Int. J. Heat Mass Transfer. Vol. 31, No. 5, pp. 969–975, 1988
Printed in Great Britain

0017-9310/88 \$3.00+0.00
© 1988 Pergamon Press plc

A theoretical analysis of heat transfer due to particle impact

J. SUN and M. M. CHEN

Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, 1206 West Green Street, Urbana, IL 61801, U.S.A.

(*Received* 23 *April* 1987 *and in final form* 22 *September* 1987)

Abstract—The heat exchange between impacting spherical particles or a particle and a surface is analyzed. The purpose of the study is to obtain a quantitative understanding of the direct conductive contribution of heat transfer between particles and surfaces in suspension flows and fluidized beds. The mechanism under investigation is the conduction through the time varying contact area during impact. It is shown that the impact Fourier number based on the maximum contact area radius and the contact duration is inversely proportional to the particle Peclet number and independent of mechanical properties. For small Fourier numbers, an analytical solution is presented. For large Fourier numbers, the solution is obtained numerically and presented in terms of a correction factor which is used with the analytical results.

1. INTRODUCTION

WHEN MOVING particles impact on a stationary surface or two particles impact each other, heat conduction occurs through the contact area of the particles. This effect constitutes one of the components of heat transfer in multiphase flows.

In attempts to formulate models for overall heat transfer in multiphase flow systems, many authors have discussed this conduction effect. Usually it is believed that its contribution is very small due to the small contact area and short impact duration [1, 2]. However, a recent model [3] states that the conduction effect will become predominant as particles become small, though the analysis invoked heuristic mechanisms which are less amenable to precise analysis. The purpose of this paper is to provide quantitative calculations of the heat transfer due to particle impact so its role in multiphase heat transfer can be properly evaluated.

The study of this problem was pioneered by Soo in 1967 [4]. He used the theory of elasticity to evaluate the area and duration of contact between the particles. However, he carried out only a semi-quantitative analysis. In choosing to use the particle diameter as the scale for conduction, the analysis may also have underestimated the heat exchange when $(\alpha t)^{1/2}$ is small relative to d.

The present analysis can be considered a quantitative evaluation of the basic concepts put forth originally by Soo [4], employing both numerical and analytical solutions of the heat conduction equation with time-dependent boundary conditions. Results can be used for particles of various materials with different impact velocities.

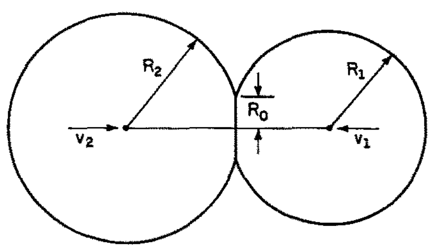

FIG. 1. Impact and deformation of two spherical particles.

2. ELASTIC COLLISION OF TWO SPHERES

When impact stresses of particles are below the yield limits of the materials, the impact can be considered elastic. The solution of elastic collision of two spheres was given by Hertz and Rayleigh [5]. When spheres of radii R_1 and R_2, elastic moduli E_1 and E_2, Poisson ratios ν_1 and ν_2, masses m_1 and m_2, impact with a normal relative velocity v as shown in Fig. 1, the boundary of the contact area A is a circle. The rate of the area change for the compression process is [5]

$$\frac{dA}{dt} = \left[(\pi v R)^2 - \frac{4}{5\sqrt{\pi}}\frac{E}{m}A^{5/2}\right]^{1/2} \quad (1)$$

where

$$R = \frac{R_1 R_2}{R_1 + R_2} \quad (2)$$

$$E = \frac{4/3}{\dfrac{1-\nu_1^2}{E_1} + \dfrac{1-\nu_2^2}{E_2}} \quad (3)$$

NOMENCLATURE

A	contact area
A_c	maximum contact area
A^*	non-dimensional area, A/A_c
C	correction factor
e	total heat transferred during each impact
E	equivalent elastic modulus
e_0	asymptotic one-dimensional heat transferred during each impact
E_1, E_2	elastic moduli
h_c	heat transfer coefficient due to particle impact based on entire surface area
k_1, k_2	thermal conductivities
m	equivalent mass
m_1, m_2	masses of particles
N	particle number density
$\dot{n}$	number flux of particles
q_w	heat flux across contact area
r	radial coordinate
R	equivalent radius
r_c	maximum contact radius
R_t	contact radius at time t
R_1, R_2	particle radii
t	time
t_c	contact duration
t_{lc}	local contact duration
T_1, T_2	temperatures
T_{01}, T_{02}	initial temperatures
v	normal impact velocity
z	longitudinal coordinate with the origin at the center of the contact area.

Greek symbols

α_1, α_2	thermal diffusivities
ν_1, ν_2	Poisson ratios
ρ_1, ρ_2	densities
τ	non-dimensional time
ϕ	volume fraction of particles.

and

$$m = \frac{m_1 m_2}{m_1 + m_2}. \tag{4}$$

The decompression process is exactly the inverse of the compression process. The maximum contact area A_c and its radius r_c are found by setting the derivative to zero

$$A_c \equiv \pi r_c^2 = \pi \left(\frac{5mR^2}{4E}\right)^{2/5} v^{4/5}. \tag{5}$$

The dependence of contact area A as a function of time can best be seen with the following dimensionless variables:

$$A^* \equiv \frac{A}{A_c} \equiv \frac{r^2}{r_c^2} \tag{6}$$

$$\tau \equiv \left(\frac{4E}{5m}\right)^{2/5} (Rv)^{1/5} t \tag{7}$$

where r and r_c are radii of A and A_c, respectively. Equation (1) can then be integrated for the compression phase to yield

$$\tau = \int_0^{A^*} \frac{\mathrm{d}x}{(1 - x^{5/2})^{1/2}}. \tag{8}$$

This is shown as the solid line in Fig. 2, with $\tau = 1.47$ at $A^* = 1$. Since the disengagement phase is identical to the compression phase, it follows a path symmetrical to the compression phase around $\tau = 1.47$, shown as the dashed line in Fig. 2. The total contact duration is then found to be

$$t_c = 2.94 \left(\frac{5m}{4E}\right)^{2/5} (Rv)^{-1/5}. \tag{9}$$

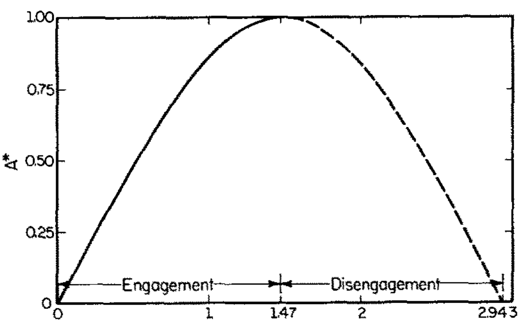

FIG. 2. Change of contact area with time.

Note that the maximum contact area increases with v whereas the impact duration decreases with v. When the impact velocity is zero, the contact area becomes zero but the impact duration tends to infinity.

3. HEAT TRANSFER ANALYSIS

3.1. *Formulation*

The elastic theory requires that the deformations of the spheres are small. For elastic impact of solid spheres, the contact area A_c is usually very small compared with the cross-sections of the spheres which implies that the curvatures of the surfaces adjacent to the contact area are very small relative to the contact area radius. The time duration of the impact is also very short. Therefore, the temperature change of the particles is confined in a small region around the contact area. The heat conduction between the two particles can then be treated as two semi-infinite media. Within the contact area, perfect thermal contact is

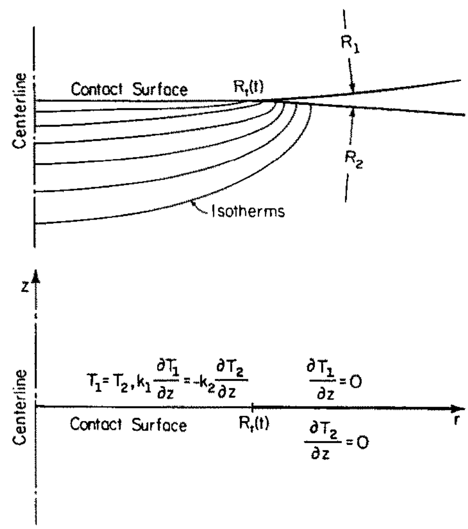

FIG. 3. Top: expected geometry and isotherms during impact. Note that the included angle of the air gap has been exaggerated. Bottom: assumed model based on flat, plane boundaries and associated boundary conditions.

assumed, that is, there is no thermal resistance between the contact surfaces. Therefore, the temperature and heat flux are continued across the contact area. The surfaces outside the contact area are assumed to be flat and insulated. With these assumptions as illustrated in Fig. 3, the problem is governed by two axisymmetric heat conduction equations with appropriate boundary and initial conditions

$$\frac{1}{\alpha_i}\frac{\partial T_i}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_i}{\partial r}\right) + \frac{\partial^2 T_i}{\partial z^2}; \quad i = 1,2 \qquad (10)$$

$$\left.\begin{array}{ll} T_1 = T_2, \quad k_1\dfrac{\partial T_1}{\partial z} = -k_2\dfrac{\partial T_2}{\partial z} & \text{for } r \leqslant R_t(t) \\ \dfrac{\partial T_1}{\partial z} = \dfrac{\partial T_2}{\partial z} = 0 & \text{for } r > R_t(t) \end{array}\right\}$$

$$\text{at } z = 0 \qquad (11)$$

$$T_1 = T_{01} \quad \text{as } z \to \infty \qquad (12)$$

$$T_2 = T_{02} \quad \text{as } z \to -\infty \qquad (13)$$

$$T_1 = T_{01} \text{ and } T_2 = T_{02} \quad \text{as } r \to \infty \qquad (14)$$

$$\frac{\partial T_1}{\partial r} = \frac{\partial T_2}{\partial r} = 0 \quad \text{at } r = 0 \qquad (15)$$

$$T_1 = T_{01} \text{ and } T_2 = T_{02} \quad \text{at } t = 0 \qquad (16)$$

where z is in the direction perpendicular to the contact area; k_1 and k_2, α_1 and α_2 are the thermal conductivities and diffusivities of the two media, respectively; $R_t(t)$ is the radius of the contact area at time t; T_{01} and T_{02} are the initial temperatures of the two media.

There is no general analytical solution for this problem, so a numerical approach has to be invoked. The numerical solution will be given later.

3.2. *Asymptotic result for small Fourier numbers*

First a simple asymptotic case is considered. When the contact duration t_c is very small, the heat conduction in the two media will not penetrate too deeply from the surfaces. This suggests that one-dimensional heat transfer between the two media may be a good approximation for this situation. This case can be characterized when the Fourier numbers, based on the total impact duration t_c and the maximum contact radius r_c, $\alpha_1 t_c/r_c^2$ and $\alpha_2 t_c/r_c^2$ are very small compared to unity (numerical computation will show that only one small Fourier number is sufficient). In this situation, the governing equation is simplified as

$$\frac{1}{\alpha_i}\frac{\partial T_i}{\partial t} = \frac{\partial^2 T_i}{\partial z^2}; \quad i = 1,2 \qquad (17)$$

with boundary and initial conditions (11)–(13) and (16).

For constant properties, the solution of equation (17) with the matched temperature and heat flux conditions at the interface leads to a constant interface temperature with the well-known error function solution [7] on each side. The value of the interface temperature can be determined algebraically by requiring the error function solution to satisfy the continuous temperature and heat flux conditions. This results in the interface heat flux

$$q_w = \frac{(T_{02}-T_{01})(\pi t)^{-1/2}}{(\rho_1 c_1 k_1)^{-1/2}+(\rho_2 c_2 k_2)^{-1/2}} \qquad (18)$$

where ρ_1 and ρ_2, c_1 and c_2 are the densities, specific heats of media 1 and 2, respectively. Here t is measured from the moment of initial contact, which is a function of r. The total energy exchange per unit contact area is thus a function of the local duration of contact, which is also a function of r. Hence the total energy exchange per impact is

$$e = 2\pi \int_0^{r_c}\int_0^{t_{lc}(r)} q_w \,\mathrm{d}t\, r\,\mathrm{d}r \qquad (19)$$

where the local contact duration $t_{lc}(r)$ can be computed from

$$t_{lc}(r) = t_c - 2t(r) \qquad (20)$$

with $t(r)$ determined from equations (6)–(8) or Fig. 2. Integration (19) is readily performed numerically, it gives

$$e_0 = \frac{0.87(T_{02}-T_{01})A_c t_c^{1/2}}{(\rho_1 c_1 k_1)^{-1/2}+(\rho_2 c_2 k_2)^{-1/2}} \qquad (21)$$

where subscript 0 for e indicates that it is for Fourier numbers approaching 0.

3.3. *Numerical results for the general case*

The above solution of the total heat exchange is derived from the heat conduction only in the direction of z. When heat conduction in the r-direction is included, we would expect that more heat will be transferred between the media. To account for this, a

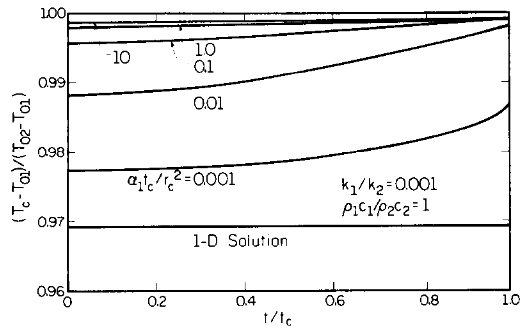

FIG. 4(a). Variations of temperature at the center of the contact area with time.

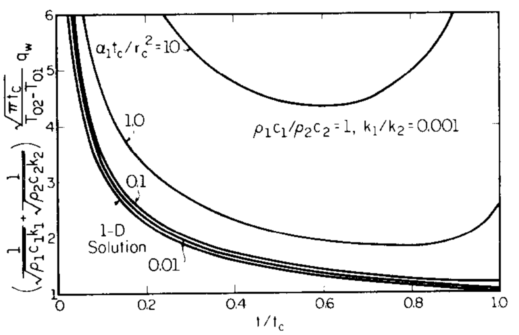

FIG. 4(b). Variations of heat flux at the center of the contact area with time.

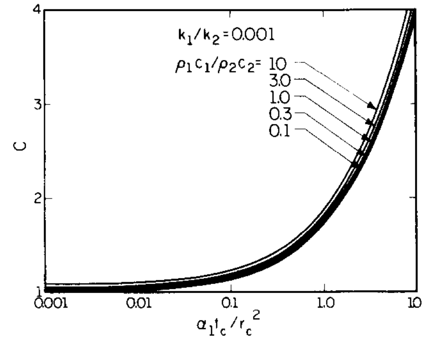

FIG. 5(a). Relations of the correction factor with the Fourier number for $k_1/k_2 = 0.001$.

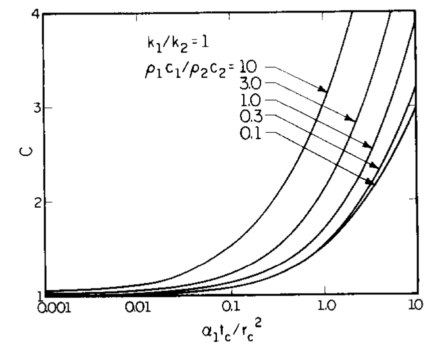

FIG. 5(b). Relations of the correction factor with the Fourier number for $k_1/k_2 = 1$.

correction factor C is multiplied to the simple solution. The total heat exchange then becomes

$$e = Ce_0 \tag{22}$$

where e_0 is calculated from equation (21). The factor C can be evaluated by numerical computation.

The heat conduction equation, equation (10), is solved by using the finite difference approach. The domain of interest is discretized by a mesh number between 20 and 50 in the r-direction with the maximum contact radius r_c at the tenth grid point, and a mesh number of 20–50 in the z-direction in each medium with different mesh sizes as that in the r-direction. The mesh numbers and sizes are adjusted to make sure that the heat exchange is within the domain of computation during the course of impact. The time step size was usually chosen to be one eightieth of the total impact duration in order to make converged solutions. Because the radius of the contact area changes with time, discontinuity exists in the boundary conditions between each time step. To minimize its influence, an alternative direction iteration scheme is used (with over-relaxation) to solve those finite difference equations.

For most of the solid materials, the parameter $\rho_1 c_1/\rho_2 c_2$ varies from about 0.1 to 10, and the parameter k_1/k_2 varies from about 0.001 to 1. Therefore, computations were performed within those ranges. The Fourier number $\alpha_1 t_c/r_c^2$ can be considered as a measure of the impact process. The larger values of this parameter represent small impact velocities.

Typical temperature and heat flux variations at the center of the contact area are plotted in Figs. 4(a) and (b) together with the solutions from the one-dimensional conduction equation. For large values of the Fourier number, present solutions give higher surface temperature and heat flux compared with the simple solutions. These are the expected phenomena since more heat is transferred from the radial direction. As $\alpha_1 t_c/r_c^2$ decreases, the surface temperature and heat flux tend to the simple solutions. As the Fourier number increases, the heat flux increases with time in the disengagement process because the change of contact area is so slow that radial heat conduction becomes significant.

The solutions for the correction factor C are plotted in Figs. 5(a) and (b) for two values of k_1/k_2. Each plot gives the variations of C with $\alpha_1 t_c/r_c^2$ for different $\rho_1 c_1/\rho_2 c_2$ values. Here, the Fourier number $\alpha_1 t_c/r_c^2$ can be considered as a measure of the degree of the two-dimensional heat conduction effect. When $\alpha_1 t_c/r_c^2$ is small, the heat conduction in the axial direction is predominant. As $\alpha_1 t_c/r_c^2$ increases, the heat conduction in the radial direction becomes significant in the total heat conduction process.

4. DISCUSSIONS

4.1. *Physical interpretations and material properties*

Equations (18) and (21) suggest that of the two materials, the one with the lower value of ρck tends to govern the total heat exchange. Using subscript 1 to refer to this material, equation (21) can be recast into a form with a clearer physical interpretation

$$e_0 = \frac{0.87(T_{02}-T_{01})\rho_1 c_1 A_c(\alpha_1 t_c)^{1/2}}{1+(\rho_1 c_1 k_1/\rho_2 c_2 k_2)^{1/2}}. \qquad (23)$$

Note that $A_c(\alpha_1 t_c)^{1/2}$ is a measure of the heated (or cooled) volume of the low ρck material, with $(\alpha_1 t_c)^{1/2}$ representing the thickness of the heat affected zone. Since the interface temperature is very close to the initial temperature of the high ρck material, the temperature difference in the low ρck material is very close to the initial temperature difference $T_{02}-T_{01}$. The denominator represents a correction factor for the temperature difference, whereas the coefficient 0.87 quantitatively accounts for the details of the complex process with time-dependent interface area and heat conduction.

It is also useful to recognize that for most non-porous materials, ρc tends to fall within very narrow limits, typically in the range 1–3 MJ m^{-3} K^{-1}. Therefore, $\rho_1 c_1 k_1/\rho_2 c_2 k_2$ tends to be of the same magnitude as k_1/k_2 and α_1/α_2. In other words, the material with the lower ρck tends also to have the lower Fourier number $\alpha t_c/r_c^2$. This suggests that the one-dimensional results of Section 3.2, represented by equations (21) and (23), are likely to be quite accurate if only $\alpha_1 t_c/r_c^2$ is small, instead of both $\alpha_1 t_c/r_c^2$ and $\alpha_2 t_c/r_c^2$ being small. For this reason, the correction factors in Figs. 5(a) and (b) are presented as functions $\alpha_1 t_c/r_c^2$, for different parameters k_1/k_2 and $\rho_1 c_1/\rho_2 c_2$. The plot suggests that for all cases when $\rho_1 c_1 k_1$ are not of the same order as $\rho_2 c_2 k_2$, only $\alpha_1 t_c/r_c^2$ is significant and that the error associated with the one-dimensional solution is only a significant function of $\alpha_1 t_c/r_c^2$.

4.2. *The heat transfer coefficient for particle/surface impact*

In solid suspensions and fluidized beds, heat transfer is the result of the impact of many particles, and the average rate of heat transfer can be expressed in terms of a heat transfer coefficient h_c

$$h_c \equiv \frac{\dot{n}e}{T_{02}-T_{01}} = \frac{0.87C\dot{n}\rho_1 c_1 A_c(\alpha_1 t_c)^{1/2}}{1+(\rho_1 c_1 k_1/\rho_2 c_2 k_2)^{1/2}} \qquad (24)$$

where $\dot{n}$ is the rate of particle surface impact per unit area. $\dot{n}$ can be evaluated as the particle number density times the impact velocity.

4.3. *Relationship between mechanical and thermal parameters*

An interesting relationship between the Fourier number and the Peclet number can be found by substituting equations (5) and (9) into the definition of the Fourier number

$$\frac{\alpha_1 t_c}{r_c^2} = 2.94 Pe_1^{-1} \qquad (25)$$

where

$$Pe_1 \equiv \frac{Rv}{\alpha_1} \qquad (26)$$

is the Peclet number based on the impact velocity and the equivalent radius. Note that mechanical properties have no direct or indirect influence on the Peclet number. This is an extremely interesting result in that it provides an easy-to-use criteria for the adequacy of the one-dimensional conduction theory. For common non-metallic solids, α is of the order of 10^{-7} m^2 s^{-1}. Referring to Figs. 5(a) and (b) it is seen that the one-dimensional conduction theory would be satisfactory if $Rv \geqslant 10^{-5}$ m^2 s^{-1}. For particles of the order of 1 mm in diameter, this requires an impact velocity greater than 1 cm s^{-1}, a condition usually satisfied in typical conditions.

Similarly, substituting equations (5) and (9) into equation (21) leads directly to an evaluation of the energy exchange

$$e_0 = \frac{5.36(m/E)^{3/5}(Rv)^{7/10}(T_{02}-T_{01})}{(\rho_1 c_1 k_1)^{-1/2}+(\rho_2 c_2 k_2)^{-1/2}}. \qquad (27)$$

The calculation of e for non-zero Fourier numbers can be done from equation (22) as before.

Equation (27) indicates that the energy exchange per impact increases with particle mass, radius, and velocity and decreases with E. It should be noted, however, that decreases in particle size as reflected in decreases in m and R, are usually accompanied by increases in the particle number density N and hence the impact frequency $\dot{n}$. Accordingly the mean surface heat transfer coefficient h_c, given by equation (24), will increase. This relationship can be exhibited by relating the mass and radius to the number density and the volume fraction of particles ϕ. Let subscript 1 refer to the particles and 2 refer to the surface. Due to the large curvature and large volume of the surface compared to the particles, $R = R_1$ and $m = m_1$. Then

$$m = \tfrac{4}{3}\pi\rho_1 R_1^3 \qquad (28)$$

$$N\tfrac{4}{3}\pi R_1^3 = \phi \qquad (29)$$

hence, from equation (24)

$$h_c = \frac{3.02C\phi(\rho_1/E)^{3/5}v^{1.7}R_1^{-1/2}}{(\rho_1 c_1 k_1)^{-1/2}+(\rho_2 c_2 k_2)^{-1/2}}. \qquad (30)$$

Therefore, h_c has a strong dependence on the impact velocity. In a random system, with a distribution of particle velocities, the impacts with the highest velocities make the greatest contribution to heat transfer.

4.4. *Comparisons with data*

At present, there appears to be no heat transfer data with sufficiently detailed supporting measurements of velocities and other parameters suitable for comparison with the present theory. However, some semi-quantitative comparisons can be made with the large body of gross heat transfer measurements in suspension flows, especially fluidized beds. Recent developments in particle velocity measurements (Lin *et al.*

[8], Moslemian *et al.* [9]) with heat transfer measurements in the same apparatus (Iwashko *et al.* [6], Moslemian *et al.* [10]) are particularly timely. The measurements were taken from a portion of a horizontal copper cylinder heated by electric power with glass particles of radius 250 μm. The particle number density is approximately equal to the packing particle density and the characteristic velocity of the particles in the bed is about 10 cm s^{-1}. They showed that the heat transfer coefficient inside the bed is of the order of 300 W m^{-2} K^{-1}.

The contact area of particles can be calculated from equation (5) for the same conditions used in the experiment. The results show that the contact area is about 3000 times smaller than the particle cross section. The contact duration is about 2.5×10^{-6} s which is about 40000 times smaller than the characteristic time (R_1^2/α_1) of the glass particle. It is also about 2000 times smaller than the characteristic flow time of the particles $(2R_1/v)$. If the impact velocity becomes 10 m s^{-1}, the contact area will still be about 100 times smaller than the cross sectional area and the contact duration will be even smaller. This verifies the assumption that heat transfer can be considered in two infinite media.

Using equation (24), for the same conditions in the experiment, the heat transfer coefficient due to solid contact is found to be about 0.2 W m^{-2} K^{-1}. This is only about 0.1% of the experimentally observed heat transfer. This in sharp contrast to the conclusion of Schlunder [3], who pointed out that the heat conduction would constitute the major contribution when the particles are small.

On the other hand, the strong dependence of e on the conductivity indicate that the mechanism investigated here can be quite important in suspensions of metallic particles.

5. CONCLUSIONS

An analysis for the energy exchange and heat transfer due to particle impact has been carried out. The analysis is based on solutions of the heat conduction equation, and represents a quantitative evaluation of an effect which previously had only been heuristically estimated. The solution is general and can be easily applied to a large variety of situations where this mechanism may be relevant. The mechanism, however, does not appear to be a dominant mechanism in fluidized bed heat transfer under typical conditions. Its importance is expected to be greater for highly conductive particles or for low pressures, where the relative contribution of the fluid is smaller.

Acknowledgements—The authors wish to express their appreciation to Professors S. L. Soo and B. T. Chao for useful discussions, and to the Publications Office, Department of Mechanical and Industrial Engineering, for preparation of the manuscript. The financial support of the Department of Energy is also gratefully acknowledged.

REFERENCES

1. C. A. Depew and T. J. Kramer, Heat transfer to flowing gas–solid mixtures, *Adv. Heat Transfer* **9**, 113–180 (1973).
2. S. C. Saxena, N. S. Grewal and J. D. Gabor, Heat transfer between a gas fluidized bed and immersed tubes, *Adv. Heat Transfer* **14**, 149–247 (1978).
3. E. U. Schlunder, Particle heat transfer, *Heat Transfer 1982, Proc. Seventh Int. Heat Transfer Conference*, Vol. 1, pp. 195–211 (1982).
4. S. L. Soo, *Fluid Dynamics of Multiphase Systems*. Blaisdell, Waltham, Massachusetts (1967).
5. S. Timoshenko and J. N. Goodier, *Theory of Elasticity*, pp. 372–384. McGraw-Hill, New York (1951).
6. M. Iwashko, D. Moslemian, M. M. Chen and B. T. Chao, Effect of solid particle velocity distribution on local heat transfer coefficients in gas fluidized bed, *ASME* **HTD-46,** 61–67 (1985).
7. H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids*, pp. 62–63. Oxford University Press, London (1959).
8. J. S. Lin, M. M. Chen and B. T. Chao, A novel radioactive particle tracking facility for measurement of solids motion in fluidized beds, *A.I.Ch.E. Jl* **31,** 465–473 (1985).
9. D. Moslemian, M. M. Chen and B. T. Chao, Measurement of turbulent stresses in a gas–solid fluidized bed, presented at the 1986 AIChE Winter Annual Meeting, Miami Beach, Florida, 2–7 November (1986).
10. D. Moslemian, M. M. Chen and B. T. Chao, Influence of solids hydrodynamics on local heat transfer from tube banks immersed in a gas fluidized bed, presented at the 1986 ASME Winter Annual Meeting, Anaheim, California, 7–12 December (1986).

ANALYSE THEORIQUE DU TRANSFERT THERMIQUE DU A L'IMPACT DE PARTICULES

Résumé—On analyse l'échange de chaleur entre des particules sphériques qui impactent ou entre une particule et une surface. Le but de cette étude est d'obtenir une compréhension quantitative de la contribution conductive directe entre particules et surfaces dans les écoulements dispersés ou les lits fluidisés. Le mécanisme considéré est la conduction dans le temps avec surface de contact variable pendant l'impaction. On trouve que le nombre de Fourier d'impact basé sur le rayon maximal de l'aire de contact et la durée du contact est inversement proportionnel au nombre de Peclet de la particule et indépendant des propriétés mécaniques. Pour des petits nombres de Fourier, une solution analytique est présentée. Pour des grands nombres de Fourier, la solution est obtenue numériquement et présentée en fonction d'un facteur de correction à utiliser avec des résultats analytiques.

EINE THEORETISCHE BETRACHTUNG DES WÄRMEÜBERGANGS BEIM ZUSAMMENSTOSS VON PARTIKELN

Zusammenfassung—Der Wärmeübergang zwischen zusammenstoßenden kugeligen Partikeln oder zwischen einem Partikel und einer Oberfläche wird analysiert. Der Zweck dieser Studie ist, ein quantitatives Verständnis über den direkten, durch Wärmeleitung übertragenen Anteil am Wärmeübergang zwischen Partikeln und Oberflächen in Suspensionsströmungen oder Wirbelschichten zu erhalten. Der untersuchte Mechanismus ist die Wärmeleitung durch die zeitlich veränderliche Kontaktfläche während des Zusammenstoßes. Es wird gezeigt, daß die Fourier-Zahl beim Zusammenstoß, gebildet mit dem maximalen Kontaktflächenradius und der Kontaktzeit, umgekehrt proportional zur Péclet-Zahl der Partikel und unabhängig von den mechanischen Eigenschaften ist. Für kleine Fourier-Zahlen wurde die Lösung numerisch ermittelt. Sie wird in Form eines Korrektur-Faktors, der zusammen mit den analytischen Ergebnissen benutzt wird, angegeben.

ТЕОРЕТИЧЕСКИЙ АНАЛИЗ ТЕПЛОПЕРЕНОСА, ВЫЗВАННОГО СТОЛКНОВЕНИЕМ ЧАСТИЦ

Аннотация—Анализируется теплообмен между соударяющимися сферическими частицами или частицей и поверхностью. Цель исследования—получение количественной оценки прямого вклада кондукции в теплообмен между частицами и поверхностями в потоках суспензий и псевдоожиженных слоях. Исследуется механизм теплопроводности через изменяющуюся во времени область контакта при столкновении. Показано, что 'столкновительное' число Фурье, образованное по максимальному радиусу контактной области и времени контакта, обратно пропорционально числу Пекле и не зависит от механических свойств. Представлено аналитическое решение для малых чисел Фурье. Для больших чисел Фурье получено численно решение, выраженное через поправочный коэффициент, используемый в аналитических результатах.