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On: FLUID-SOLID HEAT TRANSFER STUDY

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FLUID-SOLID HEAT TRANSFER

I. INTRODUCTION

The first report, submitted in December 1960, included a summary of the literature of fluidization, a critical re-evaluation thereof to enable an understanding of the nature and cause of contradicting values of the heat transfer coefficients, a discussion of specific points, a discussion of simplifying assumptions and ideal models which others have proposed, and general discussions on design of experiments and selection of equipment. Our second report submitted in December 1961, covered the building of equipment, development of theory, and some preliminary test runs to check proper functioning of the equipment and applicability of the theory to the data obtained. Calibrations of various measuring devices and measurements of physical properties of the solids used were made. The report of January, 1963, covered modifications of the previously designed equipment, a series of packed bed heat transfer experiments with the necessary development of a method of data analysis, a modification of the linear flow model equations for the description of a fluidized system, and the early test for the use of phosphors to permit the measurement of solid temperatures.

This final report is a continuation of the earlier efforts, and covers the final phases of the program including some of the conclusions; however, some work is still in progress and we will submit a supplement to this report at a later date.

II. EXPERIMENTAL

A. PACKED BED HEAT TRANSFER EXPERIMENTS

The object of these experiments was to obtain heat transfer information about the particles under packed bed conditions, since this is a limiting case of the fluidized bed system. Although the operational variables should be kept close to those of the fluidized bed experiments, this was impossible because of the wide difference in the gas flow rates required to produce the required conditions and because of other limitations of equipment. Therefore, an attempt was made to obtain a general understanding of the heat transfer to these particles and to evaluate the information that could be obtained from these experiments. We found additional need for work of this nature because virtually no heat transfer results exist for packed systems at the very low Reynolds number range concerned here. Some information is available on mass transfer and solid conduction in packed systems, but there is wide disagreement among the workers, thus requiring further investigation of this area.

The particles studied include G-1, G-6, G-8, P-1, and P-2. No useful data on G-2 could be obtained because of the extremely low gas flow rate necessary to maintain a packed system and the sharp decay of the amplitudes which are caused by the combination of the small particle diameter and low gas flow rate. The results, on plastic particles (P-1 and P-2) showed bad distortion of the sine wave, which was found to be caused by the difference in the time required for cooling and heating within a cycle. The causes of this distortion included variations of heat capacity with temperature, low thermal conductivity, and the relatively large size of the plastic particles. However, the nature of this distortion was such that analysis of the data was possible by treating heating and cooling separately, as if they were two

different systems with different heat capacities.

In analyzing the results, the approximate graphical method of data evaluation reported in the previous report worked quite satisfactorily for the particle G-1, but this method did not work for the other particles because of higher values of K and $\bar{\Phi}$, which caused the high order terms of the equations to be no longer negligible. The two plots, $\bar{\Phi}/\omega$ vs. $2K\bar{\Phi}/\omega$ and $(\bar{\Phi}^2 - K)/\omega\bar{\Phi}$ vs. $K/\omega\bar{\Phi}$ tend to deviate appreciably from straight lines as the particle size and gas flow rates are decreased. As an alternate approach to the data evaluation and at the same time to obtain general information with regard to the frequency responses of packed bed systems, a parametric study by the use of the IBM 7094 was undertaken.

B. FREQUENCY RESPONSE PARAMETRIC STUDY

The results of this study can provide a means for the complete data evaluation and further information with regard to the effect of each mechanism of transfer on the frequency response of the system. Also, such a study will aid in the design of frequency response experiments of similar and simpler systems, such as mass transfer or conduction through packing, where general magnitudes of parameters are known.

For this parametric study the two equations for data evaluation were rewritten in a more general form of dimensionless groups and variables.

$$Z_1 = \frac{4P_{eH}P_{em}XY^4(1-X^2) + P_{eH}Y^3(1-3X^2) + (P_{em} + mP_{eH})H^2XY^2 + HY}{(P_{em} + P_{eH})Y^2(1-X^2) + [(1+m)H - 1]XY}$$

$$Z^2 = (P_{eH} + P_{em})XY^2 + (Y/2) + \left[\left\{ (P_{em} + P_{eH})XY^2 + Y/2 \right\}^2 + P_{em}P_{eH} Y^4 \right]$$

$$(1 + X^4 - 6X^2) + P_{eH}Y^3(X^2-3) X + (P_{em} + m P_{eH})Y^2(1-X^2) - XYH]^{0.5}$$

where

$$P_{em} = \gamma / D_p \bar{U}$$

$$H = 6Nu/m_o \text{ Re Pr}$$

$$P_{eH} = \delta / D_p \bar{U} = k_e / C_s \rho_s (1-\epsilon) D_p \bar{U}$$

$$Y = \bar{\Phi} D_p$$

$$m = (1-\epsilon) m_o / \epsilon = (1-\epsilon) C_s \rho_s / \epsilon C_g \rho_g$$

$$X = K / \bar{\Phi}$$

The values of P_{eH} , P_{em} , and H represent the coefficients of the transfer:

Thermal conduction through the solid particles, gas back mixing, and interfacial heat transfer respectively. The parametric study has been completed and the results will be included in the supplement to this report.

C. FLUIDIZED BED EXPERIMENTS

The previous report included preliminary results and a discussion of the solid temperature measurement. Based on these results, the necessary theoretical analysis was made. However, we were forced to admit failure in our original method of measurement of the solid temperature. The limitations on experimental conditions were not anticipated originally and forced a further modification of theory and equipment.

The originally proposed solid temperature measurement technique (the use of phosphor embedded plastic particles, optic fiber and photomultiplier) did not materialize because the fluctuation of the local density of the bed was so gross that this fluctuation completely overshadowed the desired signal of temperature variation. Various means of filtering and integrating were tried without improvement. Thus, this method had to be abandoned. However,

we still feel that the basic idea is valid and plan further use of this technique in situations where the density fluctuation is negligible. There is also the possibility that the method can be adapted to the study of local density fluctuation in fluidized bed systems. Its high frequency response and sensitivity to the density change are of particular interest.

As an alternate solid temperature measuring device, a solder ball probe was made. This is essentially a 40 gage copper-constantan thermocouple imbedded in solder balls whose diameters ranged from $1/4$ to 1 mm. To test the probe, they were used to extend the Nu-Re correlation of spherical particles in air by Sidner.*

D. DESCRIPTION OF FLUIDIZED BED HEAT TRANSFER

The results of gas temperature measurements in the fluidized bed showed that it could be divided into two characteristic zones; a decaying zone (the first $1/4$ inch of the bed) and a constant gas temperature zone (the rest of the bed). In the lower portion of the decaying zone, the waves are very sinusoidal but tend to be more distorted as the distance from the support is increased. The distortion and the scatter is most pronounced at the area near the interface of the two zones. In the decaying zone, the recorded amplitude of the gas temperature was strongly affected by the probe suction rate; the higher suctions giving higher amplitudes.

In the constant gas temperature zone, the recorded sine waves had a slight superimposed random scatter but they were very stable and reproducible. Changes in suction rate did not affect the wave in this zone. Identical waves, were recorded everywhere in this zone and were equal to the exit gas temperature wave. This was taken as an indication uniform gas and solid temperatures in

*Sidner, W., M.S. Thesis, Chemical Engineering, The Ohio State University, Columbus, Ohio (1963).

this zone. If the mixing rate of gas is extremely high, a minute but uniform driving force (temperature difference between gas and the solid) could exist. In order to substantiate the results of the suction probe, use was made of mass transfer experiments, of the bare thermocouples, of the solder thermocouple probe and of a copper screen thermocouple. The results of the mass transfer experiments indicated that waves were very sinusoidal near the bottom of the bed but became very irregular and irreproducible as the distance from the supporter increases. The height at which a noticeable deformation started corresponded to that in the gas temperature. A bare 40 gage thermocouple inserted into the bed gave similar results to those of the suction thermocouples, i.e., a rapid decay of amplitude near the screen and the equal temperature in the rest of the bed. Two solder ball thermocouples which have widely varied time constants were inserted in the upper section of the bed. Both couples indicated identical temperature, thus indicating extremely high rate of interfacial transfer. These thermocouples did show a slightly different temperature in the decaying zone. The recorded temperature of the supporting copper screen was little different from that of the reference thermocouples. This and the results of solder ball experiments tend to confirm the findings of Bakker and Heertjes;* i.e., the presence of high porosity near the screen. The particles near the screen may be less mobile and less dense due to the jetting air from the openings of the screen and the limitation posed by the screen. From these various observations, we feel that the fluidized bed can be divided into two zones: transfer and near equilibrium (a small but finite Δt may exist in this zone).

*Bakker, P.I., and P.M. Heertjes, Chem. Eng. Sci., 12, 260 (1960); Brit. Chem. Eng. 4 524 (1959).

III. THEORETICAL ANALYSIS OF FLUIDIZED BED SYSTEM

A. LOCAL APPROACH ON MODIFIED LINEAR MODEL

The differential equations which have been used to describe the packed bed can be modified to describe the local conditions of the fluidized system by adding terms for solid circulation which are similar to the convective terms of the gas phase. The resulting equation can be written as

$$\frac{\partial T_g}{\partial t} + m\alpha(T_g - T_s) = -\bar{U} \frac{\partial^2 T_g}{\partial z^2}$$

and

$$\frac{\partial T_s}{\partial t} = m\alpha(T_g - T_s) - \bar{U}_s \frac{\partial T_s}{\partial t} + \frac{\partial^2 T_s}{\partial z^2}$$

and by similar methods used in the packed system, the elimination of T_s and expressions in terms of K , Φ , and coefficients can be obtained. However, the complexity of the evaluation equations and difficulties of obtaining the necessary slopes make this approach impractical.

B. VARIOUS POSSIBLE SIMPLIFICATION OF THE TWO EQUATIONS

Among the resulting simple models, the simplest form $(T_i - T_o) G C_g = MC_s \frac{\partial T_s}{\partial t} = eh A (T_o - T_s)$ did describe the results of frequency responses best. Other models either contradicted the results of frequency response data completely in the whole range of ω or in some partial range. The solution of the above equation can be expressed as:

$$R = \frac{\theta_2}{\theta_1} \omega = \frac{T_i - T_o}{T_o} \quad \left(\frac{T_i - T_o}{T_o} \right) = \text{Arctan} \frac{1}{\omega \theta_2}$$

where

$$\theta_1 = \frac{G C_g}{ehA} \text{ and } \theta_2 = \frac{MC_s}{ehA}$$

For the accurate evaluation of the angle between the vectors $(T_1 - T_0)$ and T_0 , a new technique was devised. This method can provide accuracy of the angle within a few minutes of arc. The analysis of the complete results are in progress and they will be included in the supplement.

C. MODEL STUDIES

By the use of proper approximate assumptions, various models for the fluidized bed systems can be formulated. The most reasonable model based upon the results of the various temperature measurements discussed in the previous section is a two-zone model.

where e is the fraction of solid in the transfer zone.

The differential equation for the total heat balance is

$$G C_g (T_i - T_o) = \overleftarrow{W}_{gt} C_g \frac{\partial T_{gt}}{\partial t} + e M C_s \frac{\partial T_{st}}{\partial t} + \overleftarrow{W}_{ge} C_g \frac{\partial T_{ge}}{\partial t} + (1-e) C_s M \frac{\partial T_{se}}{\partial t}$$

and for solid phase is

$$h_t A (T_{gt} - T_{st}) + (1-e) h_e A (T_{ge} - T_{se}) = e M C_s \frac{\partial T_{st}}{\partial t} + (1-e) M C_g \frac{\partial T_{se}}{\partial t}$$

This is currently being evaluated and will be included in the supplement.

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