Int J Heat Mass Transfer. Vol. 10, pp. 1793–1800. Pergamon Press Ltd. 1967. Printed in Great Britain

ON SOLID-TO-FLUID HEAT TRANSFER IN FLUIDIZED SYSTEMS

S. S. ZABRODSKY

Heat and Mass Transfer Institute, B.S.S.R. Academy of Sciences, Minsk, B.S.S.R., U.S.S.R.

(*Received* 7 *March* 1967)

Аннотация—Сопоставление коэффициентов теплообмена частиц и погруженных в псевдоожиженный слой тел подтверждает мнение, что низкие эффективные значения *Nu* твердых частиц сочетаются здесь с высокими истинными значениями, главным образом, из-за неоднородности газораспределения в слое. Дана наглядная приближенная интерпретация ухудшения междуфазового теплообмена в условно однородных зернистых слоях при низких числах Пекле.

Показано влияние схемы слоевых теплообменников и перемешивания твердой фазы на расположение зоны активного теплообмена.

NOMENCLATURE

A, B,	coefficients in equation (6) [m^{-1}];
C_1, C_2,	constants in the solution of equation (1) [dimensionless];
c,	specific heat [kcal kg^{-1} $°C^{-1}$];
d,	diameter of solid particle [m];
F_{ca},	cross-section area of bed [m^2];
F_k,	surface area of solids per unit volume of bed [m^{-1}];
G_m,	mass rate of solids [kg h^{-1}];
Gr,	Grashof number [dimensionless];
H,	bed height [m];
h,	heat-transfer coefficient [kcal m^{-2} h^{-1} $°C^{-1}$];
k,	heat conductivity [kcal m^{-1} h^{-1} $°C^{-1}$];
m,	porosity [dimensionless];
Nu,	$= hd/k_f$, Nusselt number [dimensionless];
Pe,	$= w_s d c_f \rho_f / k_f$, Péclet number [dimensionless];
Re,	Reynolds number [dimensionless];
Sh,	Sherwood number [dimensionless];
t,	$= t' - \theta$, temperature head (temperature driving force) [°C];
t',	temperature of fluid [°C];
u_s,	superficial velocity of material [m h^{-1}];
V,	sink of heat [kcal m^{-3} h^{-1}];
w_s,	superficial velocity of fluid [m h^{-1}];
x, y, z,	co-ordinates [m].

Greek symbols

β,	$= \sqrt{(\delta^2 + h_{tr} F_k / k_f)}$ [m^{-1}];
δ,	$= w_s c_f \rho_f / (2k_f)$ [m^{-1}];
ρ,	density [kg m^{-3}];
θ,	temperature of solids [°C].

Subscripts

ef,	effective;
f,	fluid;
m,	material;
0,	at zero level of z or x;
s,	based on superficial velocity;
tr,	true.

WHEN describing fluid-to-solid heat transfer in fluidized systems and even in a simple case of fixed beds many difficulties are encountered and so far the interpretation of the same experimental data has been contradictory.

The recent works of Rowe and Claxton [2] and of Cornish [1] show the real necessity for obtaining any information, even qualitative, on the subject, but preferably for working out some consistent explanation of the known experimental facts.

Perhaps, the low experimental values of the heat-transfer coefficients of solid particles obtained by various authors is the most striking thing when experimental data on fluid-to-solid heat transfer in granular beds are considered. Thus, for example, for sand particles 0·21 mm in diameter in a wide range of gas velocities in a fluidized bed Ciborowski and Roshak [10] obtained heat-transfer coefficients not higher than 2·1 kcal/m^2 degC h, while at the same gas velocities the wall heat-transfer coefficient amounted to 66–170 (and it would be higher from the data of other investigators). Taking into account that heat transfer of a solid particle in a bed can, in principle, be considered as the heat transfer between the same bed and the wall of a tiny heater or cooler, the closeness of the coefficients of the solid particle and the wall could be expected. Here an objection can be raised that in the case of a solid particle its size is commensurable with the size of other bed particles and this, perhaps, leads to some essential change of heat-transfer mechanism and to the decrease of the value of the heat-transfer coefficient. However, it is known from the literature on heat transfer between a fluidized bed and solid bodies, for example, horizontal cylinders [3], that with the decrease in the size of the body immersed in a bed its heat-transfer coefficient tends not to fall but monotonously to increase. It is sufficient to mention the well-known experiments by Jakob and Osberg [4] who obtained the heat-transfer coefficients of about 1400 kcal/m^2 h degC for the wires 0·13 mm in diameter in the air-fluidized bed of glass beads with their diameter (0·153 mm) approximately equal to the wire diameter. Thus, the change in the mechanism of heat transfer depending on the commensurability of sizes of heating surfaces and bed particles does not lead to a decrease in heat-transfer coefficient at all.

The experiments show that the main change in the gas temperature averaged over the cross-section of a fluidized bed takes place along a rather short distance from the supporting grid or that the so-called height of the active zone of solid-to-fluid heat transfer is not large. Further, the mean gas temperature changes very little and there is no possibility to determine reliably the temperature difference between gas and solid particles. This gives a good ground to consider the experimental heat-transfer coefficients obtained from the measurements beyond the limits of the active zone to be incorrect and apparent. In the experiments of some authors other sources of errors have also been found. However, with all the corrections offered, the calculated values of the heat-transfer coefficients of solid particles remained incomprehensibly low.

Then in [5] the author put forward the assumption that the explanation should be sought in the combination of rather high true solid-to-fluid heat-transfer coefficients with their very low effective values. What matters here are not only the various imperfections of the experimental methods, such as measurements beyond the active zone, but also the actual impossibility of measuring the temperature fields around individual solid particles, which fields are essentially dissimilar because of the non-uniformity of the gas distribution even for the particles situated at the same cross-section of the bed. In [5] general considerations and specific numerical examples showed how even micrononuniformities of the gas distribution sharply reduce heat transfer and lead to low effective Nusselt numbers which will differ by several orders of magnitude from the true values. Due to the non-uniformity of the gas distribution, the main part of the material surface is operating under the conditions of a negligible temperature driving force even within the height of the active zone. It should be emphasized that the gas temperature measured over the cross-section of the bed does not give a correct idea of the true local temperatures at the surfaces of the solid particles.

The well-known Nusselt statement that the true heat-transfer coefficient of a spherical solid particle cannot be lower than 2, was modified for granular beds in [5]. It was criticized by Rowe [6] but from a wrong standpoint as shown in [7]. Recent work by Rowe and Claxton [2] also includes some misleading assertions based on obvious misunderstandings. They write:

> Zabrodsky suggested that in an assembly, the fluid immediately surrounding the sphere under consideration could be imagined to be rearranged into a spherical shell in order to evaluate a limiting Nusselt number using the equation $Nu = 2/(1 - r_1/r_2)$. It is tacitly assumed that the other spheres are perfect infinite sinks. Rowe showed that this leads to:
>
> $$Nu \text{ (or } Sh) = 2/[1 - (1 - m)^{\frac{1}{3}}]$$
>
> $$\text{with } (Re = 0, Gr = 0)$$
>
> where m is the voidage or porosity of the assembly of spheres. This is not a particularly good argument as Cornish [1] showed in his recent note and in no way can generally be applied to mass transfer. The problem of minimum possible rate is a complicated one and no simple solution is available. Much depends on whether the other spheres are sources or not (Cornish points out that they cannot be sinks under steady conditions as Zabrodsky assumes). Cornish concludes that the limiting Sh is likely to approach zero in most practical situations.

This is true and also well known that the problem is a complicated one and it is doubtful whether a simple or even complex exact solution could be obtained at this moment. But a rough, semi-quantative solution could be simple enough.

What Rowe means in the above quotation by infinite and perfect sinks nobody knows. Actually in [5] Zabrodsky "tacitly assumes" merely the identity of the particles in the sense that if the sphere under consideration is a sink, then the rest of them are sinks too; if the sphere under consideration is a positive heat source, such are the rest of the spheres.

Solid particles (spheres) can also be sinks under steady-state conditions, for example, in the case of wet spheres drying at constant drying rate with continuous supply and discharge of the material. In this case preheated spheres are supplied into the bed. Under steady-state conditions spheres can also be negative sinks (positive sources). Continuous steady-state cooling of the bed of spheres heated by induction heating affords an example of the above situation.

It is easy to see, although Rowe and Claxton take no notice of it, that Cornish's conclusion mentioned in their paper that Nu (Sh) approaches zero in "most practical situations", is valid only for the effective, (diminished by small heads of potential), rather than the true values of Sh, i.e. it does not disprove but in essence only repeats the conclusion made by Zabrodsky in [5] and [7]. By the way, in [1] Cornish himself writes about Nu approach to zero not in the "majority of practical situations" but in the limiting case when the fluid velocity tends to zero and the fluid ceases to be a sink and this happens because of the vanishingly small temperature difference between the spheres and the fluid.

At present there are no perceivable logical grounds for substituting as Cornish, Rowe and Claxton do, for the obvious decrease in the temperature head the decrease of the true heat-transfer coefficient lower than its conductive component.

It is a more complicated thing to find a clear and physically justified interpretation of the effect of the longitudinal heat conduction on the heat-transfer coefficient of solid particles in a bed, which problem has not been touched in the works of Cornish [1], and Rowe and Claxton [2]. Intense longitudinal heat conduction is known [8, 9] to cause substantial reduction of solid-to-fluid heat transfer in some cases.

Later in this paper an attempt is made to interpret the influence of longitudinal heat conduction as a cause for the decrease in the effective values of Nu. Then it would be convenient to consider this influence and the non-uniformity of the gas distribution as factors acting in common. The action of both factors is not simply additive but there is some interdependence between them. But for simplicity let us consider here the influence of longitudinal heat conduction (or rather the Péclet number) in absence of any non-uniformity of gas distribution.

Consider a bed (fixed or fluidized) penetrated continuously by gas flow and with a steady onedimensional temperature field. In order to exclude from consideration for the present the effect of solid phase mixing, assume the temperature of solid particles constant (drying at constant rate). Isolate an elementary cube with edges dx, dy and dz in the bed and consider its heat balance, allowing for the heat flow contributed by longitudinal heat conduction (in z-direction); heat flow contributed by net gas flow (in z-direction) and for the heat removed by the sinks. Express the sink in terms of the true heat-transfer coefficient as $V = h_{tr}F_k\,(t' - \theta)$. For the case of fine solid particles at low gas velocities for a semi-quantitative analysis h_{tr} can be assumed equal to its conductive component calculated, for example, as proposed in [5]. Such h_{tr} and Nu_{tr} are independent of Pe, and the actual reduction of heat transfer due to low Pe will be related to the equalization of the longitudinal temperature head distribution in the bed. On denoting the excess gas temperature as $t' - \theta = t$, one can readily obtain

$$k_f \frac{\mathrm{d}^2 t}{\mathrm{d}z^2} - w_s c_f \rho_f \frac{\mathrm{d}t}{\mathrm{d}z} - h_{tr} F_k t = 0. \tag{1}$$

In the present case gas conductivity is included in the equation instead of effective thermal conductivity of the bed, since the temperature of all solid particles is the same. No corrections for cross-section blocking up by solid particles has been made which somewhat overestimates the effect of the longitudinal gas thermal conductivity.

Solution of equation (1) is of the form

$$t = C_1 \exp\left[(\delta + \beta)z\right] + C_2 \exp\left[(\delta - \beta)z\right]$$

where

$$\delta = \frac{w_s C_f \rho_f}{2k_f} \quad \text{and} \quad \beta = \sqrt{\left(\delta^2 + \frac{h_{tr}F_k}{k_f}\right)}.$$

Boundary conditions: $t = t_0$ at $z = 0$ (at the bottom of the bed); $t = 0$ at $z = H$ (it can be assumed approximately if H is sufficiently high).

Then

$$t_z/t_0 = \frac{\exp\left[(\delta + \beta)z\right] - \exp\left[(\delta - \beta)z\right]}{1 - \exp(2\beta H)} + \exp\left[(\delta - \beta)z\right] \tag{2}$$

which, again, at sufficiently high H, degenerates to

$$t_z/t_0 = \exp\left[-(\beta - \delta)z\right]. \tag{3}$$

Calculate Nu_{ef} and the ratio Nu_{ef}/Nu_{tr} according to equation (3) using the logarithmic mean temperature difference in the bed

$$h_{ef} = \frac{u_s C_f \rho_f (t'_0 - t'_z)}{F_k Z} : \frac{t_0 - t_z}{\ln(t_0/t_z)}$$

whence allowing for $F_k = 6(1 - m)/d$ and $\ln(t_0/t_z) = (\beta - \delta)z$, we have

$$Nu_{ef} = \frac{w_s C_f \rho_f (\beta - \delta)\, d^2}{6k_f(1 - m)}. \tag{4}$$

Substituting β and δ by their detailed values, introducing the Péclet number ($Pe = w_s\, d c_f \rho_f / k_f$) and dividing (4) by Nu_{tr}, we get the relation

$$\frac{Nu_{ef}}{Nu_{tr}} = \frac{Pe}{6(1 - m)} \left\{ \sqrt{\left[\left(\frac{Pe}{2Nu_{tr}}\right)^2 + \frac{6(1 - m)}{Nu_{tr}}\right]} - \frac{Pe}{2Nu_{tr}} \right\}. \tag{5}$$

In Fig. 1 equation (5) is plotted for $m = 0{\cdot}4$ and Nu_{tr} calculated from the formula: $Nu = 2/[1 - (1 - m)^{\frac{1}{3}}]$ [2]. On the line marked are the points corresponding to the performance of perfectly uniform granular beds of solid particles 100η and 1 mm in diameter at various superficial gas velocities. As seen from Fig. 1 under the influence of high longitudinal heat conduction (low values of Pe) Nu_{ef} can be a rather small fraction of Nu_{tr} only for very fine particles. On the other hand, for fine particles, under such conditions of bed uniformity, heat transfer, all the same, is practically completed at a negligible distance z from the gas inlet, as seen from Fig. 2 where the data are plotted in accordance with equation (3). Although the application of equation (3) to the distance z less than the solid particle diameter

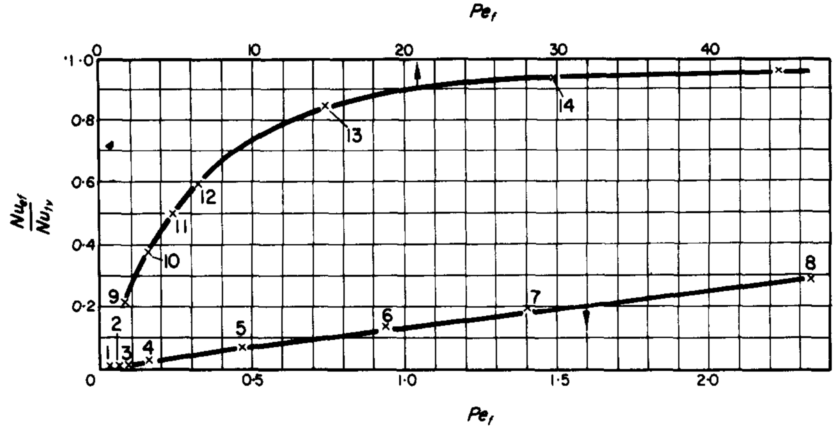

FIG. 1. Reduction of particle-to-fluid heat transfer in a conveniently uniform granular bed at low Péclet numbers and $m = 0{\cdot}4$, equation (1).

Points 1, 2, 3, 4—$d = 10^{-4}$ m; $t' = 1200°C$, w_s are 360, 720, 1080 and 1800 m h^{-1}, respectively.

Points 5, 6, 7, 8—$d = 10^{-4}$ m; $t' = 20°C$, w_s are 360, 720, 1080 and 1800 m h^{-1}, respectively.

Points 9, 10, 11, 12—$d = 10^{-3}$ m; $t' = 1200°C$, w_s are 1800, 3600, 5400 and 7200 m h^{-1}, respectively.

Points 13, 14—$d = 10^{-3}$ m; $t' = 20°C$, w_s are 1800 and 7200 m h^{-1}, respectively.

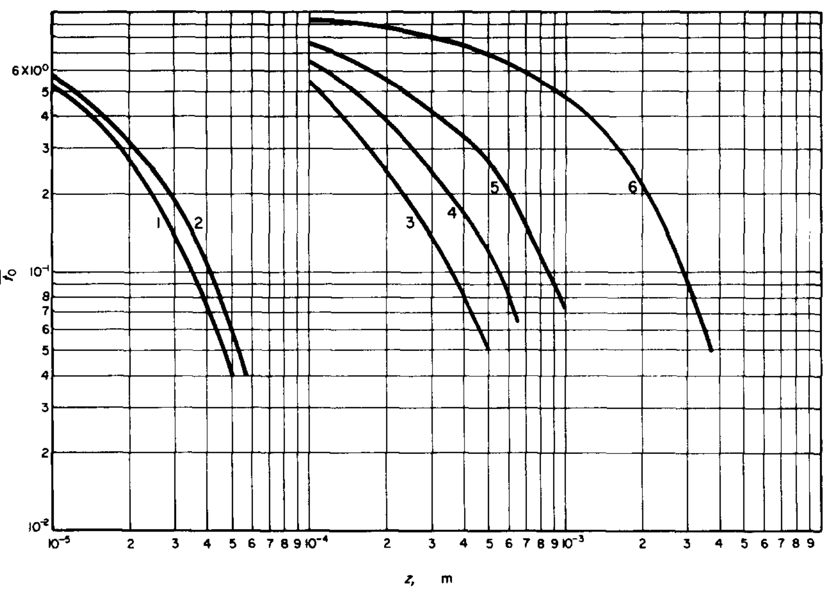

FIG. 2. Drop of relative temperature head (t_z/t_0) in a uniform granular bed at $m = 0{\cdot}4$.
(1) $d = 10^{-4}$ m, average $t' = 50°C$, $w_s = 360$ m h^{-1};
(2) $d = 10^{-4}$ m, $t' = 50°C$, $w_s = 1800$ m h^{-1};
(3) $d = 10^{-3}$ m, $t' = 1200°C$, $w_s = 1800$ m h^{-1};
(4) $d = 10^{-3}$ m, $t' = 1200°C$, $w_s = 7200$ m h^{-1};
(5) $d = 10^{-3}$ m, $t' = 100°C$, $w_s = 1800$ m h^{-1};
(6) $d = 10^{-3}$ m, $t' = 100°C$, $w_s = 7200$ m h^{-1}.

is arbitrary, it gives a true idea of the insignificance of the distances where the temperature head decreases, say, to 0·01 of its original value in a perfectly uniform bed even at an extremely low ratio of the effective to true Nusselt numbers due to longitudinal thermal conduction.

Thus, in real non-uniform fluidized systems two mechanisms will evidently cause low Nu_{ef}; namely, non-uniform gas distribution and longitudinal conductivity.

The first mechanism is more important since the heat-transfer zone considerably expands because of the gas break- or microbreak-through, as shown in [5] and [7]. Of course this mechanism operates together with the second one. Thus, for example, in a non-uniform fluidization, i.e. a break-through of a portion of gas past the solid particle packets, particularly low Pe and considerable decrease of Nu_{ef} occurs in the packets because of longitudinal heat transfer. But longitudinal heat conduction will not essentially affect either the temperature of the gas flowing out of a somewhat high packet, or the temperature field of the by-passing gas. The Pe of the by-passing gas are high.

Now let us dwell upon some peculiarities of heat transfer in granular beds with a variable temperature of the material along one or two co-ordinates. In such granular beds the very location of the active heat-transfer zone (i.e. the zone where the value of the temperature head is a significant part of its maximum value) can be different and not necessarily coincide with the inlet of the hot gases, as in the case of $\theta = \text{const}$ discussed above.

Thus, for example, in a heater with the bed moving horizontally without mixing and being in a state little above the minimum fluidization, the active zone will have the shape of some inclined "tongue" (Fig. 3) pressed to the supporting grid near the solids inlet and then moving away from it farther and farther. This shape is quite natural. At the solids inlet hot gases meet the coldest particles and soon cool down near the supporting grid. Closer to the solids outlet near the supporting grid, hot gases meet solid particles already heavily heated and the temperature head there is therefore small. Then farther from the supporting grid the temperature head somewhat increases because of the contact with less preheated "back" particles of the bed and, finally, decreases again because of the decrease of the gas temperature more rapid than that of the solid particles along this gas stream-line.

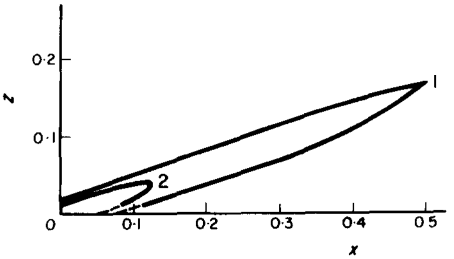

FIG. 3. The relative temperature head field in an unmixed granular bed in cross-flow of gas and material with $A = 60{\cdot}3$ m^{-1}, $B = 196$ m^{-1}, z and x—distances from gas and solid inlets, correspondingly [m].
(1) $(t' - \theta)/(t'_0 - \theta_0) = 0{\cdot}05$;
(2) $(t' - \theta)/(t'_0 - \theta_0) = 0{\cdot}10$.

In such a case the field of temperature heads can be calculated by the equation which the author derived before [11]

$$(t' - \theta)/(t'_0 - \theta_0) \approx [2\sqrt[4]{(\pi^2 ABxz)}]^{-1} \exp[2\sqrt{(ABxz)} - Ax - Bz] \tag{6}$$

where

$$A = 6h_{ef}/(C_s\rho_s u_s d);$$
$$B = 6h_{ef}(1 - m)/(C_f\rho_f w_s d);$$
$$u_s = G_m/[F_{ca}\rho_m(1 - m)]$$

G_m is the mass rate of the material.

From Fig. 3 it is seen that not the whole zone of high gas temperatures, but sometimes only a small part of it constitutes the zone of active heat transfer in the bed without mixing.

Let us consider briefly the effect of solid mixing. Longitudinal (vertical) and transverse (horizontal) mixing should be considered separately as they are known to have different rates in a fluidized bed. Usually vertical mixing is more intense. It will have double influence on the shape of the cooling curve of the gas flowing into the bed. Firstly, because of mixing, solid cold particles will go down, increasing there the temperature head and providing a steeper decrease of the gas temperature near the supporting grid; secondly, when getting into the upper part of the bed, the particles overheated below can return their heat to the gas (and the gas, in turn, to the neighbouring cold particles) somewhat extending the zone of weak solid-to-fluid heat transfer which occurs at low temperature heads. The character of the change of the gas temperature profile due to vertical solid mixing is shown in Fig. 4. However, in the case of intense vertical mixing there is no point in speaking of any extension in the heat transfer zone caused by it, since the particle overheating at the bottom of the bed and solid temperature gradient over the bed height become negligible.

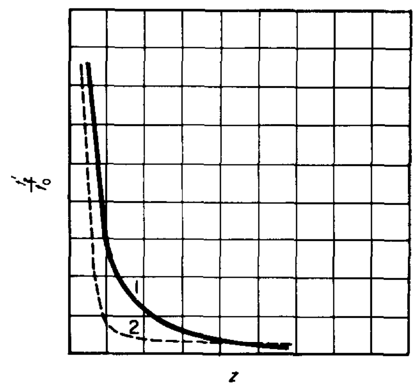

FIG. 4. The trend of change of gas temperature profile at the inlet of solid phase due to vertical mixing of the solid phase in a granular bed.
(1) bed without mixing
(2) bed with vertical solid mixing.

At cross-flow and in installations with batch fluidization, the vertical solid mixing, therefore reduces the active heat-transfer zone and brings it nearer to the supporting grid, since nowhere near it a cushion of overheated solid particles can form.

The absence of transverse solid mixing of a bed (or the presence of only slight mixing) in a cross-flow originates gradual increase of the temperature of the material towards its outlet and, accordingly, stretches the zone of essential heat transfer over there. Hindering transverse solid mixing by vertical nets and similar inserts can be effective in strengthening the effect of the cross-flow, i.e. in increasing the temperature of the solids at the outlet from the fluidized bed. Thermal calculation of shallow fluidized beds with a cross-flow of heat carriers has been analysed in Borodulya's work [12]. Under the operating conditions of heat exchangers with long and narrow fluidized beds, the transverse solid mixing is often so weak, that even without any special attempts to impede the latter, a cross-flow of heat is obtained and the mean temperature of the gas flowing out of fluidized beds is found to be considerably lower than the temperature of the discharged solids.

The effect on the solid-to-fluid heat transfer of vertical solid mixing in a fluidized bed with the supply through the top and a bottom discharge of materials, as well as with both the supply and discharge being arranged through the top have been dealt with in Baskakov's work [13] and the question will not be discussed here for want of space.

Let us only note that Baskakov's conclusion on the impossibility of counterflow in the fluidized bed of a single-compartment apparatus is somewhat hasty since it does not allow either for the possibility of operating the apparatus at gas velocities close to minimum fluidization or the possibilities afforded by the application of various inserts hindering vertical solid mixing (nets, packings with solid and netted members, etc).

REFERENCES

1. A. R. H. CORNISH, Note on minimum possible rate of heat transfer from a sphere when other spheres are adjacent to it, *Trans. Instn Chem. Engrs* **43** (10), 332–333 (1965).
2. P. N. ROWE and K. T. CLAXTON, Heat and mass transfer from a single sphere to fluid flowing through an array, *Trans. Instn Chem. Engrs* **43** (10), 321–331 (1965).

3. S. S. ZABRODSKY, *Hydrodynamics and Heat Transfer in Fluidized Beds*. Gosenergoizdat (1963).
4. A. JAKOB and L. OSBERG, Effect of gas thermal conductivity on local heat transfer in a fluidized bed, *Can. J. Chem. Engng* **35** (1), 5–9 (1957).
5. S. S. ZABRODSKY, Heat transfer between solid particles and a gas in a non-uniformly aggregated fluidized bed, *Int. J. Heat Mass Transfer* **6** (1), 23–31 (1963).
6. P. N. ROWE, Comments on heat transfer between solid particle and a gas in a non-uniformly aggregated fluidized bed, *Int. J. Heat Mass Transfer* **6** (11), 989–991 (1963).
7. S. S. ZABRODSKY, A note on heat transfer between spherical particles and a fluid in a bed, *Int. J. Heat Mass Transfer* **6** (11), 991–992 (1963).
8. Z. F. CHUKHANOV, Heat and mass transfer between gas and granular material, *Int. J. Heat Mass Transfer* **6** (8), 691–701 (1963).
9. B. N. VETROV and O. M. TODES, Thermal wave propagation with heating of charge by a gas flow, *Zh. Tekh. Fiz.* **25** (7), 1242–1247 (1955).
10. J. CIBOROWSKI and J. ROSHAK, Investigation of heat transfer between a gas and solid particles in a fluidized bed, *Inzh.-Fiz. Zh.* **2** (2), 3–9 (1959).
11. S. S. ZABRODSKY, On temperature head field and efficiency of heat exchangers with moving dense bed of granular material, *Vestsi Akad. Nauk. BSSR, Seriya Fiz.-Tekhn. Nauk* No. 1, 71–79 (1957).
12. V. A. BORODULYA, On thermal calculation of a thin fluidized bed with cross motion of heat agents, *Inzh.-Fiz. Zh.* **6** (8), 22–27 (1963).
13. A. P. BASKAKOV, The effect of agitating material in a fluidized bed on heat exchange between gas and particles, *Inzh.-Fiz. Zh.* **3** (9), 10–16 (1960).

Abstract—The comparison of the heat-transfer coefficients for particles and for bodies immersed in a fluidized bed, confirms the opinion that low effective values of *Nu* of solid particles appear here simultaneously with high true values of *Nu* mainly because of the non-uniformity of gas distribution. An approximate simple interpretation is given of the reduction of the solid-to-fluid heat transfer in conventionally uniform granular beds at low Péclet numbers. Also shown is the influence of systems of granular bed heat exchangers and of solid mixing on the position of the zone of active heat exchange.

Résumé—La comparaison entre les coefficients de transport de chaleur entre les particules et le fluide dans un lit fluidisé et entre un corps immergé et ce lit a confirmé l'opinion que des valeurs élevées du vrai *Nu* des particules solides "coexistent" ici avec des valeurs effectives faibles dues à la non-uniformité de la distribution du gaz. On donne une interprétation hypothétique pour décrire la diminution du transport de chaleur entre le solide et le fluide dans des lits granulaires convenablement uniformes à de faibles nombres de Péclet. On montre l'influence du schéma de l'échangeur de chaleur à lit granulaire et du mélange solide sur l'emplacement de la zone d'échange actif de chaleur.

Zusammenfassung—Der Vergleich der Wärmeübergangskoeffizienten für Teilchen und Körper in einem Fliessbett bestärkt die Ansicht, dass die geringen effektiven Werte für *Nu* der Festkörper gleichzeitig mit grossen wahren Werten von *Nu* vor allem wegen der Ungleichförmigkeit der Gasverteilung auftreten. Eine einfache Näherungsaussage erfolgt für den Wärmeübergang Festkörper an Flüssigkeit in gewöhnlichen einheitlichen Granularbetten bei kleinen Pécletzahlen. Daneben wird der Einfluss der Systeme der Granularwärmeübertrager und der Mischbarkeit der Festkörper auf die Lage der aktiven Wärmeübergangszone gezeigt.