Int J. Heat Mass Transfer. Vol. 9, pp. 865–870. Pergamon Press 1966. Printed in Great Britain

HEAT TRANSFER IN A MOVING BED THROUGH WHICH AIR IS FLOWING

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(*Received* 6 *January* 1966)

Abstract—Effective thermal conductivities in a radial direction and the apparent film coefficient on the wall surface were measured in moving beds of solid particles descending downwards in a steady state, heated externally by means of condensing steam. Two kinds of solids, i.e. 1-mm glass beads and 0·95-mm grains of sand, were used and air was passed upwards through the moving bed. It was concluded that the experimental data could be correlated by equations analogous to those established for fixed beds.

NOMENCLATURE

a_1, first root of Bessel equation;
C_s, C_f, specific heat of solid and fluid, respectively [kcal/kg degC];
D_p, diameter of solid particle [m];
D_T, inner diameter of the tube [m];
G_s, G_f, mass velocity of solid and fluid, respectively [kg/m^2 h];
h, $= h_w/k_{er}$ in equation (7) [m^{-1}];
h_0, overall heat-transfer coefficient in moving bed [kcal/m^2 h degC];
h_w, wall film heat-transfer coefficient in moving bed [kcal/m^2 h degC];
h_w^0, wall film heat-transfer coefficient in moving bed with stagnant fluid [kcal/m^2 h degC];
K $= \dfrac{k_{er}}{G_sC_s - G_fC_f}$ in equation (5) [m];
k_{er}, radially effective thermal conductivity in moving bed [kcal/m h degC];
k_{er}^0, radially effective thermal conductivity in moving bed with stagnant fluid [kcal/m h degC];
k_{ez}, axially effective thermal conductivity in moving bed [kcal/m h degC];
k_g, thermal conductivity of fluid [kcal/m h degC];
N_{Pr}, Prandtl number $= C_p\,\mu/k_g$;
N_{Re}, Reynolds number $= D_p\,\tilde{u}\rho/\mu$;
Nu, Nusselt number $= h_w\,D_p/k_g$;
r, distance from the centre of moving bed [m];
R, $= D_T/2$, radius of moving bed [m];
t, temperature [°C];
t_c, temperature on centre line of moving bed [°C];
t_0, inlet temperature of the bed [°C];
T_w, wall temperature [°C];
$\tilde{u}$, relative linear velocity $= u_f/\varepsilon + u_s$ [m];
u_f, u_s, superficial velocity of fluid and linear velocity of solid, respectively [m];
z, distance from entrance of moving bed [m].

Greek symbols

α, the ratio of the mass velocity of lateral mixing to the mass velocity based on the sectional area of the bed parallel to the overall direction of flowing fluid;
α_w, the ratio of the mass velocity of fluid flowing in the direction of heat transfer to the mass velocity of fluid in the direction of flowing fluid, near the wall surface;

β, the ratio of the average distance between centres of two particles touching each other;
ε, void fraction in the core portion of moving bed;
θ, contact time [h];
ρ, density of fluid [kg/m^3];
μ, viscosity of fluid [kg/m h].

INTRODUCTION

IN CONNECTION with the design calculations for chemical reactors of the moving bed type, it is necessary to know the heat-transfer characteristics of the moving bed.

Benenati *et al.* [1], and Kimura *et al.* [2] measured the void fraction of particles packed in a vertical tube. By means of high-speed photography, Brown and Richard [3] ascertained the stick slip flow of particles in moving beds. Furthermore, Brinn *et al.* [4] and Toyama [5] investigated the flow pattern of particles in moving beds. Yagi *et al.* [6] reported that back mixing in moving beds originated in the streamlining of the flow-pattern of particles in close vicinity to the wall surface of the tube.

Concerning the heat-transfer mechanism in a moving bed, Brinn *et al.* [4] measured the effective thermal conductivity in moving beds based on the following assumptions:

(i) No temperature difference between solids and gas;
(ii) Rod-like flow of solids.

In the case when the diameters of the particles are small enough, it is possible to assume there is no temperature difference between particles and gas, so that the system may be treated as a homogeneous phase. Ernst [7] investigated the wall film coefficient of heat transfer h_w for short contact time θ to the hot wall, reporting the relation between h_w and θ.

Considering the temperature difference between solids and fluid, Lovel and Karnofsky [8] measured the temperature distribution in a moving bed, analysing their data graphically. Munro and Amundson [9] gave a theoretical procedure for estimating the heat-transfer characteristics of a moving bed.

Using the same assumptions as those applied by Brinn, radially effective thermal conductivities and the apparent film coefficient of heat transfer on the wall surface have been determined in this paper from experimental data on temperature distributions in moving beds of solid particles.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Measurements were carried out for two kinds of solids, namely 1-mm glass beads and grains of sand with mean size of 0·95 mm; air was passed through moving beds of these solids. Figure 1 shows the test section of 68-mm I.D. and 600 mm long, and the arrangement of the solids circulation system in the steady state.

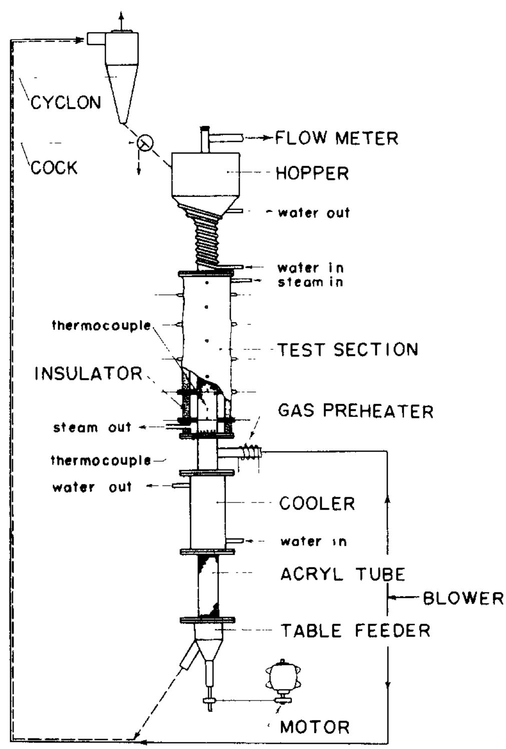

FIG. 1. Experimental equipment.

For the measurement of temperature distributions in the moving bed, two kinds of Chromel–Alumel thermocouples, namely 1-mm junctions for measuring the axial distribution and 0·3-mm junctions for the radial distribution, were located in the test section.

Special care was taken in positioning the junctions in the test section to prevent appreciable disturbance to the flow pattern of the descending solids. Both the axial and radial locations of the thermocouple junctions were measured precisely before the operation. Methods of locating the thermocouple junctions in the moving bed are illustrated schematically in Figs. 2 and 3 for the measurement of both radial and longitudinal distributions of temperature.

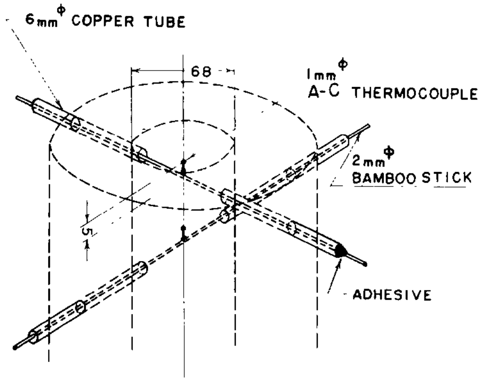

FIG. 2. Schematic view of thermocouple junctions for axial temperature distribution.

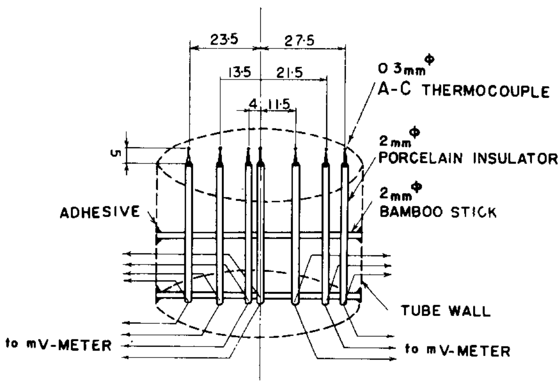

FIG. 3. Schematic view of thermocouple junctions for radial temperature distribution.

The downward velocity of the descending solids was controlled by the rotating table feeder connected to the bottom of the vertical tube. Discharged solids were transported by the air through the lift line up to the hopper and entered the top of the experimental heater.

The air was sent to the bottom of the test section and passed through the moving bed of solid particles. In order to satisfy the condition of semi-infinite tube in length, the temperature of the inlet air was controlled to keep the same value as the mean temperature of the moving bed around the sectional area just above the level for air inlet, by controlling the electric input of preheater shown in Fig. 1. The rate of the air emerging from the moving bed was measured by a flow meter in the steady state. The mass velocity of the descending solids was determined by taking out the solids during a short time interval, applying a three-way cock intermittently. Special care was taken in the above technique to prevent the air flowing through the lift line from leaking into the flow meter. For a run of given conditions in the steady state, both the rates of the air and the solids were measured several times, from which their mean values were calculated.

Since condensing steam was employed as the heating medium, the wall temperature of the heater was kept exactly constant. It required more than 2 h to attain the steady state for every experimental condition, and the measurements were carried out after confirming the condition of the steady state by preliminary observation of temperature at intervals.

RESULTS

Under the following assumptions, equation (1) can be given:

(i) Rod-like flow of solid particles.
(ii) No temperature difference between solid and fluid, in other words the bed being treated as homogeneous.
(iii) Constant physical properties throughout the bed.

$$(G_sC_s - G_fC_f)\frac{\partial t}{\partial z} = k_{er}\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r}\right) + k_{ez}\frac{\partial^2 t}{\partial z^2} \quad (1)$$

Generally the term of $k_{ez}(\partial^2 t/\partial z^2)$ is neglected, because thermal conduction is negligibly small compared with the heat transferred by the fluid. Equation (1) can be solved with the following boundary conditions:

$$\left.\begin{aligned}&\text{(i) at } z = 0\text{: } t = t_0\\ &\text{(ii) at } r = 0\text{: } (\partial t/\partial r)_{r=0} = 0\\ &\text{(iii) at } r = R\text{: } -k_{er}(\partial t/\partial r)_{r=R} = h_w(t - T_w)\end{aligned}\right\} \quad (2)$$

The solutions are

$$\frac{T_w - t_c}{T_w - t_0} = \frac{2}{R}\cdot\frac{h}{h^2 + a^2}\frac{1}{J_0(a_1 R)}\exp\left[-Ka_1^2 z\right] \quad (3)$$

$$\frac{T_w - t_r}{T_w - t_c} = J_0(a_1 r) \quad (4)$$

where

$$K = \frac{k_{er}}{G_sC_s - G_fC_f} \quad (5)$$

$$h = \frac{a_1 J_1(a_1 R)}{J_0(a_1 R)} \quad (6)$$

or

$$h = \frac{h_w}{k_{er}} \quad (7)$$

When the radial temperature ratios $(T_w - t_r)/(T_w - t_c)$ are measured, the numerical value of $a_1 r$ for the each distance from the bed centre, r, can be derived by means of the equation (4). Then the value of a_1 can be obtained from the straight line, from which the value of Ka_1^2 is temperature ratios $(T_w - t_c)/(T_w - t_0)$ plotted logarithmly against the bed length z give a straight line, from which the value of $K . a_1^2$ is derived utilizing the equation (3). As the value of a_1 is already known, the radially effective thermal conductivity k_{er} can be decided by the equation (5).

Utilizing a table of Bessel functions for the known values of a_1 and R, the value of h is obtained by means of the equation (6). Therefore the value of heat-transfer coefficient in the vicinity of the bed wall h_w is determined.

On the other hand the numerical value of overall heat-transfer coefficient h_0 can be calculated from the equation (8), according to reference [10].

$$\frac{h_0 D_p}{k_g} = \left(\frac{k_{er}}{k_g}\right)\left(\frac{D_p}{D_T}\right)\left\{(a_1 R)^2 - \frac{1}{K}\cdot\frac{R^2}{L}\ln\phi(h)\right\} \quad (8)$$

where

$$\phi(h) = \frac{4h^2}{(a_1 R)^2 (a_1^2 + h^2)}.$$

The experimental results are represented by the following dimensionless groups

$$k_{er}/k_g, \qquad Nu = h_w D_p/k_g,$$

$$N_{Re} = D_p \tilde{u} \rho/\mu, \qquad N_{pr} = C_p \mu/k_g.$$

Figure 4 shows the relation between k_{er}/k_g and $N_{Pr} N_{Re}$ for both glass beads and sand, and Fig. 5 represents the plot of $Nu = h_w D_p/k_g$ against $N_{Pr} N_{Re}$. Theoretical values of k_{er}^0/k_g and $h_w^0 D_p/k_g$ (dimensionless stagnant thermal conductivity and heat-transfer coefficient, respectively) are plotted in each figure with a circle of which half is black, and which are calculated by means of the theoretical equations which have been proposed for the packed bed by Kunii and Smith [11]. It is apparent that the dimensionless groups, k_{er}/k_g and $h_w D_p/k_g$ vary linearly with the values of $N_{Pr} N_{Re}$ as illustrated in Figs. 4 and 5, and similar conclusions have been reported for the packed bed by a number of investigators.

Therefore, empirical formulae similar to that already proposed for the packed bed can be applied here to correlate the experimental results for moving beds as follows. The effective thermal conductivity of a moving bed,

$$k_{er}/k_g = k_{er}^0/k_g + (\alpha\beta)\,\varepsilon\, N_{Pr} N_{Re} \quad (9)$$

here α means the ratio of the mass velocity of lateral mixing to the mass velocity based on the sectional area of the bed parallel to the overall direction of flowing fluid, β being the ratio of the average distance between centres of two particles touching each other. Analysing the present experimental data by application of equation (8), glass beads, 1 mm

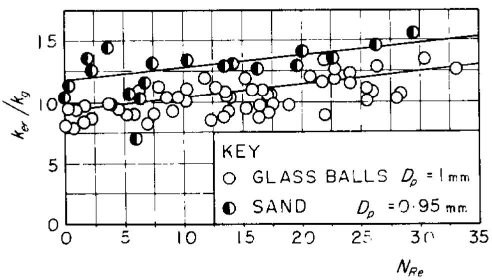

FIG. 4. k_{er}/k_g vs. N_{Re}.

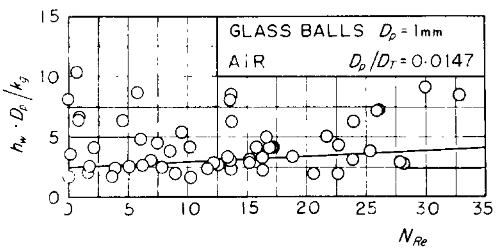

FIG. 5. $h_w D_p/k_g$ vs. N_{Re}.

$$k_{er}/k_g = 9{\cdot}7 \qquad (\alpha\beta) = 0{\cdot}39, \qquad \varepsilon = 0{\cdot}36$$

sand, 0·95 mm

$$k_{er}/k_g = 12{\cdot}0 \qquad (\alpha\beta) = 0{\cdot}36, \qquad \varepsilon = 0{\cdot}45$$

with respect to glass beads and sand, respectively.

For the heat-transfer coefficient

$$h_w D_p/k_g = h_w^0 D_p/k_g + (\alpha_w)\, \varepsilon\, N_{Pr}\, N_{Re} \quad (10)$$

where α_w is the ratio of the mass velocity of the fluid flowing in the direction of heat or mass transfer to mass the velocity of the fluid in the direction of the fluid flow, near the wall surface. For glass spheres of 1 mm, ($\varepsilon = 0{\cdot}36$)

$$h_w^0 D_p/k_g = 2{\cdot}55$$

and

$$\alpha_w = 0{\cdot}155$$

These numerical values of observed data do not agree very well with those previously reported for packed beds. It can be understood that the stick–slip flow of solid particles may result in some disturbance especially in the vicinity of the tube wall surface, from which the above difference between moving bed and fixed bed could be explained. However, it may be concluded that the heat-transfer mechanism in moving beds can be analysed in an analogous way to the packed beds.

Utilizing the theoretical solution originally given by Hatta and Maeda[12], Yagi and Kunii [10] presented a reasonable procedure for estimating the overall heat-transfer coefficient h_o in packed beds. Applying the above procedure to this present system of moving beds with flowing air, measured values of overall heat-transfer coefficients were compared with these theoretical values as shown in Fig. 6.

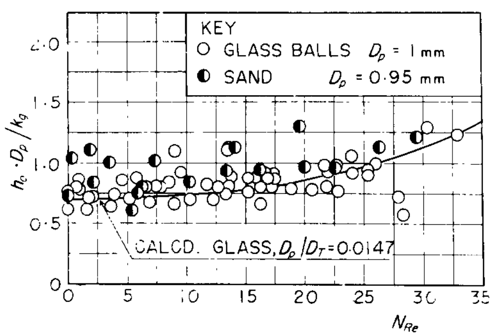

FIG. 6. Comparison of calculated values of $h_o D_p/k_g$ with experimental data.

The agreement between the computed Nusselt numbers and the observed ones in a moving bed may be considered satisfactory. These results also may support the above conclusion, namely that the similar analysis to packed beds can be applied in the case of the moving bed heat exchanger.

CONCLUSION

(1) The empirical equations [see equations (10) to (12)] have been obtained for the effective radial thermal conductivity and the wall film heat-transfer coefficient, being related to the analogous forms proposed previously for packed beds.

$$k_{er}/k_g = 9{\cdot}7 + (0{\cdot}39)\,\varepsilon\, N_{Pr}\, N_{Re} \qquad (11)$$

for glass spheres, 1 mm ($\varepsilon = 0{\cdot}36$)

$$k_{er}/k_g = 12{\cdot}0 + (0{\cdot}36)\,\varepsilon\, N_{Pr}\, N_{Re} \qquad (12)$$

for sand, 0·95 mm ($\varepsilon = 0{\cdot}45$)

$$h_w\, D_p/k_g = 2{\cdot}55 + (0{\cdot}155)\,\varepsilon\, N_{Pr}\, N_{Re} \qquad (13)$$

for glass spheres, 1 mm ($\varepsilon = 0{\cdot}36$)

(2) It may be ascertained that the heat-transfer mechanism in moving beds can be analysed by means of such terms as k_e, h_w and h_o, analogous to the heat-transfer mechanism in packed beds.

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Résumé—Les conductivités thermiques apparentes dans une direction radiale et le coefficient apparent de film à la paroi ont été mesurés dans des lits en mouvement de particules solides descendant verticalement en régime permanent et chauffés extérieurement grâce à la condensation de vapeur d'eau. Deux sortes de matières solides, c'est-à-dire des billes de verre de 1 mm et des grains de sable de 0,95 mm ont été employés avec un écoulement d'air traversant vers le haut le lit en mouvement. On en conclut que les données expérimentales pourraient être corrélées à l'aide d'équations analogues à celles établies pour les lits fixes.

Zusammenfassung—Die wirksame Wärmeleitfähigkeit in Radialrichtung und der scheinbare Filmkoeffizient an der Wandoberfläche wurden in Fliessbetten gemessen, deren feste Teilchen stationär abwärts strömen und die mit kondensierendem Dampf von aussen beheizt werden. Zwei Arten fester Teilchen wurden verwendet, nämlich 1 mm Glasperlen und 0,95 mm Sandkörner; Luft wurde von unten durch das Fliessbett geblasen. Es wurde gefolgert, dass die Versuchsergebnisse nach Gleichungen korreliert werden können, die denen für Festbetten analog sind.

Аннотация—Измерялись эффективные коэффициенты теплопроводности в радиальном направлении и кажущийся пленочный коэффициент на поверхности стенки в движущихся вниз навстречу потоку воздуха слоях твердых частиц в установившемся состоянии, причем слои нагревались снаружи конденсирующимся паром. Использовались два типа частиц, а именно, стеклянные шарики диаметром 1 мм и песок диаметром 0,95 мм. Найдено, что экспериментальные данные можно описать уравнениями, аналогичными применяемым для неподвижных слоев.