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Heat transfer in an electrostatically charged fluidized bed

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Abstract—The undesirable effect of electrification on heat transfer between the fluidized bed of dielectric particles and an immersed heating surface was studied. This effect has been explained as being the result of a change of the heat transfer mechanism from unsteady-state conduction (in the bed with no electrification) to steady-state conduction in the layer made of dielectric particles adjacent to the heating surface (in the electrostatically charged bed). The method based on adding a small amount of a fine material identical with or different from the bulk, has been proposed to intensify heat transfer. The optimum heat transfer coefficient was found for fine material concentrations in the range 0.05–0.1% ww. An increase in the heat transfer coefficient of up to 300% has been obtained. The observed interaction of such an admixture can be explained by decreasing the electrostatic charge in the bed.

INTRODUCTION

THE HEAT transfer and dynamics of a particulate system in a gas has been the subject of many intensive studies because of their applications in various chemical processes. Although the electric charge on the solid particles is often ignored in theoretical analysis electrification of the solid particles always occurs when contact and separation are made between solid particles and a wall of different materials or similar materials with different surface conditions [1]. The particles in a fluidized bed are known to be charged. Electrostatic charges can produce interparticle attractions of such magnitude that the hydrodynamics of the system are affected [2–4]. Charge generation is undesirable also for heat transfer between the heating surface and the bed because of a tendency for the particles to cling together in large agglomerates and to adhere to the walls of the heating elements. The first phenomenon results in the worsening of hydrodynamic conditions in the bed and the second one in the additional thermal resistance in the layer of particles formed at the heating surface.

In ref. [5] the authors proposed a new method of heat transfer improvement for such cases. The method is based on the addition of a small amount of a fine material to the bulk. This causes a split in the agglomerates and the disappearance of the layer of particles at the heating surface. These phenomena are associated with electric and thermal problems. The first of them has been discussed elsewhere [6], the others are presented here.

EXPERIMENTAL

Apparatus and materials

Solid particles were fluidized by air in a 90 mm I.D. glass column. The time-averaged heat transfer coefficient was measured from a 22 mm diameter and 175 mm length of the cylindrical electric heater mounted coaxially within the fluidized bed. The heater was of adiabatic design ensuring that practically all electrical power supplied to it was transferred as heat to the bed only. This power divided by the heater surface area gave the density of the heat flux, q. The bulk bed temperature, T_b, was measured with a copper–constantan thermocouple located in the middle of the bed. The temperature of the heater surface, T_w, was measured with three similar thermocouples soldered to the surface. The heat transfer coefficient was then calculated as $\alpha = q/(T_w - T_b)$. A drying column 50 l. in volume filled with silica gel was used for making measurements under low-humidity conditions (practically RH = 0 for all experiments). It is important in present investigations to remove all possible dust contamination from the fluidizing air, otherwise they can act as fine material. Therefore, a special ceramic filter was used in order to remove any dust from the air coming out of the drying column.

The particles in the fluidized bed were narrow size fraction commercial polystyrene and copolymer SAN. These materials have a high surface leakage resistance and can be easily charged. In addition, sand was used for comparison. The height of the fluidized bed was equal to the length of the electric heater.

NOMENCLATURE

a_e	effective thermal diffusivity of the packet [$m^2\ s^{-1}$]
c_{ps}	specific heat of solid [$W\ s\ kg^{-1}\ K^{-1}$]
d_p	particle diameter [m]
f_0	fraction of the total time when the probe is shrouded by gas bubbles
f_{0w}	fraction of the total time when the particle layer formed at the heating surface is shrouded by gas bubbles
n	number of layers of particles
R_w	resistance of the steady-state conduction through the particle layer [$m^2\ K\ W^{-1}$]
$R_{\lambda w}$	thermal resistance of the packet in contact with the particle layer [$m^2\ K\ W^{-1}$]
T	temperature [K]
T_b	bed temperature [K]
T_w	temperature of the heating surface [K]
t	time [s]
t	mean contact time of probe with packet [s]
t_0	mean contact time of probe with bubble [s]
t_w	mean contact time of packets with the particle layer at the heating surface [s]
w	superficial air fluidization velocity [$m\ s^{-1}$]
x	distance from the heating surface [m].

Greek symbols

α	heat transfer coefficient between fluidized bed and surface [$W\ m^{-2}\ K^{-1}$]
λ_e	effective thermal conductivity of the packet [$W\ m^{-1}\ K^{-1}$]
λ_g	thermal conductivity of gas [$W\ m^{-1}\ K^{-1}$]
λ_s	thermal conductivity of solid [$W\ m^{-1}\ K^{-1}$]
ρ_e	effective density of the packet [$kg\ m^{-3}$].

The fine materials employed were active coal (conductor), titanium dioxide (semiconductor) and A-extra pigment (dielectric). Since they can be used as colouring substances or fillers of commercial plastics they do not contaminate the fluidized particles of the bed.

Some important properties of the above-mentioned materials are listed in Tables 1 and 2.

Experimental results

Typical results are shown in Figs. 1 and 2. It can be seen that the addition of fine material increases the values of the heat transfer coefficients chiefly within the small gas velocity range (almost 300% for the fraction of the fine material—0.7% ww and at a superficial air velocity—about 0.2 m s^{-1} in the bed of polystyrene beads). It is interesting to note that the highest heat transfer coefficients were achieved in the bed with fine material at velocities not much different from the minimum fluidization velocity of the pure dielectric bed. When other bed materials and fine admixtures were used, similar results were achieved. Finally, it has

Table 1. Physical properties of materials

Material	Particle size range (mm)	Mean particle diameter (mm)	Density ($kg\ m^{-3}$)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Specific heat ($W\ s\ kg^{-1}\ K^{-1}$)	Dielectric constant	Surface resistivity (Ω)
Polystyrene	0.15–0.43	0.38	1050	0.12	1250	2.4–2.5	10^{14}
	0.43–0.60	0.51					
	0.60–1.02	0.75					
	1.5–2.5	—					
	2.5–4.0	—					
Copolymer SAN	0.43–0.60	0.48	1070	0.12	1250	2.6–2.9	10^{14}
Sand	0.60–1.02	0.71	2380	0.113*	800	—	—

* Determined experimentally according to Mickley and Fairbanks [9] (effective value).

Table 2. Physical properties of fine material

Fine material	Mean particle diameter (μm)		Dielectric constant	Density ($kg\ m^{-3}$)
	Sedimentation analysis	Microscopic analysis		
Active coal	—	1	∞	1700
Titanium dioxide	4.5	1.6	140	4300
A-extra pigment	8.0	2.3	2	2010

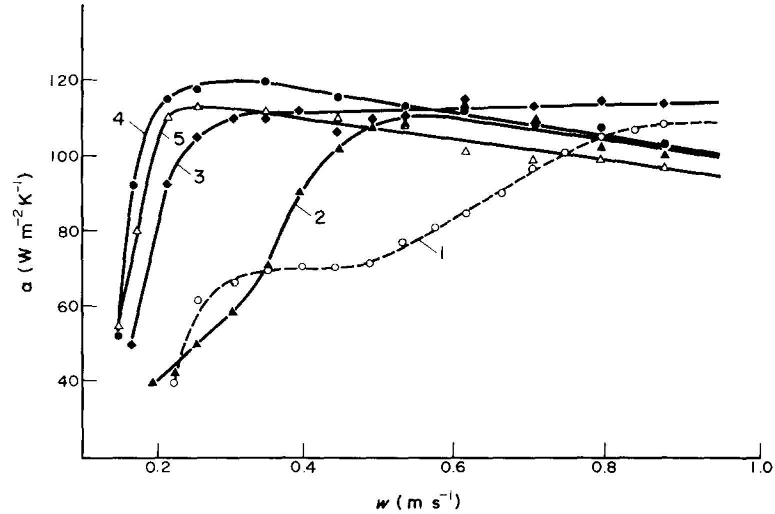

FIG. 1. Influence of the titanium dioxide admixture on the heat transfer coefficient for the bed of 0.75 mm polystyrene beads: (1) pure polystyrene beads; (2) polystyrene beads plus 0.1% ww of the titanium dioxide; (3) polystyrene beads plus 0.2% ww of the titanium dioxide; (4) polystyrene beads plus 0.7% ww of the titanium dioxide; (5) polystyrene beads plus 1.0% ww of the titanium dioxide.

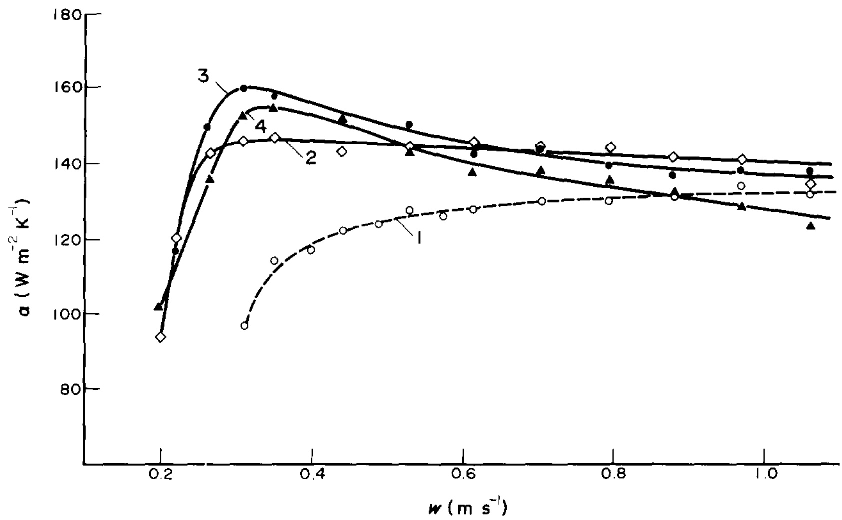

FIG. 2. Influence of the active coal admixture on the heat transfer coefficient for the bed of 0.71 mm sand particles: (1) pure sand particles; (2) sand particles plus 0.025% ww of the active coal; (3) sand particles plus 0.05% ww of the active coal; (4) sand particles plus 0.1% ww of the active coal.

been concluded that the observed improvement in heat transfer is independent of the electric nature of the fine material and it is presumably associated with the transfer of electric charge by fine particles to neutralize the whole bed.

MECHANISM OF HEAT TRANSFER BETWEEN HEATING SURFACE AND BED IN THE PRESENCE OF ELECTROSTATIC EFFECTS

Hydrodynamics of the wall surface

The hydrodynamics of the region adjacent to the wall of the heater (wall surface) was investigated by analyzing the temperature fluctuations of the low heat capacity probe previously described by Mickley *et al.* [7]. The probe used in this work consisted of a 20 μm thick, 3.5 × 8 mm strip of platinum glued to the side of a 22 mm diameter tube mounted coaxially in the fluidized bed to form a system geometrically identical to that used in the measuring of time-averaged quantities. A DC current was passed through the foil. This current both generated heat and served as the source of the potential drop used to determine the temperature of the foil. The heater temperature fluctuated in response to variations in the rate of heat transfer from its surface to the surrounding bed.

Tests were carried out in beds of polystyrene (0.38, 0.51 and 0.75 mm mean particle diameters) and in a bed of 0.71 mm diameter sand. From the oscillograms of the foil temperature fluctuations, the mean probe and

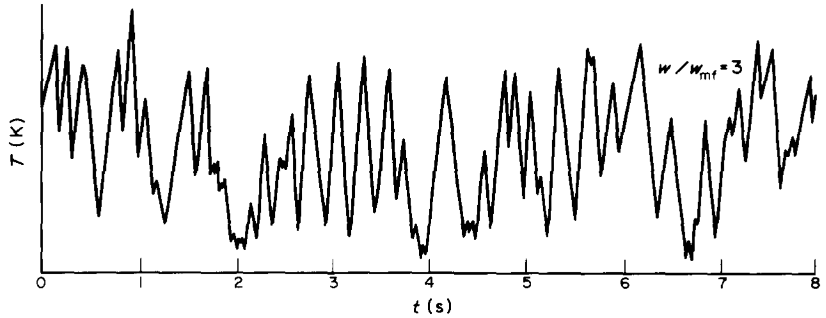

Fig. 3. Hydrodynamic structure of the wall surface for the bed of 0.51 mm polystyrene beads with 0.1% ww of the active coal admixture.

bubble contact time, t_0, and the probe and packet contact time, t, and the fraction of the time that bubbles shrouded the transfer surface, f_0, were all directly determined.

Examples of these original temperature records are shown in Figs. 3–5. Each is a section of a continuous recorder tracing in which time is the abscissa and the width of the plotted band is proportional to the instantaneous temperature difference.

In the bed with fine material for all the investigated systems, the notable characteristic of the temperature–time profiles is an abrupt change in the heater temperature (Fig. 3). This is interpreted as resulting from the sudden appearance of a fresh packet of dense phase at the heater surface and the short contact time (the fine material neutralizes the electric charge and solid circulation is improved). Thus, a high heat transfer coefficient can be expected.

In the bed of pure dielectric particles the electrostatic forces decrease the circulation of particles, also at the wall surface which controls heat transfer. Thus, the contact times of the particles with the surface are longer (Figs. 4 and 5). In accordance with the penetration theory a decrease in the heat transfer coefficient can be expected in this case. When the electrostatic forces are greater than the hydrodynamic forces, a stable layer of particles is formed at the heating surface, resulting in an additional heat resistance in the system—the steady-state conduction [Fig. 5(b)].

On the basis of these results heat transfer models for the two cases were formulated. In the above-presented analysis, some necessary numerical values of the model parameters were assumed to be equal to those of the incipient fluidized bed. The effective thermal conductivity for the bed of polystyrene particles were calculated from Kunii and Smith's correlation [8]. For the bed of sand particles this quantity was determined experimentally [9] because of the lack of reported data. The void fraction and residence times were measured for all the investigated systems.

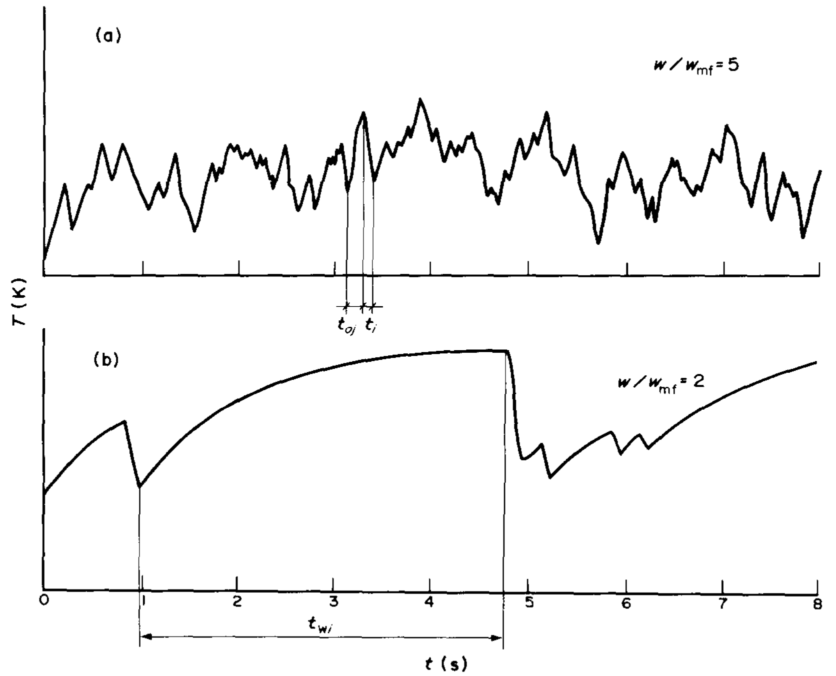

Fig. 4. Hydrodynamic structure of the wall surface for the bed of 0.75 mm pure polystyrene beads.

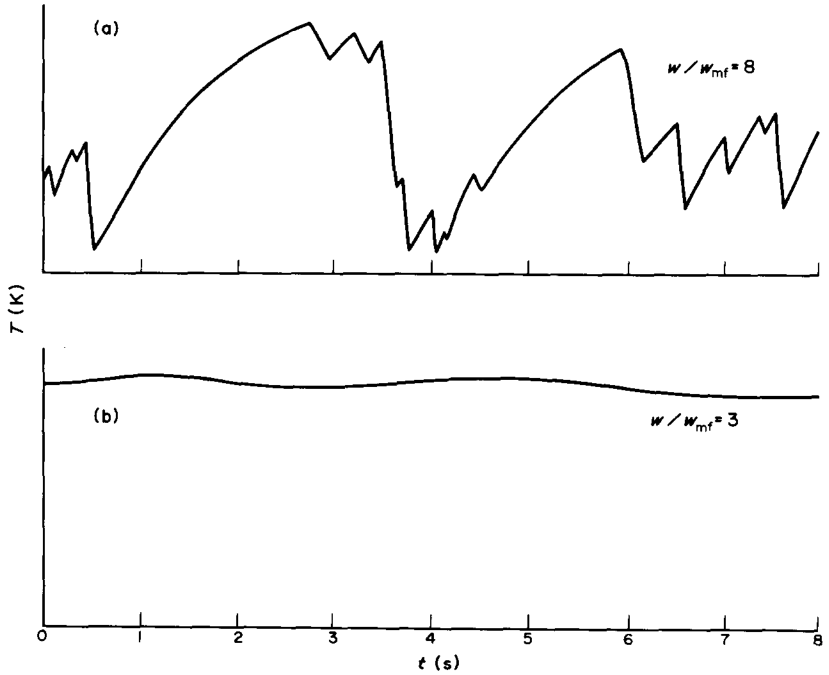

FIG. 5. Hydrodynamic structure of the wall surface for the bed of 0.51 mm pure polystyrene beads.

Predicted transport coefficients from the different penetration packet models were compared with experimental data obtained in a bed with a fine admixture (Fig. 6). It can be seen that the best agreement between theory and experiment was obtained for Baskakov's model [13]. Therefore, this model is proposed to describe the heat transfer mechanism in a bed of pure dielectric particles with regard to the electrostatic effects on the structure of the wall surface.

Heat transfer model in the presence of electrostatic effects

The mathematical formulation of a model may be based on Baskakov's idea of two thermal resistances connected in a series: steady-state contact resistance and unsteady-state conduction resistance in packets. In the presence of electrostatic effects the first of them, R_w, is created by the layer of particles adhering to the heating surface, the second one, $R_{\lambda w}$, by packets exchanged outside the layer. In accordance with the concept given above, constancy of the layer's resistance, R_w, permits us to use the unsteady-state heat conduction equation to describe heat transfer between a surface with constant temperature, T_w, and a packet with an initial temperature, T_b

$$\frac{\partial T}{\partial t} = a_e \frac{\partial^2 T}{\partial x^2} \quad \text{for } 0 \leqslant x < \infty. \tag{1}$$

Initial and boundary conditions are as follows

$$T(x,0) = T_b \tag{2}$$

$$-\lambda_e \left(\frac{\partial T}{\partial x}\right)_{x=0} = \frac{1}{R_w}(T_w - T) \tag{3}$$

$$T(\infty, t) = T_b. \tag{4}$$

The mean heat transfer coefficient is given by

$$\alpha = \frac{2(1-f_{0w})}{R_{\lambda w}} \left\{1 - \frac{\pi R_w}{2R_{\lambda w}} \times \left[1 - \exp\left(\frac{R_{\lambda w}}{R_w}\frac{1}{\sqrt{\pi}}\right)^2 \operatorname{erfc}\left(\frac{R_{\lambda w}}{R_w}\frac{1}{\sqrt{\pi}}\right)\right]\right\}. \tag{5}$$

In electrostatically charged fluidized bed, attraction forces between the packets and the layer of particles at the heating surface are strong enough that the exchange of packets occurs as a result of packets being shifted one by another and not by their separation by gas bubbles. Thus, $f_{0w} = 0$. Moreover, taking into account the fact that the transfer surface temperature remains constant during the period of contact with the packet, the complicated expression for the mean coefficient reduces to a simple approximation [16]

$$\alpha = \frac{1}{R_w + 0.5R_{\lambda w}}. \tag{6}$$

Both resistances of the wall surface which determine the heat transfer coefficient are dependent on electrostatic effects. The more susceptible the material for electrification is, the greater number of layers of particles is created at the heating surface. For fluidized beds with small particles, e.g. 0.38 mm polystyrene, where electrostatic effects are strong, two layers of particles were observed. With a bed of more coarse particles, e.g. 0.75 mm polystyrene, 0.71 mm sand, electrostatic forces were diminished and a single layer of particles at the surface was formed.

The resistance of these layers may be considered to be the sum of the resistances of the solid particles in these layers and the resistance of the gas between them

$$R_w = \sum_{i=1}^{n} \left(\frac{l_{gi}}{\lambda_g} + \frac{l_{si}}{\lambda_s} \right). \qquad (7)$$

A simple model is proposed to determine equivalent values of thickness, l_{gi} and l_{si} (Fig. 7). For the single-layer model the original arrangement of particles at the heating surface is shown in Fig. 7(a). The heat transfer mechanism for this model is assumed to be that shown in Fig. 7(b). Equivalent values of l for this case are given

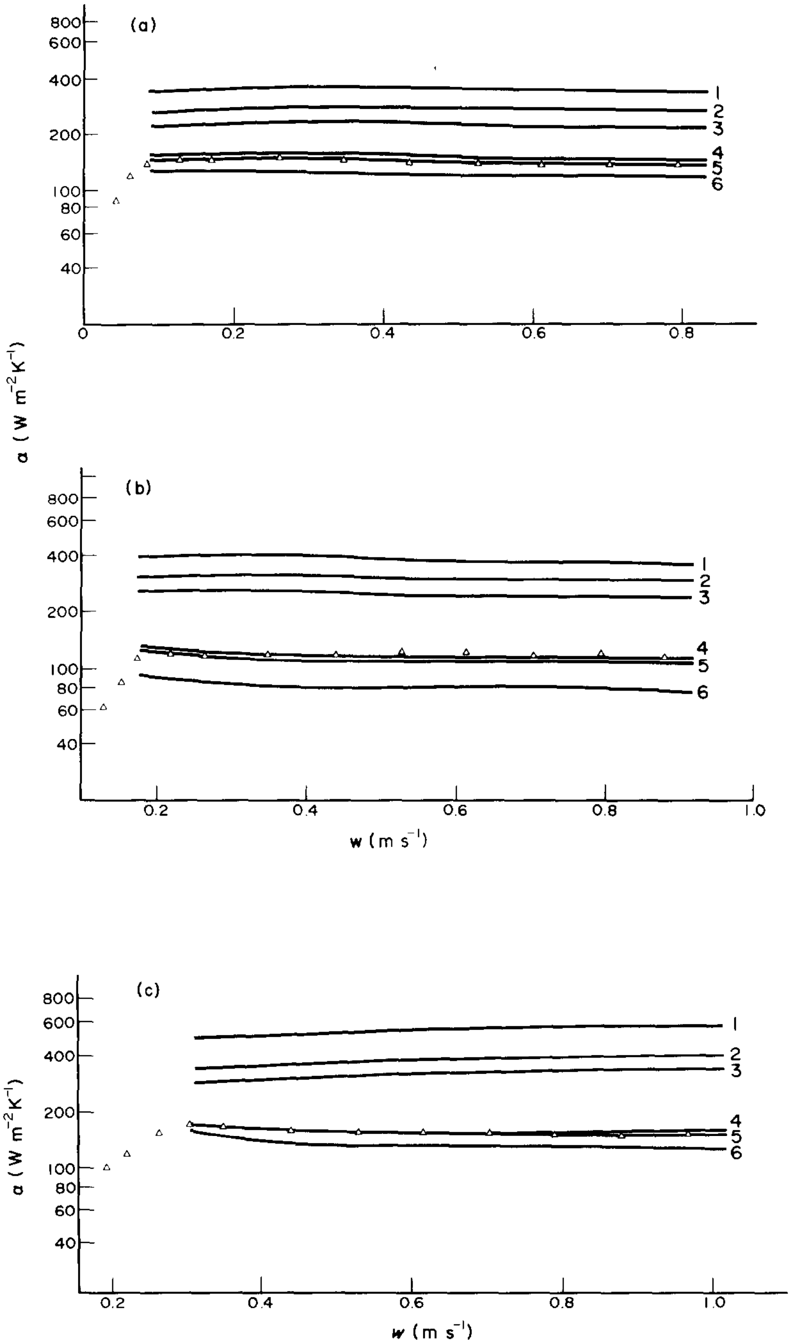

FIG. 6. Heat transfer data for the beds of dielectric particles with the optimum fine admixture compared with predictions from different penetration packet models: (a) the bed of 0.38 mm polystyrene beads with 0.15% ww of the active coal; (b) the bed of 0.75 mm polystyrene beads with 0.1% ww of the active coal; (c) the bed of 0.71 mm sand particles with 0.05% ww of the active coal. △, experimental points; (1) Mickley and coworkers [7, 9], Yoshida *et al.* [10]; (2) Gorelik [11]; (3) Yasutomi and Yokota [12]; (4) Baskakov [13]; (5) Koppel *et al.* [14]; (6) Gelperin *et al.* [15].

by Baskakov [17]

$$l_{g1} = \tfrac{1}{6}d_p \tag{8}$$

and

$$l_{s1} = \tfrac{2}{3}d_p. \tag{9}$$

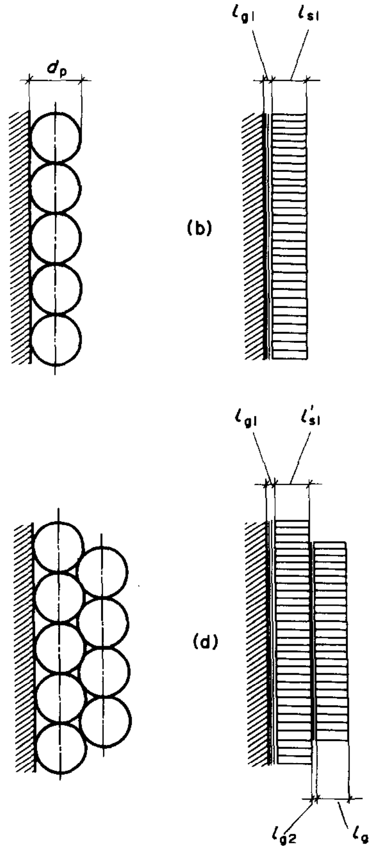

FIG. 7. Flat layer model for the determination of the equivalent thickness values, l_{gi} and l_{si}.

For the double-layer model [Figs. 7(c) and (d)] from Kunii and Smith [8]

$$l_{s1} = \tfrac{2}{3}d_p \tag{10}$$

$$l_{g2} = 0.1d_p. \tag{11}$$

Moreover, it can be seen from Fig. 7 that

$$l_{s2} = l_{s1} = \tfrac{2}{3}d_p. \tag{12}$$

The higher the electrostatic effects, the greater the attraction forces and the longer contact times of the packets with the layer t_w (as the results of oscillograph measurements indicate). They increase the thermal resistance of the packets according to the definition of $R_{\lambda w}$

$$R_{\lambda w} = \left(\frac{\pi t_w}{\lambda_e \rho_e c_{ps}}\right)^{1/2}. \tag{13}$$

t_w can be estimated from oscillograph measurements if bubbling bed conditions are provided, i.e. $w \geqslant 2w_{mf}$. The movement of the particle layer on the heating surface was recorded by an oscillograph during the intermittent passage of gas bubbles, which at the same time shifted packets in contact with the layer. It may be concluded, therefore, that the residence time of packets at the layer coating the heating surface is identical to the time of heating of the layer (recorded by the oscillograph).

COMPARISON BETWEEN HEAT TRANSFER MODELS AND EXPERIMENTAL RESULTS

As can be seen from Fig. 8, the measured heat transfer coefficients (experimental points) are in satisfactory agreement with those calculated from Baskakov's model (curve 1) and the modified model with electrostatic effects taken into account (curve 2). This confirms the hypothesis that an introduction of fine

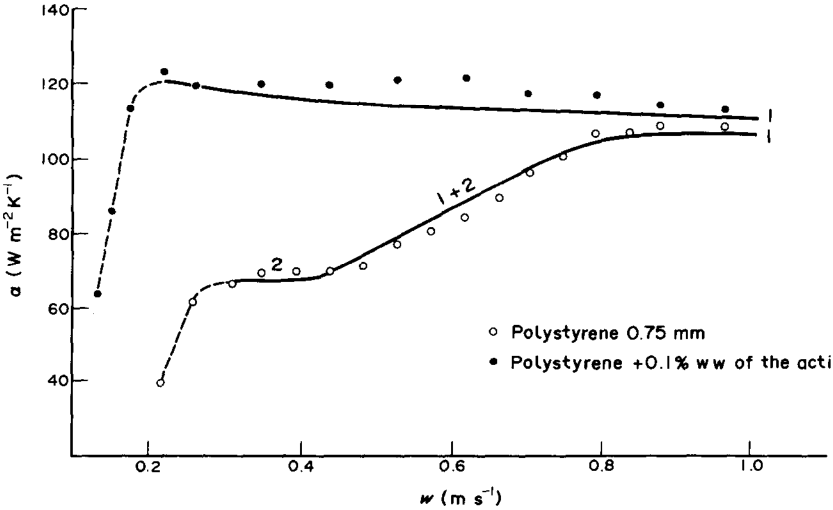

FIG. 8. Comparison between models and experimental results for the bed of polystyrene beads: (1) Baskakov's model; (2) the modified model with electrostatic effects taken into account.

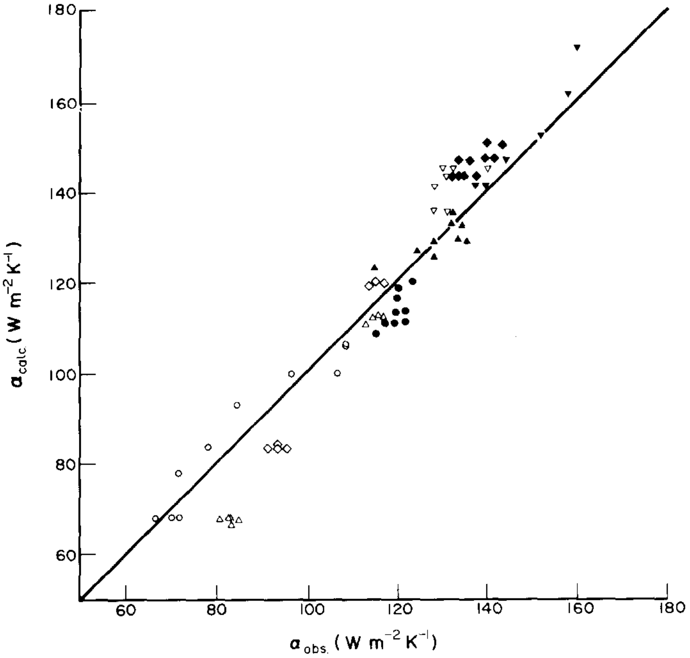

Fig. 9. Comparison between models and experimental results for the following systems: ○, 0.75 mm polystyrene; ●, 0.75 mm polystyrene plus 0.1% ww of the active coal; △, 0.51 mm polystyrene; ▲, 0.51 mm polystyrene plus 0.1% ww of the active coal; ◇, 0.38 mm polystyrene; ◆, 0.38 mm polystyrene plus 0.15% ww of active coal; ▽, 0.71 mm sand; ▼, 0.71 mm sand plus 0.05% ww of the active coal.

material changes the mechanism of heat transfer between the heating surface and the bed.

On the basis of the comparison of experimental and calculated results it can be assumed that different heat transfer mechanisms may be present in the bed of the same dielectric material depending upon the gas fluidization velocity: steady-state in the range of low velocities and unsteady-state in the range of high velocities.

Figure 9 includes data obtained for all the investigated systems.

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WÄRMEÜBERGANG IN EINER ELEKTROSTATISCH AUFGELADENEN WIRBELSCHICHT

Zusammenfassung—Die unerwünschte Auswirkung der Elektrisierung auf den Wärmeübergang zwischen den dielektrischen Partikeln eines Wirbelschichtbettes und einer darin eingetauchten Heizfläche wurde untersucht. Dieser Effekt wurde mit der Änderung der Wärmetransport-Mechanismen erklärt: Instationäre Wärmeleitung (in dem Bett ohne Elektrisierung), stationäre Wärmeleitung in der an die Heizfläche angrenzenden Schicht aus dielektrischen Partikeln (in dem elektrostatisch aufgeladenen Bett). Um den Wärmeübergang zu erhöhen wird vorgeschlagen, eine kleine Menge eines feinen Stoffes zuzugeben, der aus gleichem Material wie die Schüttung in der Wirbelschicht bestehen kann oder auch nicht. Der optimale Wärmeübergangskoeffizient wurde bei der Zugabe von 0,05–0,1% des feinen Stoffes erreicht, wobei sich der Wärmeübergangskoeffizient auf bis zu 300% erhöht hat. Die beobachtete Wirkung solcher Zusatzstoffe kann mit der Verringerung der elektrostatischen Aufladung im Bett erklärt werden.

ТЕПЛОПЕРЕНОС В ЭЛЕКТРОСТАТИЧЕСКИ ЗАРЯЖЕННОМ ПСЕВДООЖИЖЕННОМ СЛОЕ

Аннотация—Исследовано нежелательное влияние электризации на теплоперенос между псевдоожиженным слоем диэлектрических частиц и погруженной в него поверхностью нагрева. Показано, что такое влияние обусловлено изменением механизма теплопереноса от нестационарной теплопроводности (в слое без электризации) к стационарной теплопроводности через (электростатически заряженную) прослойку, образованную диэлектрическими частицами, примыкающими к поверхности нагрева. Предложен метод интенсификации теплопереноса, заключающийся во внесении в слой небольшого количества тонкодисперсного материала, идентичного материалу основного слоя или отличного от него. Было найдено, что оптимальная величина коэффициента теплопереноса достигается при концентрациях мелкодисперсного материала, находящихся в