CONDUCTIVE COMPONENT OF HEAT TRANSFER IN A FLUIDIZED BED

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It is shown that near bodies immersed in a fluidized bed there arise conditions that are not necessarily governed by conductive heat transfer.

It is well known that the coefficient of heat transfer between a fluidized bed and a surface immersed in it is smaller by an order of magnitude than under ordinary conditions. Mickley and Fairbanks [1] have proposed that such a rate of the process is a result of heat transfer by packets of particles that continuously replace one another at the heat-exchange surface. This contribution is expressed numerically, taking into account the thermal resistance [2], in terms of a coefficient:

$$\alpha_{\mathrm{cond}}=\frac{1-f_0}{R_c+0{,}5R_m}. \tag{1}$$

The contact resistance R_c in this expression is a rather complicated function of many variables and is usually determined experimentally from the cooling rate by thermoanemometric measurements.

The second term in the denominator of (1) represents the mean value of the thermal resistance of a packet over the time τ_m

$$R_m=\sqrt{\frac{\pi(1-f_0)}{\varphi_t\lambda_{\mathrm{sol}}c_M\rho_{\mathrm{sol}}}}. \tag{2}$$

It is evident from Eqs. (1) and (2) that α_{cond} depends on the pulsation characteristics of the fluidized bed f_0 and φ_t, on the thermal conductivity λ_{sol} and the density ρ_{sol} of the solid phase, and on the specific heat c_M of the material.

The frequency of packet replacements φ_t and of bubble replacements φ_0, and the relative time f_0 of contact between the surface and the discrete phase (the bubbles) are determined experimentally with the aid of photometers or thermoanemometers.

When a fluidized bed is examined photometrically, the instruments record only a change of phase and do not "see" packets replacing one another without gaseous interlayers. Therefore, ideal photometers must always read $\varphi_t = \varphi_0$.

Thermoaneomometers yield different data. They record not only a change of phase or a replacement of whole packets, but also sense incomplete packets and pulsations of the gas stream at a surface. For this reason, it may happen that $\varphi_t > \varphi_0$, especially when the probe dimensions are small.

However it is not all of the packets recorded on the oscillogram that carry heat from the fluidized bed to the surface, but only those which, rather than sliding along a given isothermal surface, separate from it and escape into the fluidized bed. If this is neglected, a large error may result. Inaccuracies may also arise if the probe dimensions, the disposition of probes in the fluidized bed, and other test conditions are not considered.

It is obvious, furthermore, that variables φ_t and f_0 in Eqs. (1) and (2) are statistical-mean characteristics of a fluidized bed and, in order to make the problem a determinate one, they should be expressed in terms of system parameters and both hydrodynamic and thermophysical constants; this is hardly feasible.

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TABLE 1. Test Values for the Porosity of a Fluidized Bed with an Immersed Plate

Layer of thickness	Layer characteristic	Chamotte $d = 0{,}32$ mm, $\varepsilon_0 = 0{,}52$			Chamotte $d = 0{,}70$ mm, $\varepsilon_0 = 0{,}51$		
	W	1	2	3	1	2	3
$1d$	ε_p	0,645	0,743	0,770	0,748	0,785	0,810
$2d$	ε_p	0,638	0,710	0,745	0,710	0,770	0,790
$3d$	ε_p	0,630	0,700	0,730	0,700	0,760	0,780
$5d$	ε_p	0,630	0,700	0,720	0,700	0,750	0,770
Over the entire section	ε_{av}	0,550	0,640	0,680	0,560	0,660	0,710

Layer of thickness	layer characteristic	Chamotte $d = 0{,}70$ mm, $\varepsilon_0 = 0{,}40$					Chamotte $d = 2{,}20$ mm, $\varepsilon_0 = 0{,}40$	
	W	1,2	2	3	5	8	1	2
$1d$	ε_p	0,577	0,680	0,725	0,750	0,800	0,627	0,755
$2d$	ε_p	0,562	0,662	0,730	0,750	0,790	0,643	0,740
$3d$	ε_p	0,570	0,650	0,720	0,740	0,780	0,654	0,730
$5d$	ε_p	0,580	0,650	0,710	0,730	0,780	0,643	0,720
Over the entire section	ε_{av}	0,490	0,550	0,625	0,680	0,755	0,500	0,620

The problem of determining the density and the thermal conductivity of the continuous nonhomogeneous fluidized phase is even more difficult and, for this reason, they must be hypothetically assumed equal to those of a solid layer where its packing is loosest [2]. Such a solution of the problem is open to objection, however.

The role of conductive heat transfer in a fluidized bed is also difficult to assess on the basis of experimental studies in this field. The overall indication is, however, that under certain conditions the particle packets play a lesser role in carrying the heat than the authors of the two-phase theory seem to believe [1].

This follows, for example, from the test data on drying in a fluidized bed of inert material [3] and on sublimation of naphthalene at the surface of plates and rods in a fluidized corundum bed [4, 5]. In those tests with industrial-size particles (d = 0.5-4.0 mm), 50-95% of the heat transfer was by convection, which, evidently, could be explained by local turbulence of the stream near surfaces immersed in the fluidized bed [6].

In studying the process of external heat transfer in a moist fluidized bed [7], results have been obtained which indicate a high rate of convective heat transfer in a fluidized bed. Those tests were performed with moist particles 60-680 μ in size, and they have shown that the overall heat-transfer coefficient does not increase much (by 10-25%) when the moisture content is 0.5-13%. The explanation offered in [7] is that the physical properties of moist air are not much different from those of dry air. According to the proposed mechanism of heat transfer, however, the dominant role in the process is played not by the fluidized medium but by the medium filling the interstitial space between particles in a packet. In tests with a moist fluidized bed such a medium may have been water, not air [8, 9], and the presence of moisture at the contact between particles and the immersed surface must have reduced the thermal conductance of the packets. To be sure, the agglomeration of particles observed in [7] may have lowered the value of α_{cond}, but it is hardly correct to assume that the opposing effects of $\lambda_b^{0.5}$ and $d^{-0.36}$ on the conductive component of heat transfer are almost equal in magnitude. Rather, it should be considered that α_{cond} increased without affecting the total heat transfer, since it was not the conductive but rather the unchanged convective component of the heat transfer that was predominant.

The question of the role of particle "packets" in external heat transfer could be answered by straightforward experiments. Unfortunately, our attempts in this direction [10] have not yet yielded the desired results.

In view of this, the author and V. N. Kovalev have in a special study analyzed the structural–hydrodynamic properties of a fluidized bed near bodies of various shapes and sizes immersed in it, to explore

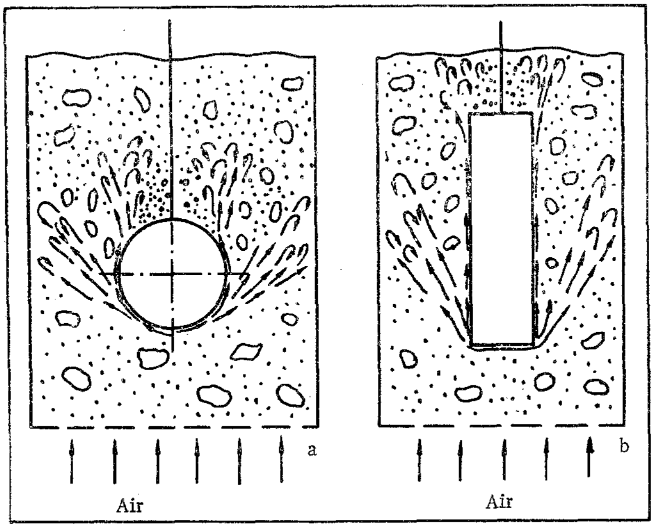

Fig. 1. Schematic diagram of the stream pattern around a ball (a) and a plate (b) immersed in a fluidized bed.

what determines the basic laws governing external heat transfer and thus to establish more precisely the mechanism of this process as well as the role of its various components on the overall effect.

In our structural analysis of a fluidized bed the time-average local porosities at various distances from the immersed surface was determined by layerwise x-radioscopy with a beam of width 0.1 mm and height 10 mm.

The tests were performed with 0.72, 0.82, 1.20, 1.70, 2.25 mm polystyrene particles and 0.32, 0.48, 0.70, 0.85, 1.20 chamotte particles. The fluidizing agent was air at room temperature. From the measured local porosities and by the conventional method we calculated the mean porosity over the entire bed section and also for boundary zones of width d, 2d, 3d, and 5d. Without dwelling very long on the procedure and all the results of this experiment, we will discuss only those results which are relevant to an evaluation of any possible errors in assessing the role of conductive heat transfer. Such data pertaining to a 70 × 80 × 10 mm plate are given in Table 1.

It is evident from Table 1 that the value averaged over time of the local porosity of a fluidized bed within a boundary zone (1-5)d thick is 1.1-1.4 times higher than the mean porosity over the entire bed section.

It has also been established that near an immersed plate the air velocity in the fluidized bed is 1.3-1.8 times higher than at some distance from it.

These results indicate that throughout the entire range of fluidization numbers W = 1-8 there arise structural and hydrodynamic conditions at the plate ($\varepsilon_p = 0.7$ and $w_p > w_{av}$) under which the fluidized bed transforms from a two-phase state to a diluted phase (pneumatic transport), i.e., to a state in which the mechanism of the process according to the packet theory must be considered dubious [2].

This conclusion was confirmed also by visual observations and by x-radiographs of the flow around plates (5, 10, 20, 50 mm thick), balls (20, 30 mm in diameter), and a cylinder (30 mm in diameter) immersed in fluidized beds of various materials. It became apparent that the air stream issuing from under the lower edge of a body immersed in a fluidized bed splits almost immediately into two. One of them, as shown in Fig. 1, deflects from the body surface at an angle of 20-30° and carries the fines downward. The other rushes along the surface confined within a very thin layer and carries the particles of the material (pneumatic transport). In the wedge region between both streams bubbles rise up and packets replace one another continuously. Their replacement frequency is much higher in this region than in the remaining bulk of the fluidized bed, but very few of them make contact with the washed surface.

The stream of catalyst rushing along the surface at a high velocity pulsates and its thickness changes continuously.

The apparent causes of such thin boundary streams are the smaller hydrodynamic drag here than in the bulk volume of a fluidized bed and the high longitudinal pressure gradients.

Observations and special measurements have also shown that the boundary stream of air "pushes out" the packets which approach the immersed surface. At the same time, there appear local dust vortices and the solid phase is transported along the immersed body surface. The particle concentration is not uniform along this surface. The shape of the body and its disposition in the fluidized bed influence the hydrodynamic conditions in the boundary zone, but generally the patterns according to Fig. 1a, b are the same. In both cases the lower part of the plate or the ball is washed by an air stream containing almost no particles. This air stream remains almost undeflected by the air filtering through the bed, which is an indication of a high stream velocity at the bow end of immersed bodies.

At the stern end of an immersed body the pattern is completely different. Here there forms a "cap" the porosity of which is close to that of a fixed bed. The lower edge of this "cap" is constantly washed by air streams rushing along its surface.

When analyzing the mechanism of external heat transfer in a fluidized bed, it is necessary also to consider the method of testing and some results of experiments obtained so far [1, 2, 7, 12]. Their common shortcoming is that the measurements of bed characteristics did not include the porosity distribution near immersed probes and α-calorimeters, without which it is difficult to assess the mechanism of external heat transfer. This deficiency can be easily overcome, however, by using the relation

$$\varepsilon_p = f_0 + (1 - f_0)\,\varepsilon_{sol}.$$

In the papers analyzed the parameter f_0 varied over a wide range and in some tests $f_0 > 0.4$. Assuming $\varepsilon_{sol} = \varepsilon_0$, from Eq. (3) with $f_0 = 0.4$ we get $\varepsilon_p = 0.7$-0.85, which corresponds to our data and confirms their reliability.

On the other hand, the porosities in the boundary zone were 0.7-0.85 when calculated by the proposed method, indicating that in these papers the two-phase theory of heat transfer was tested under conditions where gas bubbles were merging into a single stream near probes immersed in a fluidized bed and where the "packet" mechanism would already be considered unreliable [2, p. 108].

The results which have been presented here and the critical review of earlier studies concerning external heat transfer in a fluidized bed indicate that, under certain conditions, the role of conductive heat transfer in fluidized media must be smaller than was originally believed [1, 2]. In order to establish its role precisely and to derive reliable formulas for the convective and the conductive component, however, it will be necessary to engage in special studies the procedure of which has not yet been clearly defined.

NOTATION

d is the particle diameter;
c_M is the specific heat of the solid phase;
ρ_0 is the density of the fluidized bed;
ρ_{sol} is the density of the solid phase;
λ_{sol} is the thermal conductivity of the solid phase;
ε_0 is the porosity of the fluidized bed;
ε_p is the porosity of the fluidized bed in the boundary zone;
ε_{sol} is the porosity of the solid phase;
W is the fluidization number;
f_0 is the relative time of contact between the immersed surface and the gas bubbles;
φ_t is the frequency of replacement of the packets;
φ_0 is the frequency of replacement of the bubbles;
α_{cond} is the conductive component of the heat-transfer coefficients.

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