.7	25.3	163.2	531
28.7	0.344	2.71	36.6	0.448	328.45	303.0	25.45	163.2	527
32.3	0.387	3.05	36.1	0.456	328.45	302.5	25.95	163.2	517
35.9	0.431	3.39	36.1	0.456	328.05	302.05	26.0	163.5	517
43.1	0.517	4.07	35.7	0.462	328.6	301.35	27.25	163.5	494
50.3	0.603	4.74	35.6	0.463	329.0	300.65	28.35	163.8	475

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 12

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1835

Height of Bed: 35 cm

U_{mf}: 16.3 cm/s

Material: Glass Beads, $\bar{d}_p$ = 427 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: Smooth

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity U cm/s	Superficial Fluidizing Velocity G kg/m^2s	Fluidization Number G/G_{mf}	Pressure Drop CM of H_2O	Porosity ε	Average Heater Surface Temp[a] T_w, K	Average Bed Temp[a] T_b, K	$\Delta T = T_w - T_b$ K	Power Supplied to Heater Q, W	Total Heat Transfer Coeff. h_w W/m^2K
18.0	0.216	1.105	38.7	0.416	340.4	305.55	34.85	162.0	383
21.6	0.259	1.33	38.3	0.422	335.05	304.2	30.85	162.0	432
25.1	0.301	1.54	37.8	0.429	333.6	303.3	30.3	162.0	440
28.8	0.346	1.77	37.5	0.433	333.0	302.6	30.4	162.0	438
32.4	0.389	1.99	37.0	0.441	332.7	301.85	30.85	162.0	432
36.1	0.433	2.21	36.6	0.447	332.45	301.35	31.1	162.0	428
39.6	0.475	2.43	36.4	0.450	332.1	300.75	31.35	162.0	426
43.2	0.518	2.65	35.9	0.458	332.6	300.35	32.25	162.0	414
50.7	0.608	3.11	35.4	0.466	333.0	299.5	33.5	162.0	397

[a] It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b] The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 13

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1835

Height of Bed: 35 cm

U_{mf}: 16.3 cm/s

Material: Glass Beads, $\bar{d}_p$ = 427 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: 32 V-THREAD PER INCH

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity U cm/s	Superficial Fluidizing Velocity G kg/m^2s	Fluidization Number G/G_{mf}	Pressure Drop CM of H_2O	Porosity ε	Average Heater Surface Temp[a] T_w, K	Average Bed Temp[a] T_b, K	$\Delta T = T_w - T_b$ K	Power Supplied to Heater Q, W	Total Heat Transfer Coeff. h_w W/m^2K
17.9	0.215	1.20	38.5	0.418	383.5	308.7	74.8	161.9	178
21.5	0.258	1.32	38.5	0.418	333.45	308.5	24.95	162.2	535
24.9	0.290	1.53	38.1	0.425	330.5	307.5	23.0	162.2	580
28.6	0.343	1.755	37.7	0.431	328.75	306.65	22.1	162.5	604
32.3	0.387	1.98	37.4	0.435	328.1	305.95	22.15	162.5	603
35.8	0.429	2.20	37.0	0.441	326.55	304.6	21.95	162.5	609
39.4	0.473	2.42	36.7	0.446	326.35	304.0	22.35	162.5	598
43.2	0.518	2.65	36.9	0.443	326.25	303.85	22.4	162.5	597
50.4	0.605	3.09	36.7	0.446	326.8	303.2	23.6	162.5	566

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 14

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1835

Height of Bed: 35 cm

U_{mf}: 16.3 cm/s

Material: Glass Beads, $\bar{d}_p$ = 427 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: 108 V-THREAD PER INCH

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^2s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^2K
18.65	0.224	1.145	37.7	0.431	389.7	306.5	83.2	161.0	159
21.55	0.259	1.32	37.7	0.431	349.85	306.3	43.55	161.0	304
25.05	0.301	1.535	37.7	0.431	339.45	305.45	34.0	161.0	389
28.7	0.344	1.76	37.5	0.434	337.1	304.55	32.55	161.3	407
32.2	0.386	1.975	37.2	0.438	335.95	303.95	32.0	161.3	414
35.9	0.431	2.20	37.0	0.441	336.8	303.25	33.55	161.3	395
39.5	0.474	2.42	36.7	0.446	337.45	302.6	34.85	161.3	381
43.1	0.517	2.64	36.7	0.446	338.05	302.15	35.9	161.3	370
50.4	0.605	3.09	36.9	0.443	338.55	301.45	37.1	161.3	357

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

TABLE 15

TOTAL HEAT TRANSFER COEFFICIENT

Code: 1835

Height of Bed: 35 cm

U_{mf}: 16.3 cm/s

Material: Glass Beads, $\bar{d}_p$ = 427 μm

Electrically Heated Copper Tube Diameter: 12.7 mm

Type of Surface Roughness: Knurling

Distance Between Pressure Probes: 26.6 cm

Superficial Fluidizing Velocity		Fluidization Number	Pressure Drop	Porosity	Average Heater Surface Temp[a]	Average Bed Temp[a]	$\Delta T = T_w - T_b$	Power Supplied to Heater	Total Heat Transfer Coeff.
U cm/s	G kg/m^{2}s	G/G_{mf}	CM of H_2O	ε	T_w, K	T_b, K	K	Q, W	h_w W/m^{2}K
18.05	0.2165	1.11	38.1	0.425	357.65	304.95	52.7	162.5	253
21.6	0.259	1.325	38.0	0.426	335.25	304.1	31.15	162.5	429
25.2	0.302	1.545	37.7	0.431	333.05	303.45	29.6	162.5	451
28.9	0.347	1.77	37.4	0.435	332.1	302.75	29.35	162.5	456
32.3	0.387	1.98	37.0	0.441	331.3	302.2	29.1	162.5	459
35.9	0.431	2.20	36.8	0.444	331.45	302.0	29.45	162.5	454
39.6	0.475	2.43	36.6	0.447	331.7	301.75	29.95	162.9	447
43.2	0.518	2.65	36.5	0.448	332.55	301.75	30.8	162.9	435
50.2	0.602	3.08	36.1	0.455	333.7	301.6	32.1	162.9	417

[a]It is recognized that the uncertainty in T_w could be as high as 0.2 K due to averaging.

[b]The estimated uncertainty in T_b due to averaging is about 0.2 K.

* U.S. GOVERNMENT PRINTING OFFICE: 1978--740-306/9515 Region No. 4