PACKED BED HEAT TRANSFER

BY

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A THESIS

PRESENTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE WITH A MAJOR IN CHEMICAL ENGINEERING

AT

NEWARK COLLEGE OF ENGINEERING

Newark, New Jersey
1962

ABSTRACT

The use of various published correlations to determine apparent thermal conductivities was found to give results of differing magnitudes. For this reason when these values were utilized in the theoretical relationships proposed by McAdams:

$$\frac{t_w - t_2}{t_w - t_1} = 0.692e^{-23.14X} + 0.1312e^{-121.9X} + 0.0535e^{-299.6X}$$

in which X is defined as

$$X = (K_a L / C_p G_o D_t^2)$$

for packed bed systems the results were found to be inconsistent.

In this investigation a dimensionless equation:

$$\frac{K_a}{k_g} = 0.00105\left(\frac{D_p G_o}{\epsilon_p \mu}\right)^{1.32}$$

has been developed which permits the prediction of apparent thermal conductivities to air flowing through a 1 inch tube packed with glass beads. The equation gives satisfactory results for ratios of D_p/D_t from 0.15 to 0.22 and a modified Reynolds number of 526 to 3990.

The effect of voids in the packing material was studied and a porosity was included in the modified Reynolds number used in correlating the data.

APPROVAL OF THESIS

FOR

DEPARTMENT OF CHEMICAL ENGINEERING

NEWARK COLLEGE OF ENGINEERING

BY

FACULTY COMMITTEE

APPROVED: ______________________

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NEWARK, NEW JERSEY

JUNE, 1962

ACKNOWLEDGEMENT

The author acknowledges with gratitude his debt to Doctor Jerome J Salamone, who guided the course of this investigation and the writing of this manuscript. He is indebted also to Robert S. Emanuel, Division Plant Superintendent, at the Harrison Gas Plant of the Public Service Electric and Gas Company of New Jersey for supplying the space and equipment and to his wife who typed this manuscript.

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INTRODUCTION

McAdams[12] proposed that when a fluid flows at a constant mass rate through a packed bed system and heat is supplied or removed at the wall, an apparent thermal conductivity could be defined by the following equation:

$$\frac{\delta t}{\delta x} = \frac{K_a}{G_o C p}\left(\frac{\delta^2 t}{\delta r^2} + \frac{1}{r} + \frac{\delta t}{\delta r} + \frac{\delta^2 t}{\delta x^2}\right) \qquad (1)$$

Neglecting axial conduction, equation (1) was integrable for a constant wall temperature and uniform mass velocity and becomes:

$$\frac{t_w - t_2}{t_w - t_1} = 0.692e^{-23.14X} + 0.1312e^{-121.9X} + 0.0535e^{-299.6X} \qquad (2$$

in which X is defined as:

$$X = (K_a L/CpG_o D_t^2) \qquad (3)$$

For X values greater than 0.04 or for $(t_w - t_2/t_w - t_1)$ less than 0.28 equation (2) will be accurate within one percent and only the first part of equation (2) need be used.

It was also proposed by McAdams[12] that the results for packed bed systems could be expressed as the mean heat-transfer-coefficient. The mean heat-transfer-coefficient is based on the area of the tube wall and the logarithmic mean of the terminal temperature differences:

$$h_m = q/A(t_w - t)_m \qquad (4)$$

therefore for values of $(t_w - t_2/t_w - t_1)$ less than 0.28, the first part of equation (2) may be expressed in terms of the mean heat-transfer-coefficient:

$$h_m = 5.79\left(\frac{K_a}{D_t}\right) + 0.0912\left(\frac{CpG_oD_t}{L}\right) \qquad (5)$$

The theoretical relationship proposed by McAdams[12] for packed bed heat transfer has been found to be inconsistent when utilized with different apparent thermal conductivities as determined by various published correlations. The use of these correlations to calculate the apparent thermal conductivity resulted in widely different values. Due to the varying magnitudes of the apparent thermal conductivity values obtained, it was felt that these correlations were not especially practical for general design purposes. It became apparent then that these published correlations were valid only for the particular apparatus used by the various investigators.

Due to the dubious results obtained, it was felt that an investigation should be conducted to establish a relationship which would be useful for general design purposes. It is not the objective of this investigation to solve the problem of packed bed heat transfer completely. Due to the complexity of the problem this investigation was limited to the use of glass beads of several different diameters and air as the fluid medium.

The investigational data was limited to mass rates of flow and temperature differences of the fluid. It was therefore decided to utilize the mean heat-transfer-coefficient which could be calculated from the available experimental data. Once the heat-transfer-coefficient was obtained, the value of an apparent thermal conductivity was determined by use of equation (5). It then became possible to derive a dimensionless equation. This equation could then be used to determine the apparent thermal conductivity of a packed bed system within the limits of this investigation.

THEORY

Heat transfer in packed bed systems with a uniform wall temperature takes place as a result of a combination of the three basic methods of heat transfer. The temperature gradient that exists between the conduit wall and the bed transmits heat by conduction and convection to the bed particles. The mechanics of heat transfer from the bed to the fluid flowing through the bed takes place by forced-convection and is affected by the mechanics of fluid flow occurring adjacent to the solid surface. Heat transfer can take place only when the temperature of the conduit wall is different from the temperature of the fluid flowing through the conduit. The mechanism of fluid flow past a particle also governs the rate of heat and mass transfer in forced-convection. Various studies have indicated that turbulence-promoters such as bed particles materially increase the rate of heat transfer to the flowing fluid.

When heat transfer takes place, the fluid, which is flowing through a packed bed, is at the temperature of the solid particles which make up the bed. At some distance from the bed, the fluid is at a temperature of the undisturbed stream which is known as the thermal boundary region. During turbulent flow the resistance to heat transfer is composed of the resistance of the laminar sublayer, the buffer layer, and the turbulent core[7].

Since the investigations of Colburn[4] in 1931, numerous studies have been conducted with different types of packing material to evaluate the relationship that exists between heat-transfer coefficients, effective thermal conductivity, and radial profiles within a packed bed. The heat transferred to air flowing through a tube packed with solid spherical particles and having a uniformly heated wall temperature were measured by Colburn. These studies were primarily conducted from an academic standpoint; however, with the increased interest of the process industries in regenerators, which contained catalytic beds, they stimulated the interest of numerous investigators in the mechanism of heat transfer within packed bed systems. The various mechanisms of transfer of heat which contribute to the heat-transfer-coefficient have been investigated and an <u>effective thermal conductivity</u> has been defined. Argo[1] suggests that the effective thermal conductivity consists of various heat transfer mechanisms and proposed the theory that there was molecular conduction in the fluid phase, radiation from one solid particle to another adjacent particle; turbulent mixing in the fluid phase, and by conduction from particle to particle by direct solid contact. Kwong[8] found, in his investigations, that the variations in the effective thermal conductivity were only about 2% between alumina particles and steel balls when used as packing material so that the heat transfer characteristics of a packed bed are not greatly improved by changing the packing material.

Colburn established a relationship as a result of experimental data by which heat-transfer-coefficients could be predicted when the pressure drop through the packed bed is determined. Leva[9] advances the theory that radial heat conduction through the packing material affected the heat-transfer-coefficient, and that the greater portion of the heat transferred to the core of the tube was through convection and turbulence. It was also assumed that due to the point to point contact between spheres in the packed bed, the gas stream conveys heat to the side of the particle that is nearer the center of the tube. The mechanism is characterized by heat flowing through the interface between the packing material surface and the gas fluid stream. It was also established by experimental data that heat exchange between rough surfaces and moving fluids occurs at a faster rate than heat exchange over smooth planes. These results are corroborated by findings of Reynolds and others.

The local convection-heat-transfer-coefficient is related to the temperature gradient at the surface of the solid particle. Knudsen[7] proposed the following equation for flow past immersed particles:

$$h_c = \frac{kg}{t_w - T_\infty} \left(\frac{\partial t_2}{\partial x} \right) x = 0$$

Dimensionless groups such as the Nusselt, Prandtl, Peclet, and Stanton numbers are of particular interest and physical significance. The Nusselt number is a ratio of temperature gradients; the Prandtl number is a ratio of the molecular diffusivity of momentum and molecular diffusivity of heat; the Peclet number is a ratio of heat transferred by convection and the heat transferred by conduction; the Stanton number is a ratio of the wall heat transfer rate and the heat transferred by convection. The viscosity ratio group is also important in which it is a ratio of the viscosity of fluid at bulk temperature and the viscosity of the fluid at wall temperature.

REVIEW OF PRIOR WORK

A search of a number of the numerous studies has been made and an abstract of their significant findings in relationship to heat transfer, packing material, correlating factors, proposed equations to determine heat-transfer-coefficients and the mechanics of heat-transfer-coefficients and the mechanics of heat transfer is presented in the works of the following authors:

The relationship of heat-transfer-coefficients to the packing material in a uniformly heated cylinder wall with a fluid flowing through the bed was first investigated by Colburn[4]. He established, by experimental data, that the heat-transfer-coefficients varied with the 0.83 power of the mass velocities and with a function of the container. Heat-transfer-coefficients could be estimated when air was used as the fluid medium from the following derived equation:

$$h = A' G_o^{0.83} \tag{7}$$

To obtain a general equation that would apply to any gas in turbulent flow, the Reynolds equation was modified and included with equation (7) to give the following general equation:

$$h = 8A' Cp^{0.2} G_o^{0.83} \tag{8}$$

The experimental data obtained indicated that the ratio of the diameter of the particle to the diameter of the tube was the controlling factor in the differences obtained with the various types of packing material studied. The maximum heat-transfer-coefficient occurred at a ratio of 0.15. Heat-transfer-coefficients were predicted for all sizes of tubes and particles which have a ratio of D_p/D_t between 0.04 to 0.32.

The thermal conductivity of packed beds without fluid flow was investigated by Polock, Schumann, and Voss[21] in 1934. The thermal conductivity of a packed bed without fluid flow which was due to radiation was derived by use of the following equation:

$$K_r = 0.692 \epsilon_p \, D_p \left(\frac{T}{100} \right)^3 \tag{9}$$

In the absence of radiation and natural-convection, the thermal conductivity of the bed was correlated by the use of the following ratio of relationships:

$$K_B/k_g \text{ verses } k_s/k_g \tag{10}$$

Further investigations to determine a steady-state heat transfer to gases flowing in turbulent flow through packed tubes was started by Leva[9,10,11] in 1947 and continued for a number of years. Heat-transfer-film-coefficients were determined and a general working equation which could be used to predict heat-transfer-coefficients for similar systems was established. The original packing material used has a low thermal conductivity and the shape was roughly spherical, the surface smooth, and the ratios of Dp/D_t was varied between 0.05 to 0.30.

The following equation was derived for the determination of heat-transfer-coefficients for Dp/D_t from 0.05 to 0.30:

$$h = 0.813\left(\frac{kg}{D_t{}^e}\right)^{-6Dp/D_t}\left(\frac{DpG_o}{\mu}\right)^{0.90} \tag{11}$$

equation (11) has a limitation in which heat-transfer-coefficients can be predicted only when the value of the Prandtl number was allowed to vary between 0.74 to 0.80. This investigation also substantiated Colburn's data in which the maximum heat-transfer-coefficient is attained when the ratio of Dp/D_t is equal to 0.15.

Further investigations were conducted with the use of several smooth, spherical non-uniform packings with differently shaped particles such as smooth cylinders and Raschig rings. The thermal conductivity of these various packings with differently shaped particles and varying surface roughness could be predicted when the average arithmetic diameter of the packing mixture was chosen for the diameter of the material (Dp). Thermal conductivity of the various packing materials was also found to influence the heat transfer through the packed tubes. In order to substantiate equation (11) the following equation was proposed to predict heat-transfer-coefficients:

$$h = 0.813 \int \frac{kg}{D_t} e^{-6\ Dp/D_t} \left(\frac{DpG_o}{\mu} \right)^{0.90} \tag{12}$$

Systems having a ratio of Dp/D_t greater than 0.35 were found to have an effect on heat-transfer-coefficients because of fluid channeling. Fluid channeling between the bed and the tube wall resulted as the diameter ratio of Dp/D_t was increased. When spherical packing arrangement along the inside tube was in a regular geometric pattern, the void space was predicted to be 47.5%. To compensate for the variation created by fluid channeling, the following equation was proposed for values of Dp/D_t that varied from 0.35 to 0.60:

$$h = 0.125\ \frac{kg}{Dp} \left(\frac{DpG_o}{\mu} \right)^{0.75} \tag{13}$$

Radial temperature profiles of packed beds of alumina and steel spheres were investigated by Kwong[8] and Smith. The effective thermal conductivity was calculated with the use of an IBM card-programmed computer from temperature profiles at two bed depths. It was found that the thermal conductivity varied considerably with the change of radial positions within the packed bed and decreased rapidly near the tube wall. When based on theory, calculated values of the effect of particle size, fluid properties, and solid properties were within reasonable limits at high Reynolds numbers but below reasonable limits at low Reynolds numbers. However, to apply the calculations of the theory proposed by Argo, Kwong found it necessary to have information of the mass velocities, Peclet number, void fraction profiles, and convection heat-transfer-coefficients between the bed particles and the fluid.

The radial temperature profiles of a packed tube of alumina cylinders were measured by Bunnell[3] et al. The measurements were made at seven points across the bed diameter and at various bed depths. Measurements indicated that the gas and solid temperatures were identical near the center of the tube. Temperature was found to vary considerably with the mass velocity, which indicated that under the conditions of the investigation the radial heat transfer depended primarily on the characteristics of the gas rather than the packing material. Effective thermal conductivities were found to be about 0.1 to 0.4 B.t.u./(hr)(ft)(^{o}F), and were directly proportional to the mass velocity of the fluid flow.

In an attempt to remove the effect of temperature, the effective thermal conductivity was related to the physical properties of the system. The final form of the proposed relationship for the central portion of the tube is:

$$\frac{Ka}{kg} = 5.0 + 0.061 \left(\frac{DpG_o}{\mu} \right) \tag{14}$$

When the effect of temperature was considered in the calculations of effective thermal conductivity, it was found that it increased in direct proportion to the Reynolds number. Results of the investigations also indicated that there was no appreciable change in the effective thermal conductivity with radial position until the tube wall was approached.

The effective thermal conductivity of lead and steel balls was investigated from the view-point of the theory of heat-transfer mechanics by Singer and Wilhelm[18]. It was proposed that the transfer of heat flows between particles through the points of contact of the bed particles and the adjoining stagnant fluid. The heat flow then continues through the fluid phase by molecular conduction and turbulent eddy conduction. An equation was derived from this theory to calculate the effective conductivity of a system:

$$\frac{Ka}{kg} = \frac{ks}{kg} + \epsilon_p + \frac{E}{\infty} \tag{15}$$

in which kg is a function of the Reynolds number. With particles of low conductivity, the ratio of K_s/kg can be neglected in equation (15). A correlation of K_a/kg as a function of the Reynolds number was not obtainable for lead and steel ball particles.

The effective thermal conductivities for cylindrical and spherical packings having thermal conductivities from 0.1 to 100 B.t.u./(hr)(ft)(°F) were calculated by Felix and Neill[12]. Their investigations resulted in a correlation in which the following equation was proposed to calculate effective thermal conductivities:

$$\frac{K_a}{k_g} = \frac{1}{D_t}\left(\frac{k_s}{k_g}\right)^{0.12}\left(C_1 + C_2\,\frac{D_p G_o}{\epsilon_p \mu}\right) \tag{16}$$

in which the values of C_1 and C_2 were 3.65 and 0.0106 for cylindrical packings, and 3.4 and 0.00584 for spherical packings.

The effective thermal conductivities of packing material were investigated by Hougen and Piret[6] in relationship to the surface area of one piece of packing material in a packed bed. With the use of dimensionless analysis a correlation was obtained for the effective thermal conductivity of a packed bed. The proposed equation is:

$$\frac{K_a}{k_g} = \frac{2.74}{\epsilon_p}\left(\frac{G_o\sqrt{A_p}}{\mu}\right)^{1/3} \tag{17}$$

where the value of $(G_o\sqrt{A_p/\mu})$ varied from 130 to 2800 in the investigations.

Values of effective thermal conductivities were also investigated by Vershoor and Schuit[12]. Various types of packing material were investigated and a correlation was obtained with experimental data which were valid within 16% accuracy.

$$\frac{K_a}{k_g} = 1.72\left(\frac{k_s}{k_g}\right)^{0.26} + 0.1\left(aD_t\right)^{0.5}\left(\frac{G_o}{\mu_a}\right)^{0.69} \tag{18}$$

equation (18) was modified so that it could be used for spherical particles:

$$\frac{K_a}{k_g} = 1.72\left(\frac{k_s}{k_g}\right)^{0.26} + \frac{0.071(D_pG_o/\mu)^{0.69}}{(D_p/D_t)^{0.5}(1-\varepsilon_p)^{0.19}} \tag{19}$$

The heat and mass transfer from a tube wall to the fluids flowing through packed beds were investigated by Yogi and Wakao[23]. In heat transfer, air was used as the fluid and solid particles with low and high thermal conductivities were included in their investigation to determine the effective thermal conductivities and wall heat-transfer-coefficients. The dissolution rate of the coated material on the innerwall of the packed tube was measured and wall mass-transfer coefficients were calculated. A close similarity was found to exist between the jH and jD factors for wall-transfer coefficients in the turbulent flow region.

Steady-state heat transfer experiments were carried out by Baumeister and Bennett[2] in a 4 inch I.D. transite tube which was packed with steel spheres that varied from 5/32 to 3/8 inch diameters. Heat was generated in the pellets by means of a high-frequency induction coil surrounding the packed bed section. Average heat-transfer-coefficients were calculated between the packing bed steel spheres and the stream of air passing through the bed for Reynolds numbers in the region of 200 to 10,400.

Reilly[17] proposed a new method by which the differential equations which describe the unsteady-state heat transfer in a stationary bed of small granular solid particles through which a fluid is flowing could be solved. The method permits an arbitrary initial solid temperature distribution and an arbitrary variation of inlet fluid temperature. The solution derived from the new method appeared easier to apply in practical applications rather than methods previously published and that it afforded an example of the versatility of the Fourier integrals and series.

DESCRIPTION OF APPARATUS

The apparatus used to obtain the experimental data consisted of an air compressor, an air storage tank, a pressure reducing regulator, a rotameter, a heat transfer chamber and other auxiliary equipment. A schematic diagram of the apparatus is illustrated by Figure No. 1.

The air compressor was used to compress the air from atmospheric pressure to 80 psig. The compressed air was then stored in a storage tank so as to eliminate the pressure pulsations of the air compressor. The pressure reducing regulator was then used to reduce the pressure of the compressed air in the storage tank to operating conditions. The needle valve located on the downstream side of the pressure reducing regulator was used to control the rate of flow of the air into the apparatus.

The air was introduced into the bed chamber through the side of a tee so as to create a turbulance and eliminate any temperature gradients that might exist in the air. To eliminate the possibility of fluidization of the bed particles during the flow of air, the direction of flow was from the top to the bottom of the bed chamber. The construction of the bed chamber is illustrated by Figure No. 2.

A 2 inch pipe was utilized to provide a steam chest around the bed chamber. The steam chest pipe wall was then drilled and tapped to install a steam trap, vents, a steam gauge and a thermocouple well. The entire apparatus was then lagged with 2 inches of magnesia pipe insulation and Super 66 insulation cement.

The temperature of the air at the rotameter was measured by a mercurial thermometer, while the air at the top of the packed bed particles, bottom of the packed bed particles, and the inner tube wall surrounded by the steam chest was measured by use of iron-constantan thermocouple wire. One thermocouple well was placed approximately 1/4 inch below the perforated screen, another was placed approximately 1/2 inch above the bed particles while a third was inserted into the steam chest so that it touched the wall of the bed chamber. All the thermocouple wells were held in place by a special designed stuffing box which is illustrated by Figure No. 3. The voltages produced by these thermocouples were measured with a portable millivolt potentiometer with an ice bath as the cold reference junction.

The various potentials produced by the thermocouples immersed in the area above and below the packed bed particles were influenced by local convection and radiation heat transfer. It was therefore necessary to correct the potentials to obtain the true temperature of the air.

In order to ascertain the validity of the thermocouple temperature as that of the entire bed chamber wall, a steam pressure gauge was installed quite a distance from the point of installation of the thermocouple in the steam chest. An investigation was made of the wall temperature of the bed chamber obtained by the thermocouple and the saturated steam pressure. Comparison of the temperatures indicated that the temperature difference obtained by the two methods were negligible. Due to this fact the temperature of the thermocouple was considered valid for the entire wall surface of the bed chamber.

The rotameter was of the conventional laboratory test type. Due to its range a set of two test meters were used to calibrate the rotameter to standard conditions. The calibration curve is illustrated by Figure No. 4.

The porosity of the various packed bed particles was determined by first weighing a number of the glass particles and then relating this weight to the weight of the actual bed particles. The volume they occupied was then compared to the volume of the empty tube. Then the porosity of the packed bed was calculated.

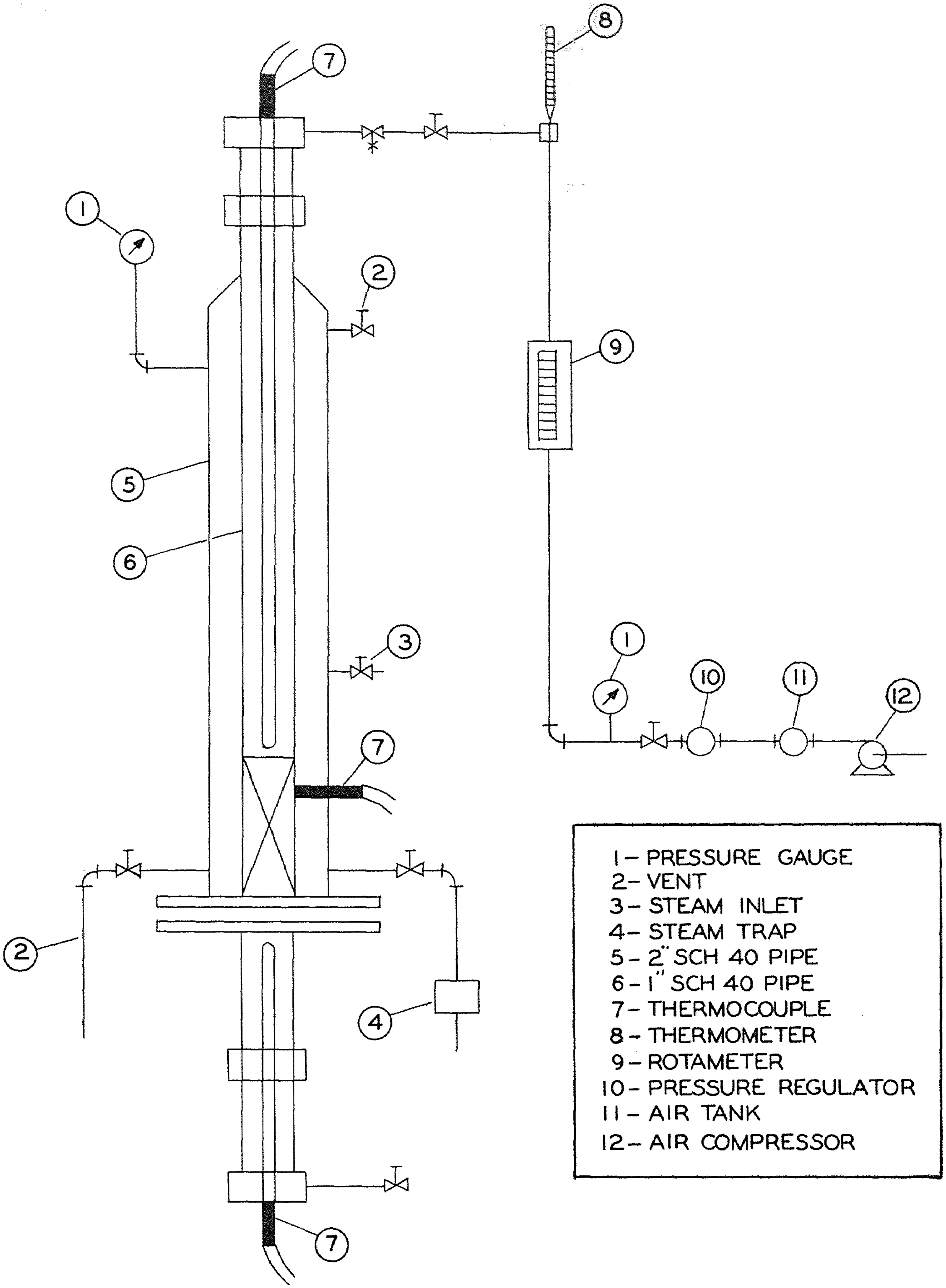

FIGURE N°1: APPARATUS FOR DETERMINATION OF HEAT-TRANSFER COEFFICIENTS

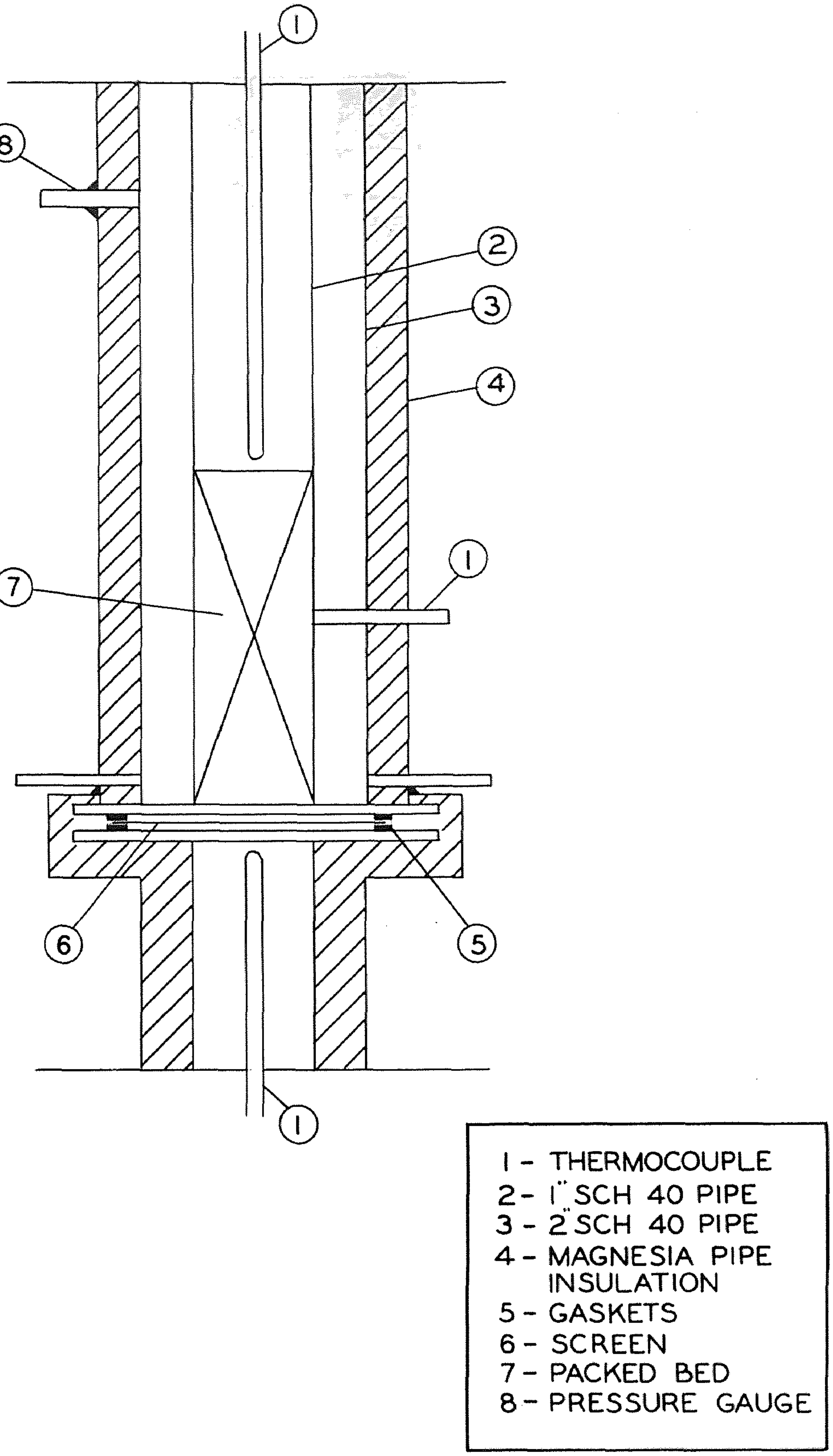

FIGURE N°2: HEAT TRANSFER BED CHAMBER

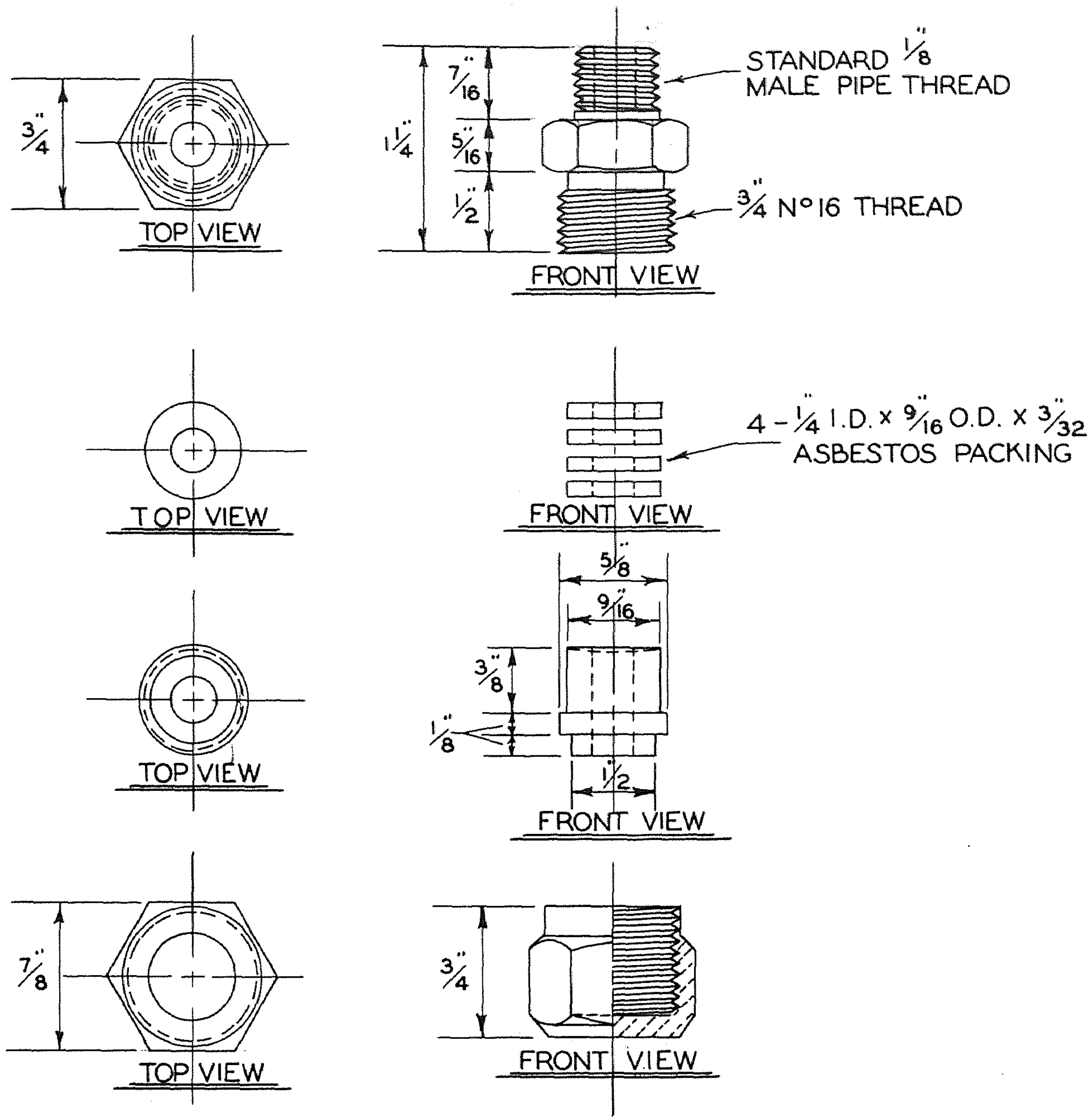

FIGURE N° 3: THERMOCOUPLE WELL STUFFING BOX

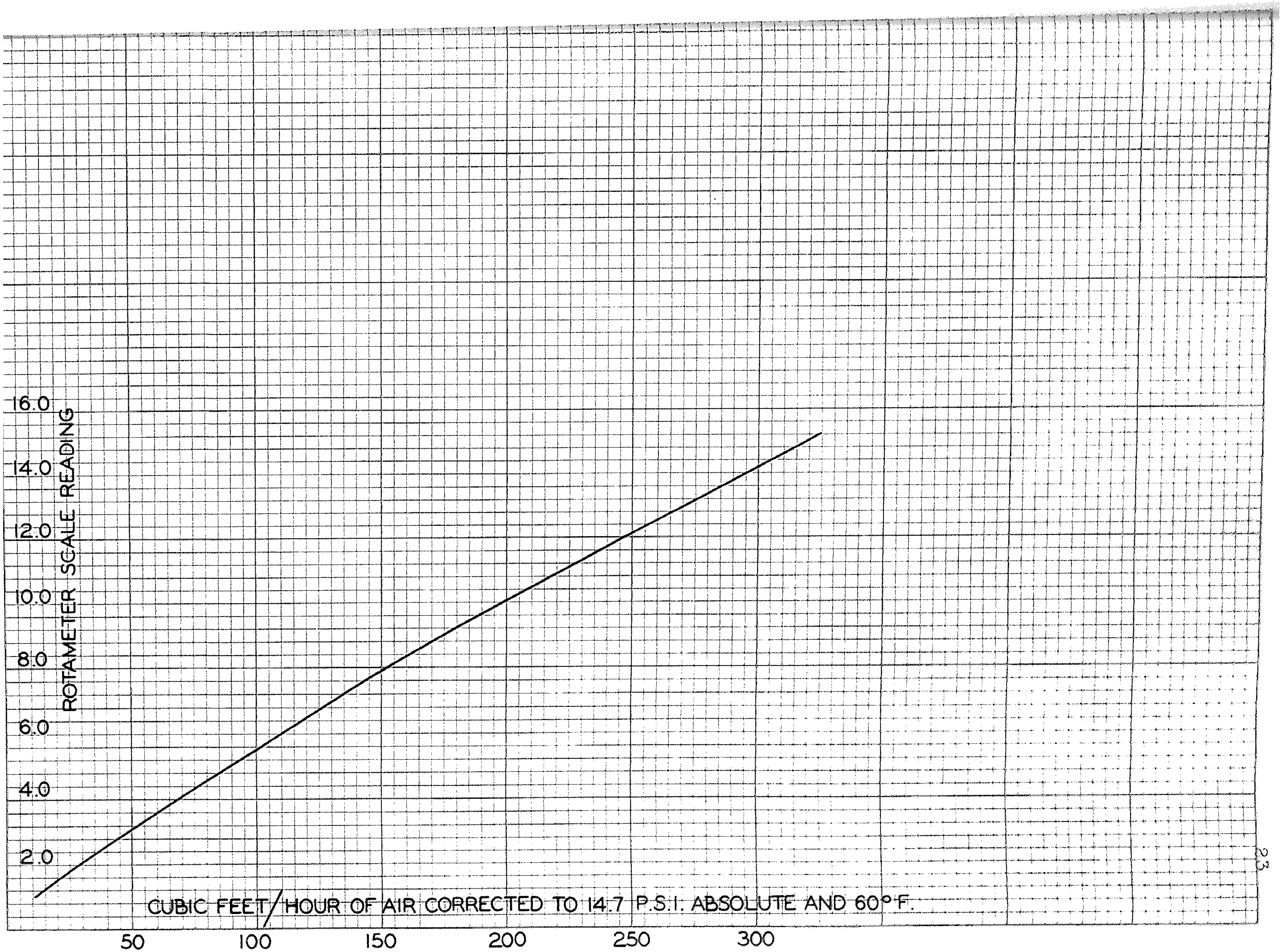

FIGURE N° 4: ROTAMETER CALIBRATION CURVE

TABLE No. 1

ROTAMETER CALIBRATION CURVE DATA

SCALE READING	CUBIC FEET PER HOUR	TEMP. DEG F	BARO + METER PRESS. " Hg	CORR FACTOR[23]	CORR. VOL. CF/HR
1.0	10.68	70.0	30.20	.9806	10.48
1.5	21.40	71.0	30.25	.9795	20.97
2.0	32.95	69.0	30.33	.9876	32.55
3.0	51.15	70.0	30.32	.9846	50.37
5.0	91.37	70.0	30.41	.9875	90.23
7.0	134.25	71.0	30.40	.9845	132.17
9.0	180.88	72.0	30.52	.9858	178.32
11.0	226.28	70.0	30.71	.9920	224.47
13.0	273.16	70.0	30.74	.9985	272.76
15.0	322.66	71.0	30.76	.9964	321.50

TEST PROCEDURE

The following procedure was followed to obtain experimental data for the various packed beds at different superficial velocities:

1. The 1 inch bed chamber was filled with 4mm diameter glass particles to a height of 12 inches. The weight of the glass particles needed for this bed height was determined by taking the weight of the particles before and after the bed height was established. The bed chamber was then closed and the thermocouple above the bed particles was adjusted to 1/2 inch above the 12 inch bed. The apparatus was then pressure tested for leaks by closing the downstream cock of the bed chamber and allowing the pressure within the bed chamber to build up to 5 psig. At this point the upstream cock to the bed chamber was closed. If the pressure remained constant, both cocks were opened.

2. Once the apparatus was pressure tested, air was allowed to flow through the rotameter and into the bed chamber. The rate of flow through the bed chamber was then adjusted to the desired rate by use of the needle valve at the pressure regulator.

3. Steam was then admitted to the steam chest. To eliminate any trapped air or water, the steam chest was vented through the vent located at the top of the steam

chest and the condensate drain valve. After the steam chest was completely vented and drained, the vent was closed and the steam trap was put into service.

4. The air and steam were allowed to enter the apparatus until a steady-state of heat transfer had occurred. A steady-state of heat transfer was indicated by constant voltage readings from the various thermocouples installed in the apparatus.

5. The rotameter was then rechecked for the desired rate of flow through the bed chamber.

6. After the air rate and the voltages produced remained constant, the following experimental data was obtained:

a. Voltages produced at the top of the bed, bottom of the bed, and at the steam chest.

b. Mercurial thermometer reading at the rotameter.

c. Rotameter tube scale reading.

7. The experimental data was obtained at 5 minute intervals for a period of 20 minutes. The average arithmetic value of the data obtained for the 20 minute test period was then used for the final data calculation.

8. The air rate through the bed chamber was then

changed and steps 5 through 7 were repeated for the new rate of flow.

9. Step 8 was then repeated for at least five different rates of flow through the bed chamber.

10. In order to reproduce the experimental data, steps 2 through 9 were repeated with the same bed height.

11. The bed chamber was then disconnected and the bed height was raised to 24 inches. The weight of the glass particles needed for the increase of the bed height was then determined by taking the weight of the particles before and after the bed height was established. The bed chamber was then pressure tested for leaks.

12. A series of tests was then conducted for the 24 inch bed height as outlined in steps 2 through 10.

13. The bed chamber was then disconnected and the bed height was raised to 36 inches. The weight of the glass particles needed for the increase in bed height was then determined by taking the weight of the particles before and after the bed height was established. The bed chamber was then pressure tested for leaks.

14. A series of tests was then conducted, namely steps 2 through 10 for the 36 inch bed height.

15. The bed chamber was then disconnected and the 4mm diameter particles were removed from the chamber.

16. Steps 1 through 15 were then repeated for the 5mm diameter particles.

17. Steps 1 through 15 were then repeated for the 6mm diameter particles.

DISCUSSION OF RESULTS AND CONCLUSIONS

It is difficult to prepare packed beds of various particle diameters with the same tube diameter that would result in the same percentage voids. For this reason, the porosity of the various packed beds investigated was determined and was found to vary from 0.308 to 0.386. As the ratio of the particle diameter to the tube diameter increases, so does fluid channeling through a packed bed system. The increase in fluid channeling results in lower rates of heat transfer at similar rates of mass flow velocities. This fact is shown by the experimental data which indicates that the mean heat-transfer-coefficient increased as the porosity decreased. Since the porosity of a packed bed system was found to exert an influence on the rate of heat transfer, it became necessary to include it in one of the parameters of the proposed new correlation.

The value of the mean heat-transfer-coefficient was found to increase as the mass rate of flow was increased. The experimental data indicates that the value of the mean heat-transfer-coefficient varied from 0.747 to 69.0 as the superficial velocity was increased from 132 to 4130. The increase in heat transfer in turn resulted in apparent thermal conductivity values which varied from 0.0099 to 0.979. Since the apparent thermal conductivity increased with an increase in the mass rate of flow it became evident that it must also be included in any new correlation.

The height of the steam chest was 48 inches, regardless of the height of the particles in the bed chamber. Review of the experimental data obtained with the 12 inch bed height indicated that the results were not reliable. Furthermore the values of the unaccomplished temperature ratio were greater than 0.28 which were not within the limits of this investigation. For these reasons the data obtained with the 12 inch bed heights were not included in deriving the new correlation.

A plot of the average value obtained in the other two runs conducted for the various diameter particles at bed height of 24 inches and 36 inches are illustrated by Figure No. 5. Inspection of the experimental data plotted in Figure No. 5 indicated that a fairly good straight line existed between the two parameters. The equation of this line is:

$$K_a/kg = 0.00105(Dp/G_o/\epsilon_p \mu)^{1.32} \qquad (20)$$

The values of the ratio of the apparent thermal conductivity and the thermal conductivity of the gas were calculated by means of equation (20). Comparison of the results calculated by means of equation (20) and the experimental data resulted in a scattering of ± 15 percent. This indicates that equation (20) can be used to estimate heat transfer values for packed bed systems when the ratio (Dp/D_t) is 0.15 to 0.22 and the modified Reynolds number falls between 526 and 3990.

The Prandtl numbers of carbon monoxide, hydrogen, nitrogen, and oxygen are similar to air when calculated at one atmosphere and 212 degrees Fahrenheit. Due to this fact it is feasible to assume that heat transfer data may be estimated for gases other than air by means of equation (20). However due to the limited scope of this investigation it is only possible to predict heat transfer data for a system of air and glass bead particles.

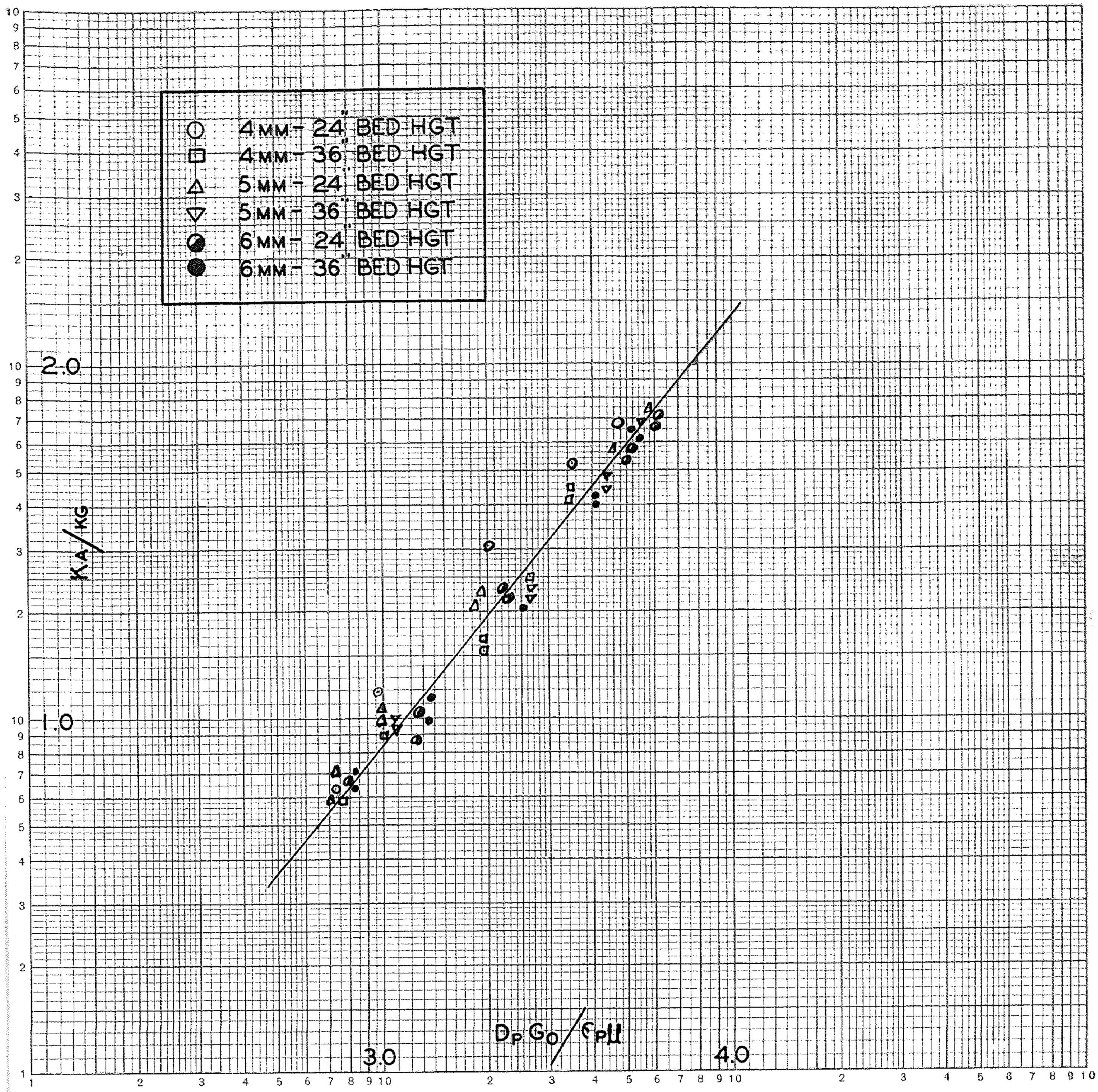

FIGURE N° 5: HEAT TRANSFER THROUGH THE PACKED BED

RECOMMENDATION FOR FUTURE WORK

This investigation indicates that heat transfer data through packed tubes could be predicted for an air and glass bed system by use of equation (20). However this equation does not show the relationship that may exist in different packing material or gas characteristics.

Due to the limits of this investigation future work should give consideration to the effects of various types of packing material such as iron balls, zinc balls, aluminum balls and copper balls. Other gases such as nitrogen, oxygen and carbon dioxide should also be considered as the fluid medium. Another variable to be considered is tube diameter and its effect on heat transfer values. It is suggested that the tube diameters be varied from 1/2 inch to 3 inches.

Future work should also indicate whether equation (20) may be applied to other packed tube systems or must be modified so that it would predict heat transfer data for different packing material or gas characteristics.

TABLE OF NOMENCLATURE

A Area of heat transfer surface, square feet; Ap for surface area of particle; A' for ratio of Dp/D_t.

a Surface area of packing per unit volume of packed bed, square feet per cubic foot.

Cp Specific heat of fluid at constant pressure, Btu/(lb)(deg F).

D Diameter, feet; D_o for the outside diameter of tube; Dp for particle diameter; D_t for inside diameter of tube.

E Eddy diffusivity of heat, sq ft per hr.

e Base of Napierian or natural logarithms, 2.718.

f Friction factor, dimensionless, defined by Eq. (12).

G Mass velocity of fluid, lb/(hr)(sq ft); G_o for superficial mass velocity based on total cross section without particles.

g_c Conversion factor in Newton's law of motion, 32.2 (ft)(pounds matter)/(sec)(sec)(pounds force).

h Coefficient of heat transfer, Btu/(hr)(sq ft)(deg F); h_m for mean coefficient of heat transfer; h_c for local convection heat-transfer-coefficient; h_{ca} for local convection heat transfer correction; h_r for local radiation heat transfer correction.

K Thermal conductivity of a fluid-solid system, Btu/(hr)(sq ft)(deg F per ft); K_a for apparent thermal conductivity; K_B for thermal conductivity of packed bed without fluid flow; K_r for thermal conductivity of packed bed due to conduction through solids and fillets at points of contact.

k True thermal conductivity, Btu/(hr)(sq ft)(deg F per ft); k_g for the gas; k_s for the solid particles.

L Length of exchanger or packed bed, feet.

Q Volumetric flow rate, cubic feet per second.

q Heat transfer rate, Btu/hour.

r Radius, feet; r_B for volume of packing per unit surface of packing.

T Temperature, degrees Fahrenheit absolute; (t+460).

t Temperature, degrees Fahrenheit; t_1 at inlet; t_2 at outlet; t_g of gas; t_p at potentiometer; t_∞ of undisturbed stream; t_w at wall.

V Velocity, feet per second.

w Mass rate of flow of fluid, pounds per hour.

X Dimensionless group defined by Eq. (3).

x Axial position from inlet, feet.

Greek

α Molecular thermal diffusivity of fluid, sq ft per hr.

δt Maximum fluctuation in regenerator outlet.

ϵ Emmissivity of solid surface, dimensionless.

ϵ_p Average fraction void in bed, dimensionless.

μ Viscosity of fluid, lb/(hr)(ft).

ρ Density of fluid, lb per cubic foot; ρ_g for the density of the gas; ρ_s for the true density of the solid particles.

σ Stefan-Boltzman constant, 0.1714×10^{-8}.

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APPENDIX

Conversion Factors.

1 foot	=	304.8mm
1 centipoise	=	2.42 lb/ft-hr

Dimensions of Steel Pipe.

1 inch Sch 40 steel pipe

Inside diameter	0.0875 ft
Cross sectional area	0.006 sq ft
Surface area	0.2745 sq ft/ft

Ref: McCabe and Smith[13], Appendix 4, page 912

Viscosity of Air.

100°F	0.0438 lb/ft-hr
150°F	0.0479 lb/ft-hr
180°F	0.0484 lb/ft-hr
190°F	0.0490 lb/ft-hr
200°F	0.0503 lb/ft-hr
210°F	0.0510 lb/ft-hr
220°F	0.0517 lb/ft-hr
230°F	0.0524 lb/ft-hr

Ref: McCabe and Smith[13], Appendix 7, page 917

Specific Heat of Air.

0°F	0.250 Btu/(lb)(°F)
200°F	0.252 Btu/(lb)(°F)

Ref: McAdams[12], Figure A-3, page 464

Thermal Conductivity.

Air:

32°F	0.0140 Btu/(hr)(sq ft)(°F/ft)
150°F	0.0169 Btu/(hr)(sq ft)(°F/ft)
180°F	0.0173 Btu/(hr)(sq ft)(°F/ft)
190°F	0.0178 Btu/(hr)(sq ft)(°F/ft)
200°F	0.0181 Btu/(hr)(sq ft)(°F/ft)
212°F	0.0184 Btu/(hr)(sq ft)(°F/ft)
220°F	0.0187 Btu/(hr)(sq ft)(°F/ft)
230°F	0.0190 Btu/(hr)(sq ft)(°F/ft)

Ref: McAdams[12], Table A-12, page 457

Packing Material:

Borosilicate type glass = 0.63 Btu/(hr)(sq ft)(°F/ft)

Ref: McAdams[12], Table A-5, page 450

Emissivity of Material.

Stainless steel-type 304(Cr;18Ni) = 0.44-0.36

Ref: McAdams[12], Table A-23, page 475

Bill of Material.

Quantity	Description
1	2"X48" Sch 40 steel pipe
1	1"X48" Sch 40 steel pipe
1	1/2"X48" Sch 40 steel pipe
1	1"X12" Sch 40 steel pipe
2	1"X3" Sch 40 nipples
4	1"X6" Sch 40 nipples
4	1/2"X6" Sch 40 nipples
3	1/2"X1" Sch 40 reducers
2	1/2"X1/2" Sch 40 elbows
4	1"X1"X1" Sch 40 tees
2	1" Sch 40 unions
2	1" Sch 40 screw type flanges
2	1" Bronze stop cocks, 150 psig WOG
1	1/4" Bronze test cock
3	1/2" Bronze gate valves, 125 psig WOG
4	3/8"X4" bolts
4	3/8" nuts
2	1/8" thick durabula gaskets
50 ft	1/2" O.D. copper tubing, type "M"
4	1/4"X1/2" copper tubing adaptors
4	1/2" O.D. copper tubing flare fittings
1	1-1/2" diameter steel screen, .0030" thick, .0420" hole diameter, .0782" holes, center to center
6-1/2 ft	2" pipe size magnesia pipe insulation

Bill of Material (continued)

Quantity	Description
1/2 ft	5" pipe size magnesia pipe insulation
2 lbs	Super 66 insulation cement
1	1/4" steam pressure gauge, 0-30 psig range
1	1/4" steam trap, 0-200 psig range, type AHV, Nicholson Trap Co.
15 ft	1/2" O.D. stainless steel tubing, type #304(18-8), .020" wall thickness
50 ft	No. 20 gauge thermocouples, Iron-constantan, fiber-glass insulated
3	1/2" bronze tubing adapters, swagelok type
1	1/2" pressure regulator, 0-30 psig range, type 67-49, Fisher Govenor Co.
1	Rotameter, 0-325 cubic feet per hour range
1	Millivolt potentiometer, model #8686, Leeds-Northrup Co.
3 lbs	4mm diameter glass beads, Kimax-KG-33
3 lbs	5mm diameter glass beads, Kimax-KG-33
3 lbs	6mm diameter glass beads, Kimax-KG-33
1	Test meter, type #AL, 0-20 cfh range, American Meter Co.
1	Test meter, model #10-500, 0-600 cfh range, Rockwell Manufacturing Co.
1	Stop watch
1	Manometer, 0-12" differential

Bill of Material (continued)

Quantity	Description
1	Barometer
1	Glass beaker, 60 mls
1	Copper beaker, 1,000 mls
1	Balance, Model Selecta, Sartorius Instrument Co.
1	Balance, double beam
2	Mercury thermometers, 0-220 deg F range
2 ft	1/4" I.D. rubber tubing
20 lbs	Crushed ice
1	1/4" needle valve

To substantiate the validity of the use of equation (5), the mean heat-transfer-coefficient was equated to its values in the following manner:

$$\frac{t_w - t_2}{t_w - t_1} = \frac{0.692}{e^{23.14X}} \qquad X = \frac{K_a L}{CpG_o D_t^2}$$

$$h_m = \frac{G_o S Cp (t_2 - t_1)}{A\left[\dfrac{(t_w - t_1) - (t_w - t_2)}{\ln\left(\dfrac{t_w - t_1}{t_w - t_2}\right)}\right]} = \frac{G_o S Cp}{A} \ln\left(\frac{t_w - t_1}{t_w - t_2}\right)$$

$$\frac{S}{A} = \frac{\pi/4\ D_t^2}{\pi D_t L} = \frac{D_t}{4L}$$

$$h_m = \frac{G_o Cp D_t}{4L} \ln\left(\frac{t_w - t_1}{t_w - t_2}\right)$$

$$\ln\left(\frac{t_w - t_1}{t_w - t_2}\right) = \frac{4Lh_m}{G_o Cp D_t}$$

$$\ln\left(\frac{t_w - t_2}{t_w - t_1}\right) = \frac{-4Lh_m}{G_o Cp D_t}$$

$$e^{\frac{-4Lh_m}{G_o Cp D_t}} = \frac{t_w - t_2}{t_w - t_1} = 0.692\, e^{\frac{-23.14 K_a L}{G_o Cp D_t^2}}$$

$$0.692 = e^{\frac{23.14 K_a L}{G_o Cp D_t^2} - \frac{4Lh_m}{G_o Cp D_t}}$$

$$\ln 0.692 = \frac{23.14K_aL}{G_oCpD_t^2} - \frac{4Lh_m}{G_oCpD_t} = -0.3677$$

$$\frac{4Lh_m}{G_oCpD_t} = 0.3677 + \frac{23.14K_aL}{G_oCpD_t^2}$$

$$\underline{4Lh_m} = 0.3677(G_oCpD_t) + \frac{23.14K_aL}{D_t}$$

$$h_m = \frac{0.3677(G_oCpD_t)}{4L} + \frac{23.14K_a}{4\ D_t}$$

$$h_m = \frac{.0912G_oCpD_t}{L} + \frac{5.79K_a}{D_t}$$

In order to obtain an average curve of the experimental data, the logarithm of average points resulted in a group of five points which are listed below:

y	0.640	0.981	1.225	1.464	1.633
x	2.774	3.031	3.220	3.404	3.515

the average point of the first two points is (0.811, 2.903); the average point of the last three points is (1.441, 3.380); the slope was calculated by means of the following relationship:

$$\frac{y_2-y_1}{x_2-x_1} = \frac{(1.441-0.811)}{(3.380-2.903)} = 1.32$$

Since the points lie in an approximate straight line on logarithmic coordinate paper, a curve of the power form is indicated.

$$y-y_1 = m(x-x_1)$$

$$y-0.811 = 1.32\,(x-2.903)$$

$$y = 1.32x-3.021 = cx^b$$

Therefore b = 1.32 and log c = (-3.021), so that c = .00105 the resultant equation is:

$$y = .00105x^{1.32}$$

in which y is equal to K_a/kg and x is equal to $(DpG_o/\epsilon_p\mu)$.

SAMPLE CALCULATIONS

The following calculations are an example of the numerous results found in the experimental data summaries of this thesis. Run No. 1, Test No. 3 of the 4mm diameter glass beads at a bed height of 36 inches was selected as an example.

Standard Cubic Feet Per Hour.

1. Uncorrected volume = 32.55 cfh
2. Air temperature, ^{o}F = 72.0
3. Temperature correction factor:

$$\sqrt{\frac{\text{Abs. temp. } ^{o}F}{520}}$$

$$\sqrt{\frac{460 \quad 72.0}{520}} = 1.012$$

4. Corrected volume to standard conditions:

   (Uncorr. Vol.) (Temp. Corr. Factor) = Corr. Vol. at 60^{o}F (32.55) (1.012) = 32.94 cfh at 60^{o}F

Density.

(29)(492)/359(Abs.temp.^{o}F) = lbs/cf

(14,270)/(191,000) = 0.0747 lbs/cf

Mass Flow.

(Corr.Vol. at std. conditions) (Density) = lbs/hr

(32.94)(.0747) = 2.46 lbs/hr

Superficial Velocity.

$$\frac{\text{Mass flow}}{\text{Cross sectional area of empty tube}} = \text{lbs/hr-sq ft}$$

$(2.46)/(0.006) = 409$ lbs/hr-sq ft

Thermocouple Temperature Radiation Correction.

1. Local convection heat transfer correction.

$$h_{ca} = 0.011 \; Cp \; G_o^{0.6}/ \; D_o^{0.4}$$

$$= (0.011)(.252)(409)^{0.6}/(.02)^{0.4}$$

$$= 4.92$$

2. Local radiation heat transfer correction.

$$h_r = \epsilon\sigma(T_w^{\,4} - T_p^{\,4})/(T_w - T_p)$$

For t_2:

$$h_r = (.44)(.1714 \times 10^{-8})(210 \times 10^8)/(15.5)$$

$$= 1.025$$

For t_1:

$$h_r = (.44)(.1714 \times 10^{-8})(1133 \times 10^8)/(105.0)$$

$$= 0.815$$

3. Temperature difference between thermocouple reading and true temperature.

$$t_p - t_g = (t_w - t_p)(h_r)/(h_{ca})$$

For t_2:

$$t_p - t_g = (235.0-219.5)(1.025)/4.92 = 3.23 \; ^oF$$

$$t_p - t_g = (235.0-130.0)(.815)/4.92 = 17.4 \; ^oF$$

Porosity of Packed Bed.

$$\frac{\text{Volume of voids}}{\text{Total vol. of empty tube}} = \text{Porosity}$$

1. 50 particles of 4mm size = 3.6382 grams

2. 36 inch bed height = 738.6 grams

3. (738.6 / 3.6382) = 203.4

4. (203.4)(50) = 10,185 particles

5. Volume of 4mm sphere:

   $(\text{Diameter of sphere})^3(0.5236)$

   $(0.01312 \text{ ft})^3(0.5236) = 1.194 \times 10^{-6}\text{cf}$

6. 36 inch bed of 4mm particles:

   (Vol. of 1 sphere)(Total number of particles in bed)

   $(1.194 \times 10^{-6}\text{cf})(10{,}185) = .01215$ cf(Vol. of bed)

7. Volume of empty tube:

   $(\text{Diameter of circle})^2(.7854)(\text{feet of bed})$

   $(.0875)^2(.7854)(3.0) = 0.01806$ of(Vol. of tube)

8. Porosity of bed:

   $$\frac{(\text{Area of tube} - \text{Area of particles})}{\text{Area of empty tube}}$$

   $$\frac{(.01806 - .01215)}{0.01806} = 0.328$$

Average Mean Heat-Transfer-Coefficient.

$$h_m = q/A(t_w - t)_m$$

$$= \frac{(w)(Cp)(t_2 - t_1)}{A\left[(t_2 - t_1)/\ln(t_w - t_1)/(t_w - t_2)\right]}$$

$$= \frac{(2.46)(.252)(103.7)}{(.8235)\left[(103.7)/\ln(2.088/1.272)\right]}$$

$$= 2.84$$

Apparent Thermal Conductivity.

$$h_m = 5.79K_a/D_t + 0.0912(CpG_oD_t/L)$$

$$= 5.79K_a/0.0875 + 0.0912\,[(.252)(409)(.0875)/3.0]$$

$$K_a = (2.84-.273)(.0875)/(5.79)$$

$$= .0389$$

Ratio K_a/kg.

$(.0389)/(.0171) = 2.27$

Log $2.27 = 0.356$

Ratio $DpG_o/\epsilon p\mu$.

$(.01312)(409)/(.328)(.0482) = 339$

Log $339 = 2.530$

Unaccomplished Temperature Ratio.

$(t_w-t_2)/(t_w-t_1)$

$(235.0-216.3)/(235.0-112.6) = 0.166$

TABLE No. 2

TEMPERATURE SUMMARY

4 mm GLASS BEADS - 24 INCH BED HEIGHT

RUN NO.	TEST NO.	POTENTIOMETER						DEG F (CORR.)		AIR TEMP. DEG F	$\frac{t_w - t_2}{t_w - t_1}$
		MILLIVOLTS			DEGREES F						
		t_w	t_2	t_1	t_w	t_2	t_1	t_2	t_1		
1	1	6.110	5.662	3.985	240.0	225.0	169.1	222.7	159.2	70.0	0.214
1	2	6.090	5.810	3.170	239.3	230.0	142.0	228.9	133.0	70.3	0.098
1	3	6.075	5.851	2.874	239.0	231.5	131.7	230.9	124.3	71.3	0.070
1	4	6.015	5.850	2.690	236.9	231.3	125.7	231.0	119.6	74.3	0.050
1	5	5.965	5.810	2.605	235.3	230.0	122.9	229.6	117.8	73.3	0.049
2	1	6.115	5.660	3.980	240.1	225.0	169.0	222.8	159.2	77.3	0.214
2	2	6.080	5.795	2.954	239.0	229.5	133.9	228.4	124.4	74.1	0.093
2	3	6.085	5.850	2.775	239.1	231.3	128.5	230.9	120.9	74.1	0.069
2	4	6.070	5.900	2.775	238.7	233.0	128.5	232.6	122.3	73.9	0.052
2	5	6.080	5.930	2.995	239.0	234.0	135.9	233.7	131.0	74.1	0.049

TABLE No. 3

TEMPERATURE SUMMARY

5 mm GLASS BEADS - 24 INCH BED HEIGHT

RUN NO.	TEST NO.	POTENTIOMETER MILLIVOLTS			POTENTIOMETER DEGREES F			DEG F (CORR.)		AIR TEMP. DEG F	$\frac{t_w - t_2}{t_w - t_1}$
		t_w	t_2	t_1	t_w	t_2	t_1	t_2	t_1		
1	1	6.025	5.865	5.355	237.1	231.9	214.9	230.8	211.2	80.5	0.243
1	2	6.190	5.940	4.075	242.7	234.3	172.2	233.4	165.3	83.1	0.120
1	3	6.255	6.000	3.815	243.6	236.3	163.4	235.8	157.3	86.1	0.090
1	4	6.205	6.020	3.625	243.1	237.0	157.2	236.6	152.7	85.7	0.072
1	5	6.190	6.010	2.535	242.7	236.7	120.4	236.4	115.4	84.0	0.050
2	1	6.245	6.045	5.425	244.1	237.8	217.1	237.1	212.9	83.1	0.224
2	2	6.275	5.990	4.285	245.1	236.0	179.1	239.1	172.2	83.3	0.137
2	3	6.300	6.065	3.845	246.0	238.5	164.5	237.7	157.9	80.5	0.094
2	4	6.295	6.095	3.725	245.9	239.5	160.4	239.0	155.8	79.7	0.077
2	5	6.295	6.110	2.605	245.9	240.0	122.8	239.6	117.7	81.1	0.040

TABLE No. 4

TEMPERATURE SUMMARY

6 mm GLASS BEADS - 24 INCH BED HEIGHT

RUN NO.	TEST NO.	POTENTIOMETER						DEG F (CORR.)		AIR TEMP. DEG F	$t_w - t_2$ / $t_w - t_1$
		MILLIVOLTS			DEGREES F						
		t_w	t_2	t_1	t_w	t_2	t_1	t_2	t_1		
1	1	6.160	5.840	4.915	241.7	231.0	200.1	229.5	193.8	74.9	0.255
1	2	6.170	5.940	4.635	242.0	234.3	190.9	233.6	185.6	74.7	0.149
1	3	6.165	5.965	4.335	241.9	235.1	180.9	234.5	176.0	76.0	0.112
1	4	6.175	5.975	3.945	242.1	235.5	167.9	235.1	163.9	75.9	0.089
1	5	6.205	6.035	3.710	243.1	237.5	160.0	237.2	156.1	75.7	0.068
2	1	6.120	5.800	4.900	240.3	229.7	199.7	228.2	193.9	77.0	0.261
2	2	6.135	5.905	4.645	240.9	233.1	191.1	232.3	186.3	77.0	0.157
2	3	6.135	5.935	4.310	240.9	234.1	180.0	233.5	175.1	77.1	0.112
2	4	6.145	5.945	3.905	241.1	234.5	166.5	234.1	162.5	77.1	0.089
2	5	6.115	5.950	3.730	240.1	234.7	160.7	234.5	157.1	77.3	0.067

TABLE No. 5

TEMPERATURE SUMMARY

4 mm GLASS BEADS - 36 INCH BED HEIGHT

RUN NO.	TEST NO.	POTENTIOMETER MILLIVOLTS			POTENTIOMETER DEGREES F			DEG F (CORR.)		AIR TEMP. DEG F	$\frac{t_w - t_2}{t_w - t_1}$
		t_w	t_2	t_1	t_w	t_2	t_1	t_2	t_1		
1	1	6.015	5.320	3.660	237.9	213.7	158.3	205.2	132.1	75.3	0.309
1	2	5.925	5.295	3.520	233.9	212.9	153.7	207.4	134.0	75.3	0.265
1	3	5.960	5.495	2.820	235.0	219.5	130.0	216.3	112.6	72.7	0.166
1	4	5.940	5,585	2.170	234.3	221.3	108.0	219.6	93.8	72.0	0.105
1	5	6.010	5.710	2.120	236.7	226.7	106.0	225.4	95.1	72.0	0.080
1	6	6.010	5.760	2.045	236.7	228.7	103.5	228.0	95.1	72.7	0.062
1	7	6.010	5.780	1.965	236.7	229.0	100.9	228.4	93.1	72.7	0.058
1	8	6.010	5.855	1.800	236.7	231.1	95.0	230.8	88.0	72.5	0.040

TABLE No. 6

TEMPERATURE SUMMARY

4 mm GLASS BEADS - 36 INCH BED HEIGHT

RUN NO.	TEST NO.	POTENTIOMETER						DEG F (CORR.)		AIR TEMP. DEG F	$\frac{t_w - t_2}{t_w - t_1}$
		MILLIVOLTS			DEGREES F						
		t_w	t_2	t_1	t_w	t_2	t_1	t_2	t_1		
2	1	5.960	5.264	3.625	235.0	211.8	157.1	204.0	131.7	75.0	0.300
2	2	5.955	5.316	3.530	234.8	213.6	154.0	208.1	134.2	75.0	0.266
2	3	5.950	5.500	2.815	234.7	219.6	129.9	216.4	112.5	72.5	0.150
2	4	5.940	5.540	2.175	234.3	221.0	108.1	219.3	93.9	72.3	0.107
2	5	5.950	5.660	2.105	234.7	225.0	105.5	223.9	94.9	72.7	0.078
2	6	5.950	5.620	1.990	234.7	223.7	101.7	222.8	93.5	72.5	0.084
2	7	6.010	5.785	1.970	236.7	229.1	101.0	228.5	93.2	72.7	0.057
2	8	5.950	5.790	1.790	234.7	229.3	94.7	229.0	87.9	72.7	0.039

TABLE No. 7

TEMPERATURE SUMMARY

5 mm GLASS BEADS - 36 INCH BED HEIGHT

RUN NO.	TEST NO.	POTENTIOMETER						DEG F (CORR.)		AIR TEMP. DEG F	$\frac{t_w - t_2}{t_w - t_1}$
		MILLIVOLTS			DEGREES F						
		t_w	t_2	t_1	t_w	t_2	t_1	t_2	t_1		
1	1	6.305	5.970	3.000	246.1	235.3	136.0	233.0	121.5	83.1	0.105
1	2	6.275	6.060	2.695	245.1	238.3	125.9	237.0	114.9	85.0	0.062
1	3	6.335	6.195	2.690	247.1	241.5	125.7	241.3	117.2	85.3	0.045
1	4	6.230	6.090	2.410	243.7	239.3	116.0	239.0	109.0	83.3	0.035
1	5	6.190	6.090	2.310	242.7	239.3	112.7	239.1	106.9	83.1	0.027
2	1	6.280	5.950	2.980	245.3	234.7	135.3	232.4	120.4	89.3	0.103
2	2	6.240	6.035	2.755	244.0	237.5	127.9	236.8	117.3	89.3	0.057
2	3	6.210	6.020	2.680	243.3	237.0	125.3	236.6	117.3	89.9	0.053
2	4	6.170	6.045	2.535	242.0	237.9	120.5	237.6	113.9	85.0	0.034
2	5	6.235	6.130	2.430	243.9	240.7	116.7	240.5	111.0	85.7	0.026

TABLE No. 8

TEMPERATURE SUMMARY

6 mm GLASS BEADS - 36 INCH BED HEIGHT

RUN NO.	TEST NO.	POTENTIOMETER MILLIVOLTS			POTENTIOMETER DEGREES F			DEG F (CORR.)		AIR TEMP. DEG F	$\frac{t_w - t_2}{t_w - t_1}$
		t_w	t_2	t_1	t_w	t_2	t_1	t_2	t_1		
1	1	6.180	5.880	2.360	242.3	232.3	114.3	230.8	98.4	75.3	0.080
1	2	6.180	5.960	2.265	242.3	235.0	111.1	234.3	99.7	75.3	0.056
1	3	6.180	6.010	2.060	242.3	236.7	104.0	236.3	95.3	75.1	0.041
1	4	6.200	6.055	1.990	243.0	238.1	101.7	237.7	94.2	75.3	0.035
1	5	6.185	6.055	1.905	242.5	238.1	98.9	237.7	92.4	75.0	0.032
2	1	6.210	5.905	2.315	243.3	233.1	112.9	231.6	97.4	76.0	0.080
2	2	6.240	6.000	2.175	244.0	236.3	108.1	235.6	96.3	76.0	0.057
2	3	6.270	6.090	2.050	245.0	239.3	103.7	238.7	94.1	75.9	0.042
2	4	5.930	5.790	1.965	234.0	229.7	100.9	228.9	94.0	76.9	0.036
2	5	5.970	5.845	1.860	235.3	231.1	97.3	230.9	91.2	78.5	0.031

TABLE No. 9

EXPERIMENTAL DATA SUMMARY

4 mm GLASS BEADS - 24 INCH BED HEIGHT

RUN NO.	TEST NO.	SCFH	ρ_a	w	Go	kg	μ	h_m	K_a	$\frac{K_a}{k_g}$	Log K_a/k_g	$\frac{D_pG_o}{\epsilon_p\mu}$	Log $\frac{D_pG_o}{\epsilon_p\mu}$
1	1	50.62	.0743	3.77	628	.0182	.0492	6.35	.0867	4.76	0.678	545	2.735
1	2	91.58	.0739	6.76	1127	.0173	.0484	14.26	.203	11.72	1.068	992	2.995
1	3	146.50	.0740	10.88	1810	.0173	.0484	25.00	.352	20.35	1.308	1550	3.189
1	4	199.80	.0739	14.76	2460	.0173	.0484	42.00	.598	34.55	1.538	2170	3.335
1	5	272.10	.0745	20.28	3380	.0172	.0483	58.80	.837	48.60	1.687	2970	3.472
2	1	51.88	.0739	3.82	637	.0182	.0492	6.40	.0873	4.80	0.680	545	2.735
2	2	91.13	.0741	6.75	1126	.0172	.0483	14.34	.200	11.57	1.063	988	2.994
2	3	142.80	.0740	10.55	1760	.0173	.0484	25.25	.356	20.52	1.312	1550	3.189
2	4	199.80	.0739	14.76	2460	.0173	.0484	41.20	.585	33.81	1.529	2170	3.335
2	5	272.10	.0741	20.20	3365	.0173	.0484	60.00	.858	49.80	1.697	2960	3.471

Note: Porosity of bed is 0.308

TABLE No. 10

EXPERIMENTAL DATA SUMMARY

5 mm GLASS BEADS - 24 INCH BED HEIGHT

RUN NO.	TEST NO.	SCFH	ρ_a	w	G_o	kg	μ	h_m	K_a	$\frac{K_a}{kg}$	Log K_a/kg	$\frac{DpG_o}{\epsilon_p\mu}$	Log $\frac{DpG_o}{\epsilon_p\mu}$
1	1	51.38	.0735	3.78	630	.0187	.0517	5.47	.0732	3.93	0.593	546	2.737
1	2	92.31	.0732	6.76	1127	.0181	.0503	13.90	.1935	10.65	1.027	1002	3.000
1	3	140.00	.0728	10.20	1700	.0180	.0499	23.20	.326	18.05	1.275	1525	3.182
1	4	264.00	.0728	19.21	3205	.0180	.0499	48.8	.691	38.35	1.583	2890	3.460
1	5	338.10	.0731	24.75	4125	.0173	.0484	69.0	.979	56.5	1.754	3820	3.581
2	1	51.53	.0732	3.77	629	.0189	.0523	7.05	.0972	5.19	0.714	539	2.730
2	2	92.31	.0732	6.76	1127	.0182	.0507	13.30	.1840	10.15	1.006	998	2.998
2	3	138.90	.0735	9.90	1650	.0180	.0499	22.21	.3110	17.26	1.236	1485	3.170
2	4	262.00	.0735	19.28	3215	.0180	.0499	47.50	.6700	37.30	1.571	2895	3.461
2	5	338.00	.0734	24.78	4130	.0173	.0484	69.10	.9810	56.70	1.754	3820	3.581

Note: Porosity of bed is 0.365

TABLE No. 11

EXPERIMENTAL DATA SUMMARY

6 mm GLASS BEADS - 24 INCH BED HEIGHT

RUN NO.	TEST NO.	SCFH	ρ_a	w	G_o	kg	μ	h_m	K_a	$\frac{K_a}{kg}$	Log K_a/kg	$\frac{DpG_o}{\epsilon_p \mu}$	Log $\frac{DpG_o}{\epsilon_p \mu}$
1	1	51.0	.0741	3.78	630	.0184	.0511	6.18	.0841	4.56	0.660	638	2.804
1	2	91.5	.0741	6.78	1130	.0183	.0510	13.59	.1855	10.10	1.005	1141	3.056
1	3	134.5	.0741	9.96	1660	.0182	.0507	22.10	.310	17.00	1.230	1688	3.227
1	4	253.5	.0741	18.75	3130	.0181	.0503	44.50	.625	34.50	1.538	3210	3.506
1	5	316.2	.0741	23.45	3915	.0180	.0499	62.20	.882	49.00	1.690	3990	3.600
2	1	51.1	.0739	3.78	630	.0184	.0511	6.13	.0839	4.55	0.658	638	2.804
2	2	91.7	.0739	6.75	1126	.0183	.0510	9.73	.1270	6.94	0.841	1141	3.056
2	3	134.5	.0739	9.91	1654	.0182	.0507	21.95	.307	16.85	1.226	1638	3.227
2	4	253.5	.0739	18.70	3120	.0181	.0503	43.70	.6150	33.95	1.530	3210	3.506
2	5	316.2	.0739	23.40	3898	.0180	.0499	63.20	.8970	49.80	1.697	3990	3.600

Note: Porosity of bed is 0.381

TABLE No. 12

EXPERIMENTAL DATA SUMMARY

4 mm GLASS BEADS - 36 INCH BED HEIGHT

RUN NO.	TEST NO.	SCFH	ρ_a	w	G_o	kg	μ	h_m	K_a	$\frac{K_a}{kg}$	Log K_a/kg	$\frac{DpG_o}{\epsilon p\mu}$	Log $\frac{DpG_o}{\epsilon p\mu}$
1	1	10.64	.0743	.79	132	.0171	.0482	.75	.0099	.59		110	2.041
1	2	21.28	.0743	1.58	264	.0169	.0479	1.56	.0209	1.24	0.092	220	2.343
1	3	32.94	.0747	2.46	409	.0171	.0482	2.84	.0389	2.27	0.356	339	2.530
1	4	50.97	.0747	3.80	633	.0170	.0480	4.94	.0684	4.02	0.604	526	2.722
1	5	94.40	.0745	7.05	1174	.0171	.0482	10.18	.142	8.30	0.918	977	2.990
1	6	151.60	.0745	11.28	1880	.0171	.0482	18.20	.256	14.98	1.174	1564	3.194
1	7	178.90	.0745	13.32	2212	.0171	.0482	20.00	.311	18.16	1.259	1836	3.264
1	8	214.00	.0745	15.92	2660	.0171	.0482	28.75	.407	23.80	1.376	2210	3.344

Note: Porosity of bed is 0.328

TABLE NO. 1[illegible]

EXPERIMENTAL DATA SUMMARY

4 mm GLASS BEADS - 36 INCH BED HEIGHT

RUN NO.	TEST NO.	SCFH	ρ_a	w	G_o	kg	μ	h_m	K_a	$\frac{K_a}{kg}$	Log K_a/kg	$\frac{DpG_o}{\epsilon_p \mu}$	Log $\frac{DpG_o}{\epsilon_p \mu}$
2	1	10.64	.0743	.79	132	.0171	.0482	.75	.0100	.59		110	2.041
2	2	21.28	.0743	1.58	264	.0169	.0479	1.56	.0209	1.24	0.092	220	2.343
2	3	32.90	.0747	2.46	409	.0171	.0482	2.87	.0392	2.29	0.360	339	2.530
2	4	50.97	.0746	3.80	633	.0170	.0480	4.89	.0676	3.98	0.600	526	2.722
2	5	94.40	.0745	7.05	1174	.0171	.0482	10.28	.1435	8.39	0.923	977	2.990
2	6	151.60	.0745	11.28	1880	.0171	.0482	15.92	.222	12.98	1.112	1564	3.194
2	7	178.90	.0745	13.32	2212	.0171	.0482	22.00	.311	18.16	1.259	1836	3.264
2	8	214.40	.0745	15.92	2660	.0171	.0482	32.00	.458	26.80	1.428	2210	3.344

Note: Porosity of bed is 0.328

TABLE No. 14

EXPERIMENTAL DATA SUMMARY

5 mm GLASS BEADS - 36 INCH BED HEIGHT

RUN NO.	TEST NO.	SCFH	ρ_a	w	G_o	kg	μ	h_m	K_a	$\frac{K_a}{kg}$	Log K_a/kg	$\frac{D_pG_o}{\epsilon_p\mu}$	Log $\frac{D_pG_o}{\epsilon_p\mu}$
1	1	51.48	.0732	3.77	628	.0173	.0484	4.97	.0690	3.98	0.600	670	2.826
1	2	92.49	.0730	6.75	1125	.0173	.0484	11.08	.1565	9.04	0.956	1202	3.080
1	3	144.00	.0730	10.51	1751	.0173	.0484	20.40	.292	16.85	1.226	1874	3.273
1	4	209.60	.0732	15.34	2556	.0173	.0484	33.82	.485	28.05	1.448	2730	3.436
1	5	277.80	.0732	20.34	3390	.0173	.0484	54.90	.795	45.90	1.662	3630	3.560
2	1	51.63	.0725	3.74	623	.0173	.0484	4.99	.0692	4.00	0.602	667	2.824
2	2	92.49	.0725	6.71	1120	.0173	.0484	11.60	.164	9.48	0.976	1200	3.079
2	3	145.00	.0725	10.52	1758	.0173	.0484	18.78	.266	15.40	1.188	1882	3.274
2	4	210.20	.0732	15.49	2582	.0173	.0484	36.02	.519	29.98	1.476	2770	3.442
2	5	278.60	.0735	20.48	3410	.0173	.0484	57.75	.836	48.45	1.684	3630	3.560

Note: Porosity of bed is 0.316

TABLE No. 15

EXPERIMENTAL DATA SUMMARY

6 mm GLASS BEADS - 36 INCH BED HEIGHT

RUN NO.	TEST NO.	SCFH	ρ_a	w	G_o	kg	μ	h_m	K_a	$\frac{K_a}{Kg}$	Log K_a/kg	$\frac{DpG_o}{\epsilon_p \mu}$	Log $\frac{DpG_o}{\epsilon_p \mu}$
1	1	51.1	.0741	3.79	632	.0171	.0482	5.42	.0756	4.42	0.645	668	2.824
1	2	91.6	.0741	6.78	1129	.0171	.0482	12.74	.1813	10.60	1.026	1191	3.076
1	3	138.9	.0741	10.30	1718	.0171	.0482	19.35	.276	16.10	1.207	1814	3.258
1	4	199.2	.0741	14.78	2462	.0171	.0482	31.20	.446	26.18	1.418	2601	3.414
1	5	263.5	.0741	19.50	3255	.0171	.0482	43.75	.631	36.90	1.566	3458	3.535
2	1	51.1	.0741	3.79	632	.0172	.0483	5.42	.0756	4.42	0.645	668	2.824
2	2	91.6	.0741	6.78	1129	.0172	.0483	11.18	.1578	9.23	0.964	1191	3.076
2	3	138.9	.0741	10.30	1718	.0172	.0483	19.48	.2780	16.25	1.211	1814	3.258
2	4	199.2	.0741	14.78	2462	.0172	.0483	31.70	.4550	26.58	1.424	2601	3.414
2	5	263.8	.0738	19.40	3240	.0170	.0480	47.00	.6780	39.60	1.598	3455	3.535

Note: Porosity of bed is 0.386