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# Discontinuity of particle contact with the surface and heat transfer in fluidized beds

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**Abstract**—The finite-element method has been applied to solve the unsteady-state heat transfer equation for solid particles heated at the surface. The results are given as a series of temperature profiles for these systems and are used to estimate the depth of the heat penetration region in the particles and the heat transfer coefficients between a fluidized bed and an immersed heating surface. From calculations it appears that for the typical conditions of bubbling fluidization, i.e. residence times at the heat transfer surface $\tau = 0.1$ s, this region exceeds many times the one found experimentally. This provides theoretical support for the earlier hypothesis that particles in fluidized beds are separated from the heating surface by an air gap. The close agreement between this result and the experimental values requires the assumption of a gap thickness $\delta = 0.1d_p$. Owing to the long contact times of the particles with the heating surface in the electrostatically charged fluidized bed the particle penetration theory of the heat transfer from the surface has been also verified. The heat transfer coefficients derived from this theory agree with the authors' previous experimental work. On the basis of the results obtained some assumptions concerning a generalization of the heat transfer theories have been formulated.

## INTRODUCTION

THE ADVANTAGEOUS heat–mass transfer characteristics are an important property of the wall-to-bed transport processes in gas fluidized beds. This property is closely connected with the region adjacent to the surface of the heat–mass transport elements (wall-surface), which at the same time is the most difficult region of the bed to describe.

Most of the attempts for the improvement of the wall-surface structure description were undertaken in various theoretical models of heat transfer from surface to bed. The packet model developed by Mickley [1, 2] was the first one which explained that the high temperature gradients in the particles heated for a short time at the surface were the reason for the large heat transfer rate. The following models tended towards removing from Mickley's model some of the theoretical shortcomings that result from the assumption of uniform packet properties throughout the volume and taking the packet to be a semi-infinite body. Baskakov [3] has considered dissimilarity of the packet structure at the heating surface introducing a contact resistance. Koppel [4] has introduced contact resistance and finite thickness of the packet. In order to specify mathematical formulation of conditions in the wall-surface, Gorelik [5], Gelperin [6] and Yasutomi [7] have assumed a division of the packet into two regions that differ in respect of their thermal properties. Finally, Yoshida [8, 9] has proposed a general model with two different flow structures. Therefore, the description of the heat transfer from the surface is possible either by the packet structure (for small immersed surfaces) or the layer structure (for high surfaces surrounding the bed).

Independently of a considerable number of models and extensive study of the above question, the hydrodynamic description of the wall-surface is still not closed. The discrepancies between heat transfer coefficients predicted by the particle penetration theory and experimental data gave rise recently to the discussion on the discontinuity of particle contact with the heating surface [10–12]. Moreover, the packet penetration models have also been included in this discussion [13–15]. The numerical verification of this problem is presented in this paper. On the other hand, some information on electrostatic phenomena in fluidized beds has been published recently. In some circumstances the electrostatic forces are strong enough to form a stable layer of particles adhering to the heating surface. As packets come into contact with this layer, the pattern of the two structures (i.e. the layer and packet structures) occurring simultaneously should be taken into consideration—the model of heat transfer in the presence of electrostatic effects [16].

The above structure pattern may also be applied to verify the particle penetration theory of heat transfer for various contact times of bed particles with the layer. The contact times are dependent on static electricity effects. These latter are changing with the nature and dimensions of the bed particles and the fluidization velocity. Therefore it is possible to obtain and compare some experimental and theoretical data on heat transfer coefficients for various contact times.

## NOMENCLATURE

- $c_p$ specific heat [$W\,s\,kg^{-1}\,K^{-1}$]
- $d_p$ particle diameter [m]
- $k$ relative thickness of the zone in the particle with a temperature gradient different from zero
- $R_k$ contact thermal resistance [$m^2\,K\,W^{-1}$]
- $r_p$ particle radius [m]
- $T$ temperature [K]
- $T_0$ temperature of the heating surface [K]
- $T_p$ initial temperature [K]
- $w$ superficial air fluidization velocity [$m\,s^{-1}$]
- $x$ thickness of the zone in the particle with a temperature gradient different from zero [m].

Greek symbols

- $\alpha$ heat transfer coefficient between fluidized bed and surface [$W\,m^{-2}\,K^{-1}$]
- $\delta$ thickness of the gas gap between particle and heating surface [m]
- $\lambda$ thermal conductivity [$W\,m^{-1}\,K^{-1}$]
- $\rho$ density [$kg\,m^{-3}$]
- $\tau$ mean contact time of particles with the heating surface [s].

Subscripts

- g gas phase
- s solid phase
- mf minimum fluidization conditions.

## FORMULATION OF THE DISCONTINUITY PROBLEM AND METHOD OF SOLUTION

The discontinuity of the contact between the surface and the particles of a bed may be found if the evidence is given that the real, experimental heat transfer resistance will be greater than the theoretically calculated one for the particle in direct contact with the surface. For the following considerations, the concept of the heat transfer resistance should be introduced. Therefore, Baskakov's contact resistance which is informally defined and depends on contact time of packets with the surface may be applied:

$$R_k = \frac{d_p}{\pi\lambda_g[\ln(\lambda_s/k\lambda_g) - 1]} \tag{1}$$

where $k$, which depends on time, is the relative thickness of the zone in particles with a temperature gradient different from zero, and

$$k = \frac{x}{r_p}. \tag{2}$$

There are two ways to determine the value of $k$. The first is the experimental way [3]; the second is the numerical solution of the transient heat conduction equation. The solution gives the distributions of the temperature in a particle heated at the surface during any contact time. It results in the thickness of the zone in the particle with a temperature gradient different from zero, which determines the value of $k$.

The appropriate cylindrical form of the Laplace equation for the thermal conduction within the gas and solid phase as shown in Fig. 1 is:

$$\rho c_p \frac{\partial T}{\partial \tau} = \lambda\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right) \tag{3}$$

where

$\rho = \rho_s$, $c_p = c_{ps}$ and $\lambda = \lambda_s$ for solid phase

and

$\rho = \rho_g$, $c_p = c_{pg}$ and $\lambda = \lambda_g$ for gas phase.

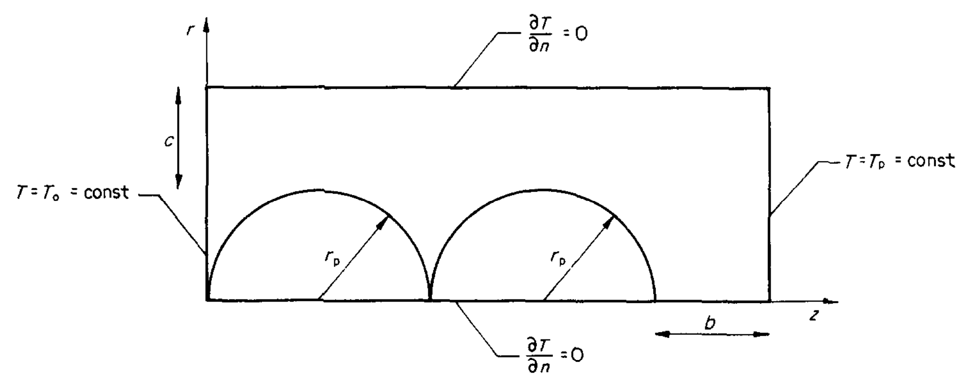


FIG. 1. Particle array for numerical calculations.

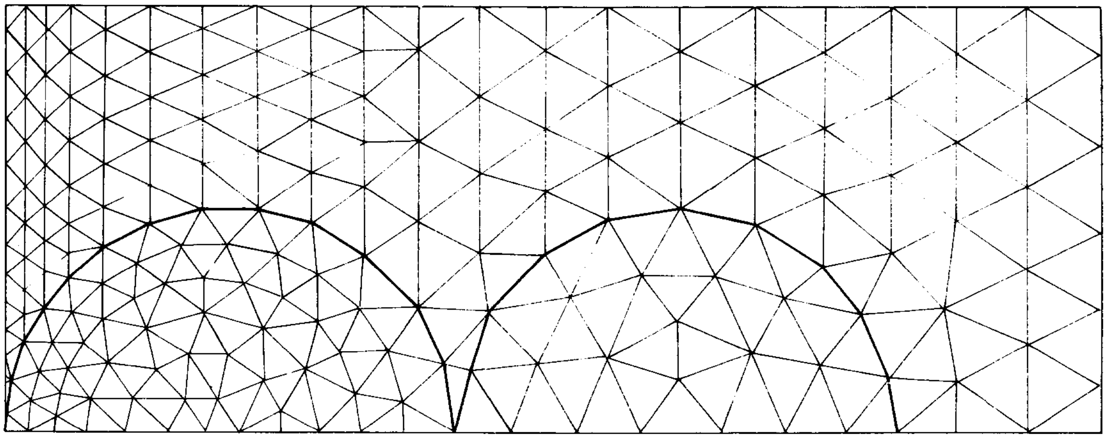

FIG. 2. Grid diagram for particles in air contacting the heating surface.

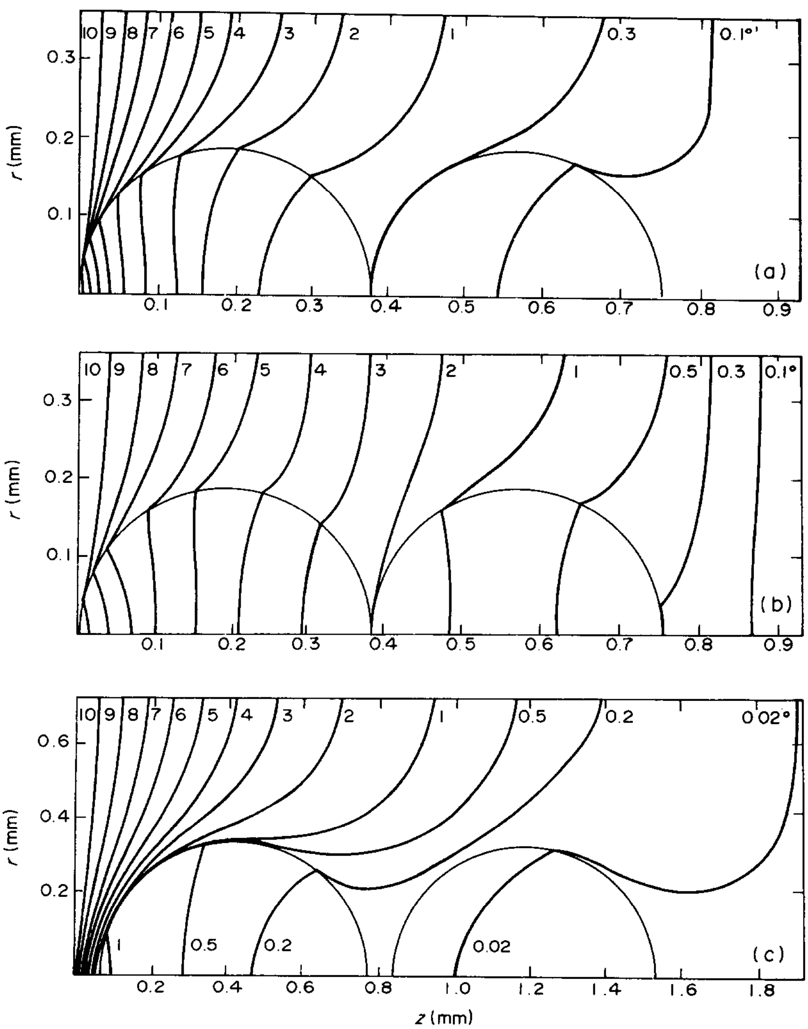


FIG. 3. Isotherms for particles in static air at heating surface. (a) Polystyrene beads 0.38 mm; residence time 0.1 s. (b) Polystyrene beads 0.38 mm; residence time 0.3 s. (c) Sand particles 0.71 mm; $\delta = 0.1d_p$; residence time 0.1 s.

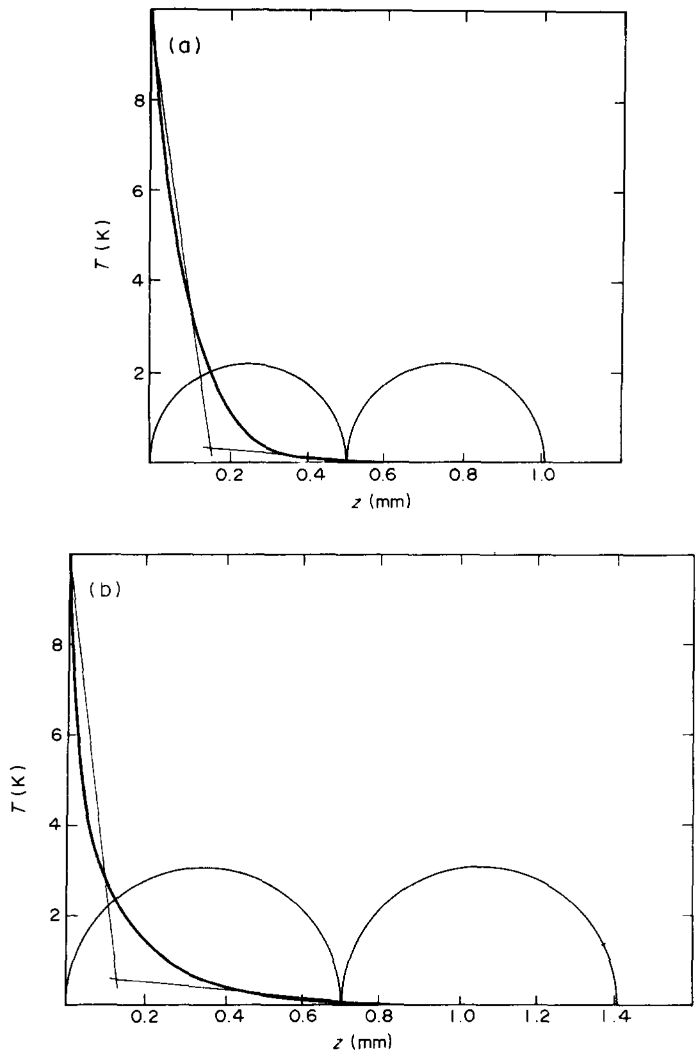


FIG. 4. Temperature distributions for particles directly contacting the heat transfer surface (0.1 s residence time). (a) Polystyrene beads 0.51 mm; $k = 0.6$. (b) Sand particles 0.71 mm; $k = 0.4$.

The equations of the boundary conditions are:

$$r = 0 \quad z \in (0, 4r_p + b) \quad \partial T/\partial r = 0 \tag{4a}$$

$$z = 0 \quad r \in (0, r_p + c) \quad T = T_0 = 10.0 \tag{4b}$$

$$r = r_p + c \quad z \in (0, 4r_p + b) \quad \partial T/\partial r = 0 \tag{4c}$$

$$z = 4r_p + b \quad r \in (0, r_p + c) \quad T = T_p = 0.0 \tag{4d}$$

$$T(r, z) = T_0(r, z) = 0.0. \tag{4e}$$

Equation (3) with the boundary conditions (4) was solved numerically by the method of finite elements [17–22]. The region of temperature variability was divided into triangle elements for which linear shape functions were used. The division of this region into the elements is shown in Fig. 2.

## RESULTS AND DISCUSSION

Figure 3 presents some exemplary isotherms for particles of various materials and time contacts with the heating surface. Temperatures of the nodal points lying on the $z$ axis were taken to obtain the one-dimensional temperature distributions. These distributions were approximated by two straight lines and their intersection point gave the value of $k$. The temperature distributions were obtained for various residence times from 0.1 s up to those at which the steady-state heat transfer conditions appeared: Figs. 4–7 and Table 1.

The postulated discontinuity of contact finds expression in the discrepancy of the calculated results with the reported data. The latter, as was mentioned above, can be obtained from Baskakov [3] who—for typical conditions of fluidization, i.e. the mean contact time with the heating surface $\tau = 0.1$ s—found $k = 0.1$. From Table 1 it is evident that this real*

* The validity of Baskakov's heat transfer model [3] for different systems studied by the authors [16] and others is the evidence of the correctness of the experimental value of $k$.

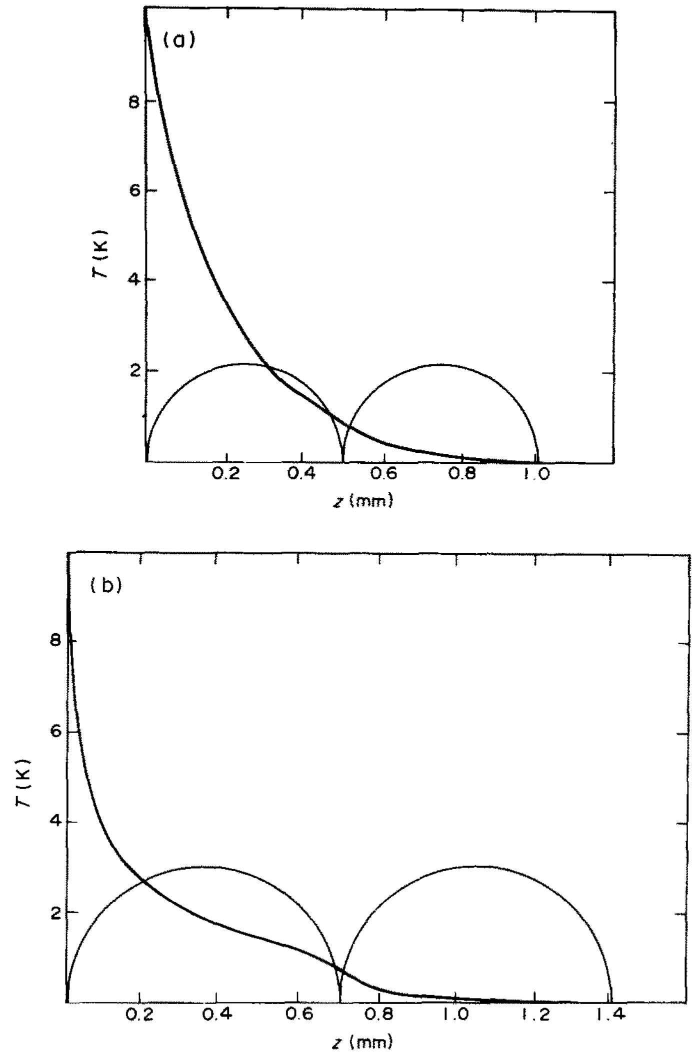


FIG. 5. Temperature distributions for particles directly contacting the heat transfer surface (0.3 s residence time). (a) Polystyrene beads 0.51 mm; $k = 1.0$. (b) Sand particles 0.71 mm; $k = 1.0$.

experimental value of $k$ has been greatly exceeded by the calculated one. This discrepancy is too high to be explained by inaccuracy of the numerical solution. It must rather be connected with the wrong formulation of the problem which does not take into account the element that considerably effects $k$. From the overstated calculated values of $k$ the conclusion may be drawn that an additional heat transfer resistance between surface and particles has been neglected. It seems that this thermal resistance is due to an insulating gas gap at the heating surface. Assuming that the thickness of this gap is $\delta = 0.1 d_p$ one obtains $k = 0.1$ and the agreement between the calculated values of wall-to-bed heat transfer resistance and the experimental ones.

Validity of the model presented here concerns the bubbling fluidized bed only, i.e. at $w \geqslant 2w_{mf}$. At low fluidization velocities the existence of the gas gap is not possible.

## HEAT TRANSFER CALCULATIONS

Figures 8–10 illustrate some selected isotherm diagrams showing the variation in the temperature of the sphere with residence time for polystyrene beads and sand particles.† Heat transfer coefficients were calculated by multiplying the heat fluxes (taken directly from the isotherm diagrams) by the number of particles in contact with unit area of the heat transfer and modifying the values for unit initial temperature difference. In the above calculations a triangular pitch packing of particles and initial temperature difference between the surface and sphere of 10°C were assumed.

As noted earlier the residence times are dependent on the electrostatic effects which are occurring to a high

† All the experimental data mentioned in this part of the paper, i.e. materials of bed particles, contact times, layer resistances and measured values of heat transfer coefficients have been reported in the authors' previous paper [16].

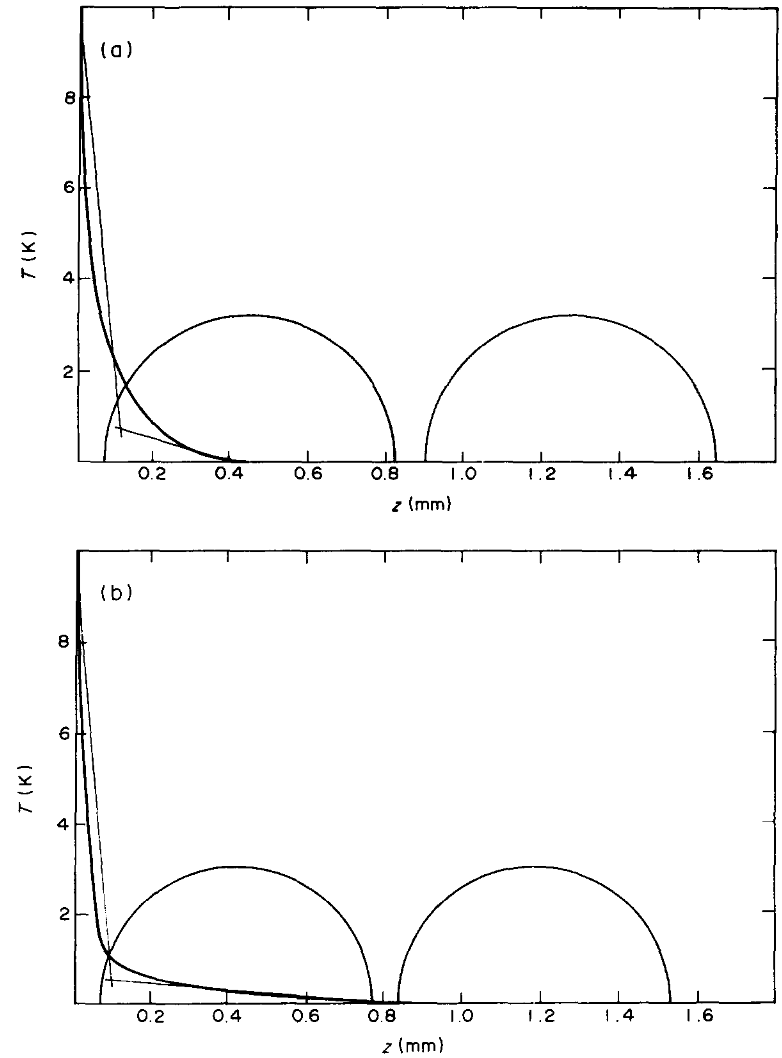


Fig. 6. Temperature distributions for particles removed from the heat transfer surface ($\delta = 0.1d_p$; residence time 0.1 s). (a) Polystyrene beads 0.75 mm; $k = 0.1$. (b) Sand particles 0.71 mm; $k = 0.07$.

degree in the beds of pure dielectric particles. At the heating surface of such beds a stable layer of particles is formed (due to surface–particle attractions). The residence times of the bed particles which are coming into contact with the layer are longer than the times normally encountered (particle–particle attractions) and include the range 0.2–1.5 s. Owing to the existence of the layer, the manner of the heat transfer calculations should be corrected. The instantaneous resistance of heat transfer from the surface to a fluidized bed will be, therefore, the sum of the layer resistance and the instantaneous thermal resistance of the particles for a given residence time. This is justifiable since resistance of the layer is independent of time and both the above thermal resistances are connected in series.

Table 1. Values of $k$ for different contact times and particle materials

| Material | Mean particle diameter (mm) | $\delta = 0$ | | $\delta = 0.1d_p$ |
|---|---|---|---|---|
| | | $\tau = 0.3$ s $w \simeq w_{mf}$ | $\tau = 0.1$ s $w \geqslant 2w_{mf}$ | $\tau = 0.1$ s $w \geqslant 2w_{mf}$ |
| Polystyrene | 0.38 | 1.0 | 0.7 | — |
| | 0.51 | 1.0 | 0.6 | — |
| | 0.75 | 0.7 | 0.4 | 0.1 |
| Sand | 0.71 | 1.0 | 0.4 | 0.07 |

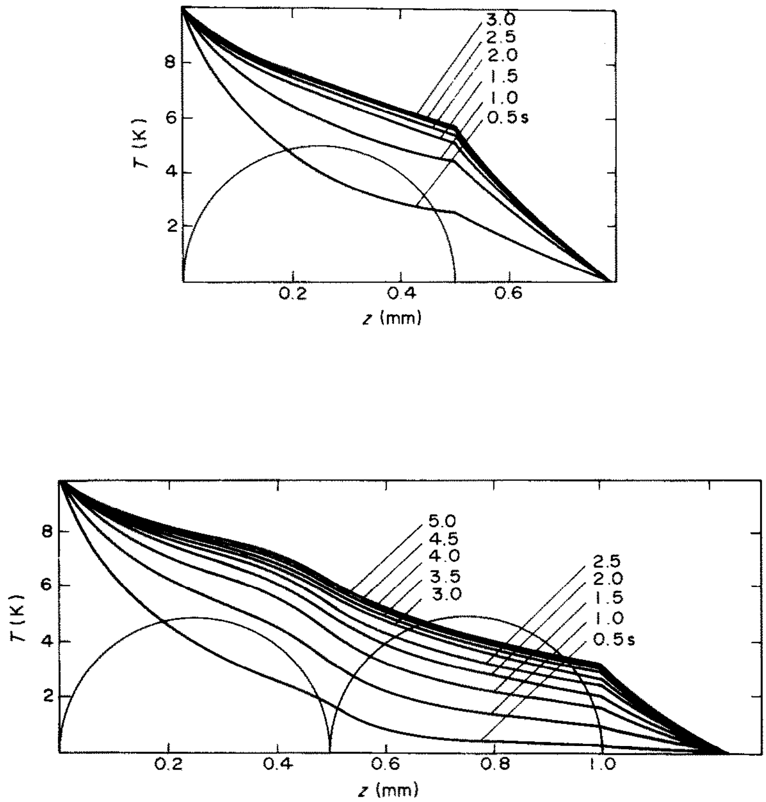


FIG. 7. Temperature distributions in polystyrene beads for various residence times at the heating surface.

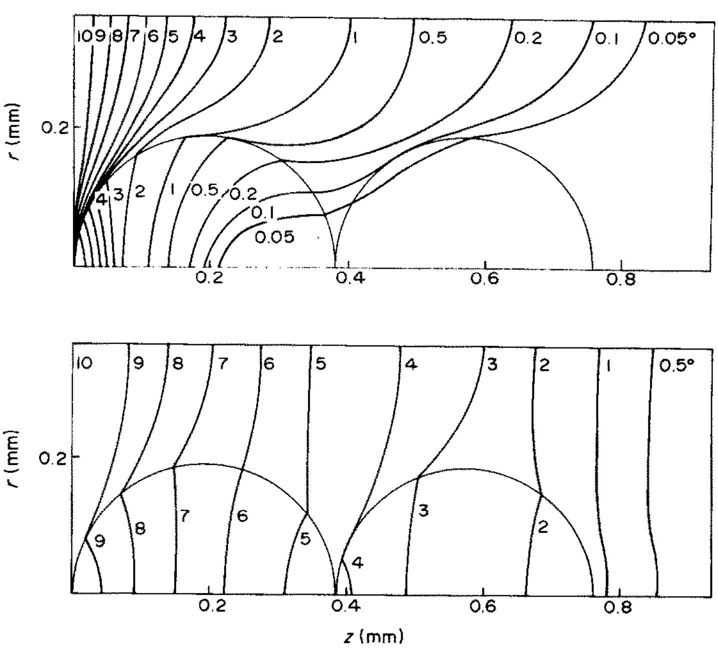


FIG. 8. Isotherms for 0.38-mm polystyrene beads in static air contacting the heat transfer surface (residence times: 0.03 and 1.0 s).

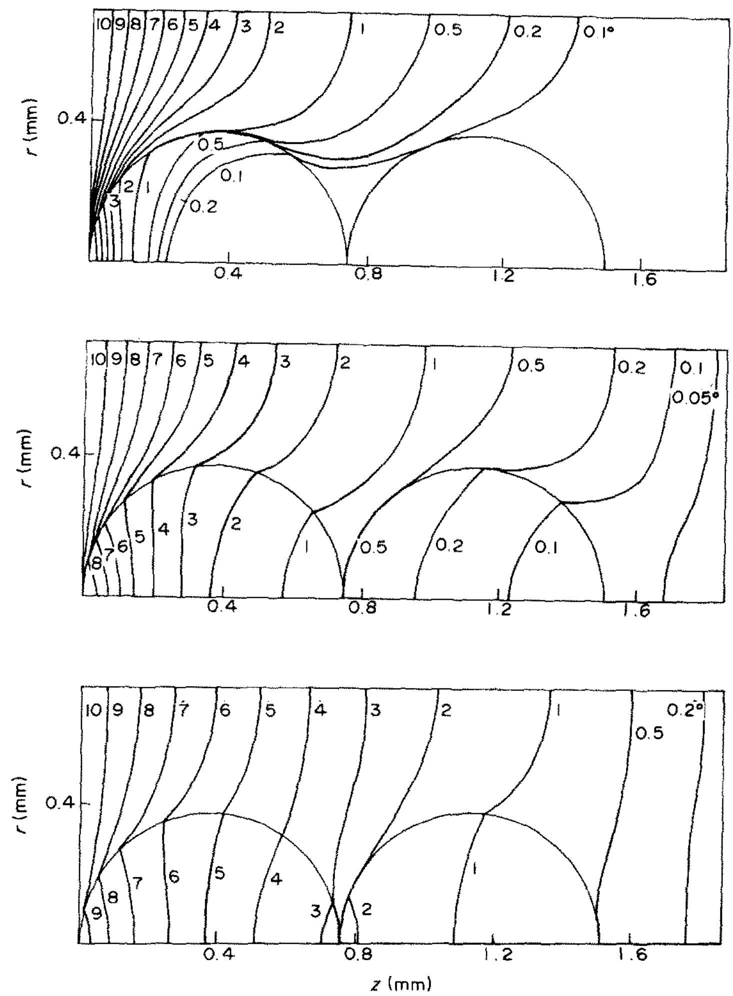


FIG. 9. Isotherms for 0.75-mm polystyrene beads in static air contacting the heat transfer surface (residence times: 0.045, 0.5 and 1.5 s).

The average heat transfer coefficients for double particles during a given residence time have been calculated by integration of the instantaneous values of the heat transfer coefficients between the limits of the residence period and averaging over that period. In Fig. 11 these theoretical predictions (the solid lines) are compared with the experimental data obtained earlier. As can be seen the measured heat transfer coefficients (experimental points) are generally lower than predicted by the model. As would be expected the reasons of the discrepancy may be both particle residence times that are longer than actually measured and a reduction in heat removal capacity by bubbles, which are not taken into account in the calculations.

## CONCLUSIONS

The work described here is a new contribution towards a generalization of the theories of heat transfer from the surface to a fluidized bed. Results are given which enable some general assumptions concerning the wall-surface structure to be formulated at which the data obtained from both the particle penetration and the packet model agree with the experimental data. These assumptions are as follows:

(1) For longer contact times ($\tau \geq 0.2$ s) the direct contact of particles/packets with the heating surface should be assumed. Thus, the rate of heat transfer from the surface is controlled only by unsteady-state conduction resistance in particle–particle theory, or in packet–packet theory. When a more complicated structure of the wall-surface is encountered, e.g. the layer of particles adhering to the heating surface in the presence of electrostatic effects, the additional steady-state resistance of the layer should be taken into account. With the assumptions formulated above, both theories are in good agreement with the same experimental data: for packet theory agreement has been shown earlier [16]; for the particle one it is presented here. Therefore it may be considered as support for the thesis concerning the agreement of both theories with one another.

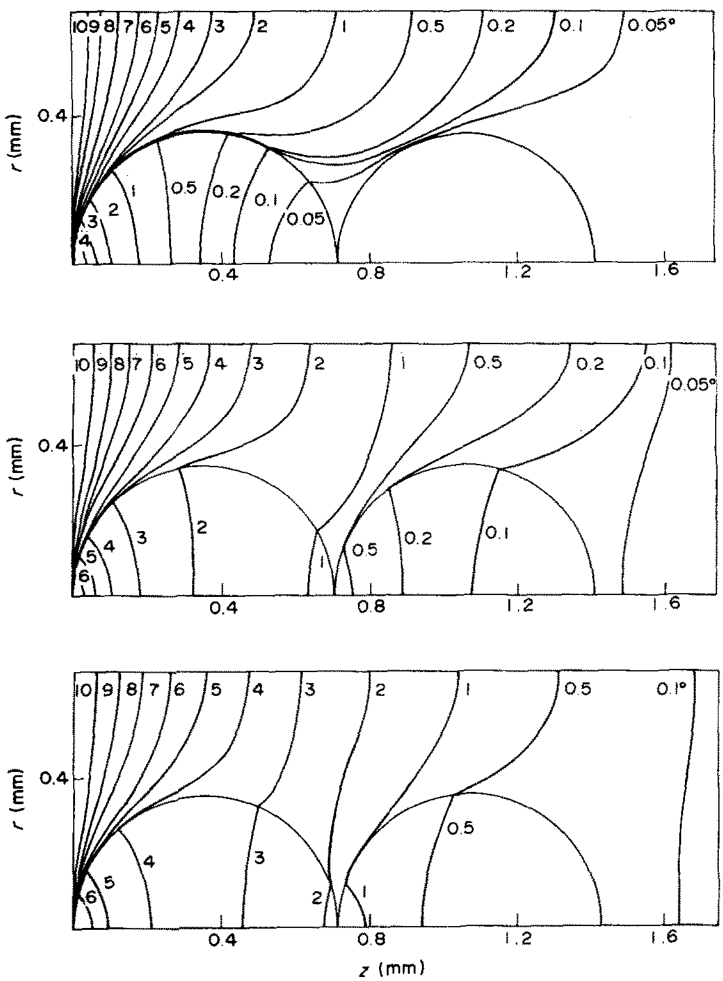


FIG. 10. Isotherms for 0.71-mm sand particles in static air contacting the heat transfer surface (residence times: 0.05, 0.3 and 0.6 s).

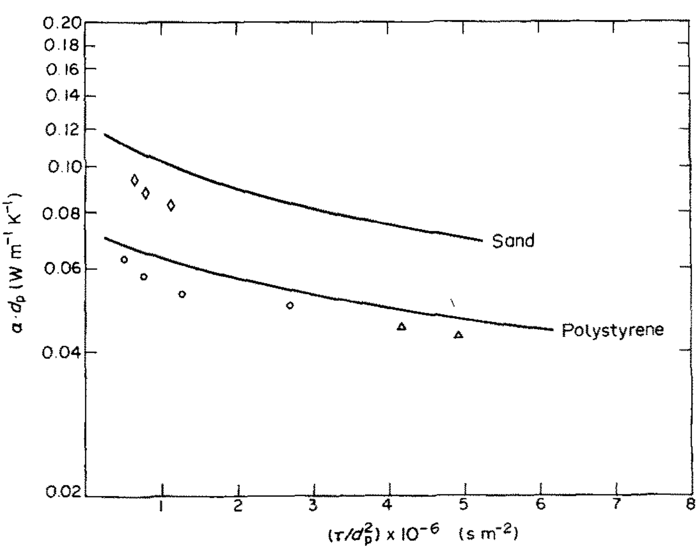


FIG. 11. Comparison of the experimental data [16] with theoretical predictions for the following systems: △, 0.38 mm polystyrene; ○, 0.75 mm polystyrene; ◇, 0.71 mm sand.

(2) For short contact times ($\tau = 0.1$ s) allowance should be made for the gas gap between the particles/packets and the exchange surface. The use of the $0.1d_p$ for the thickness of the gas gap gives the value of $k = 0.1$ in Baskakov's contact resistance, which provides the best agreement of the packet theory with reported data [3, 4, 16]. The gas gap should also be considered to be valid as far as the agreement between the particle theory and data is concerned. The thickness of the gap suggested by some authors [10, 12] is an identical one to the value of $0.1d_p$ proposed here.

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## DISCONTINUITE DU CONTACT ENTRE PARTICULE ET SURFACE, ET TRANSFERT THERMIQUE DANS LES LITS FLUIDISES


**Résumé**—La méthode des éléments finis est appliquée à la résolution de l'équation de transfert thermique variable pour des particules solides chauffées sur la surface. Les résultats sont donnés, sous forme d'une série de profils de température, et ils sont utilisés pour estimer la profondeur de pénétration dans les particules et les coefficients de transfert thermique entre un lit fluidisé et une surface chaude immergée. Les calculs montrent que pour les conditions typiques de fluidisation avec bullage, pour des temps de résidence à la surface $\tau = 0{,}1$ s, cette région dépasse plusieurs fois celle trouvée expérimentalement. Ceci fournit un support pour l'hypothèse des particules dans le lit fluidisé séparées de la surface chaude par une couche d'air. Le bon accord entre ces résultats et les valeurs expérimentales nécessite une épaisseur $\delta = 0{,}1d_p$. Etant donné les grands temps de contact des particules avec la surface chaude dans un lit fluidisé chargé électrostatiquement, la théorie de la pénétration de la particule est aussi vérifiée. Les coefficients de transfert thermique dérivés de cette théorie s'accordent avec un travail expérimental fait antérieurement par l'auteur. Sur la base des résultats obtenus, on formule quelques hypothèses concernant une généralisation des théories de transfert de chaleur.

## UNSTETIGKEIT DES KONTAKTES ZWISCHEN PARTIKEL UND OBERFLÄCHE—WÄRMEÜBERTRAGUNG IN WIRBELBETTEN

**Zusammenfassung**—Das Finite-Elemente-Verfahren wurde zur Lösung der instationären Wärmeübertragungsgleichung für Feststoffpartikel, die an einer Oberfläche erhitzt werden, angewandt. Die Ergebnisse werden als Reihe von Temperaturprofilen für diese Systeme dargestellt. Sie dienen zur Abschätzung der Wärmeeindringtiefe in den Partikeln und des Wärmeübergangs-Koeffizienten zwischen einem Wirbelbett und einer darin eingetauchten Heizfläche. Berechnungen lassen vermuten, daß für die typischen Bedingungen bei der Verwirbelung die Verweilzeiten auf der Wärmeübertragungsfläche $\tau = 0,1$ s sind, dieser Bereich überschreitet den experimentell ermittelten um ein Vielfaches. Dies unterstützt theoretisch eine frühere Hypothese, wonach Partikel in Wirbelbetten von der Heizfläche durch eine Luftschicht getrennt sind. Die enge Übereinstimmung zwischen diesem Ergebnis und den experimentellen Werten legt eine Schichtdicke von $\delta = 0,1d_p$ nahe. Durch die langen Verweilzeiten der Partikel auf der Heizfläche im elektrostatisch aufgeladenen Wirbelbett wurde die Partikel-Eindring-Theorie der Wärmeübertragung an der Oberfläche ebenfalls erhärtet. Die von dieser Theorie abgeleiteten Wärmeübergangs-Koeffizienten stimmen mit der früheren experimentellen Arbeit des Autors überein. Aufgrund der ermittelten Ergebnisse wurden einige Annahmen für eine Verallgemeinerung der Wärmeübertragungs-Theorien formuliert.

## РАЗРЫВНОЙ ХАРАКТЕР КОНТАКТА ЧАСТИЦЫ С ПОВЕРХНОСТЬЮ И ТЕПЛОПЕРЕНОС В ПСЕВДООЖИЖЕННЫХ СЛОЯХ

**Аннотация**—Методом конечных элементов получено решение уравнения нестационарного теплообмена твердых частиц, нагреваемых на поверхности. Результаты представлены в виде ряда температурных профилей, с помощью которых рассчитана глубина области проникновения тепла в частицы и коэффициенты теплопереноса между псевдоожиженным слоем и погруженной поверхностью нагрева. Рассчеты показывают, что для типичных условий пузырькового псевдоожижения, т.е. когда время пребывания частиц у поверхности нагрева $\tau = 0,1$ с размер указанной области во много раз превышает экспериментально полученное значение. Тем самым теоретически подтверждается выдвинутая ранее гипотеза, что в псевдоожиженных слоях частицы отделены от поверхности нагрева прослойкой воздуха. В предположении, что толщина прослойки составляет $\delta = 0,1d_p$, теоретические и экспериментальные результаты совпадают. Большие времена контакта частиц с поверхностью нагрева в электростатически заряженном псевдоожиженном слое также дали возможность проверить справедливость теории проникновения тепла в частицы. Рассчитанные по этой теории коэффициенты теплопереноса согласуются с экспериментальными значениями, полученными авторами ранее.