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HEAT TRANSFER FROM HEATED WALLS TO PACKED BEDS OF METAL PARTICLES AT VARIOUS PRESSURES

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Abstract—Based on experimental results the hypothesis is established, that the heat transfer from a heated metal wall to a packed bed of metal spheres is governed by three mechanisms: molecular conduction, electromagnetic radiation and electron transfer. The third mechanism can originate heat fluxes, which are much higher than those coming from the second one.

NOMENCLATURE

C_{p_b},	heat capacity of the packed bed;
C,	electromagnetic radiation constant;
d,	sphere diameter;
δ,	gap width;
ε,	emissivity for electromagnetic radiation;
E_e,	electron energy;
γ,	accommodation coefficient;
h,	heat-transfer coefficient;
h^*,	Plancks constant;
k,	surface roughness;
λ_g,	heat conductivity of the continuum gas;
λ_b,	heat conductivity of the packed bed;
λ_s,	heat conductivity of the particles;
Λ_g,	mean free path of the gas molecules;
Λ_e,	wave length of the de Broglie waves related to the free electrons in the metal phase;
m_e,	mass of an electron;
ψ,	void fraction of the packed bed;
$\dot{q}_b$,	heat flux;
r,	particle radius;
ρ_b,	density of the packed bed;
S,	bed height;
σ,	$= \Lambda_g \frac{2-\gamma}{\gamma}$, modified mean free path of the gas molecules;
t,	time;
u,	velocity.

STUDYING the heat transfer from heated plates to packed beds of spheres under various pressures and varying contact time, one discovers an anomalous behavior, when the material of the spheres is a metal. In order to analyze this effect one has to remember fundamental laws governing the unsteady state heat transfer from a heated wall to a packed bed as far as they are already known [1].

(1) If the depth of intrusion Δ of the temperature profile is larger than some particle diameters, see Fig. 1, the packed bed can be considered to be a quasi homogenous medium, having a uniform heat conductivity λ_b as well as a uniform density ρ_b and a uniform heat capacity C_{p_b}.

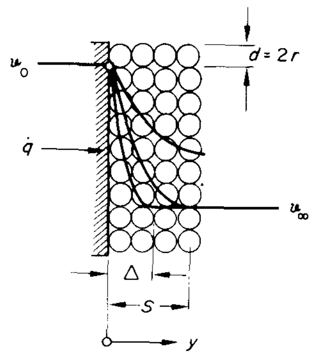

FIG. 1. Unsteady state temperature profiles in a packed bed.

In this case the Fourier theory is applicable, from which the time dependent heat-transfer coefficient, defined by

$$h \equiv \frac{\dot{q}_b}{\vartheta_0 - \vartheta_b} \qquad (1)$$

can be derived. $\dot{q}_b$ is the amount of heat supplied to the bed and ϑ_b is the integral mean temperature of the bed

$$S\rho_b C_{p_b}(\vartheta_b - \vartheta_\infty) = \int_0^t \dot{q}_b \, dt. \qquad (2)$$

In the experiments referred to later, the boundary condition of constant heat supply to a plate of finite capacity being in contact with the bed was verified. For this case the Fourier theory leads to

$$h = \frac{2}{\sqrt{\pi}} \frac{\sqrt{(\lambda_b \rho_b C_{p_b})}}{\sqrt{t}} \tag{3}$$

for developing temperature profiles and

$$h = 3\frac{\lambda_b}{S} \tag{4}$$

for fully developed temperature profiles, see also [2].

(2) If the depth of intrusion Δ of the temperature profile is smaller than one particle diameter, the packed bed is to be considered as a heterogenous medium. For very small values of Δ, i.e. for very short contact times all the heat transfer resistance is concentrated in the gaseous gap between the wall and the particle, since the particle temperature is still the initial temperature ϑ_∞, see Fig. 2.

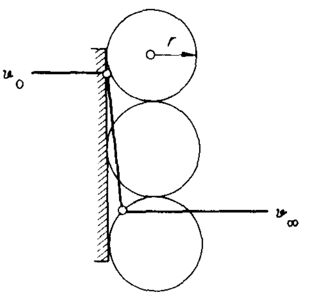

FIG. 2. Temperature profile for very short contact time.

Calculating the heat-transfer coefficient h for a perfect sphere being in contact with a perfectly plane wall, assuming that heat is transferred by conduction through the gaseous gap along parallel paths and in addition by radiation, one obtains [1]:

$$h = 2\frac{\lambda_g}{r}\left\{\left(\frac{\sigma}{r}+1\right)\ln\left(\frac{r}{\sigma}+1\right)-1\right\} + 0{\cdot}04 . C . \varepsilon\left(\frac{T_m}{100}\right)^3 . \tag{5}$$

In this equation λ_g is the heat conductivity of the continuum gas, and σ is the modified mean free path Λ_g of the gas molecules

$$\sigma \equiv \Lambda_g \frac{2-\gamma}{\gamma} \tag{6}$$

where γ is the accommodation coefficient. The first term in equation (5) accounts for the heat conduction taking into consideration, that near the touching point of the sphere with the wall there is always a region, where the width of the gaseous gap is smaller than the mean free path of the gas molecules. The second term in equation (5) accounts for the radiation, providing that the temperature difference $\vartheta_0 - \vartheta_\infty$ is not too large.

(3) The validity of these fundamental laws had been tested by experiments described elsewhere [3]. The results are shown in Figs. 3–5, where the heat-transfer coefficient h is plotted against the contact time t for packed beds of spheres from polystyrene, glass and bronze. Parameter is the gas pressure p in the packing. The gas was always air. At the left side of the

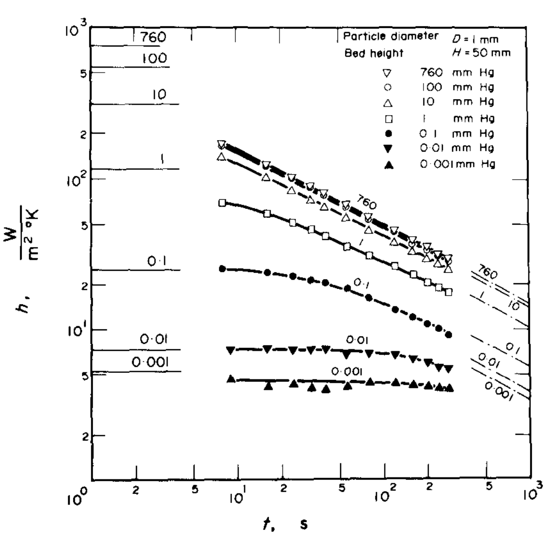

FIG. 3. Experimental data and theoretical prediction of heat-transfer coefficients h vs contact time t at various pressures for packed beds of 1·0 mm glass spheres.

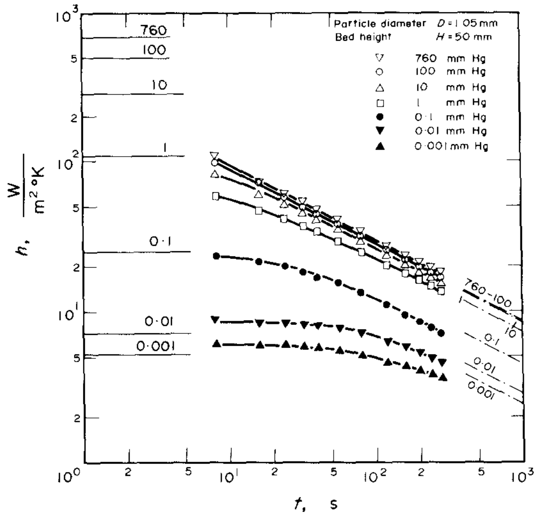

FIG. 4. Experimental data and theoretical prediction of heat-transfer coefficients h vs contact time t at various pressures for packed beds for 1·05 mm polystyrene spheres.

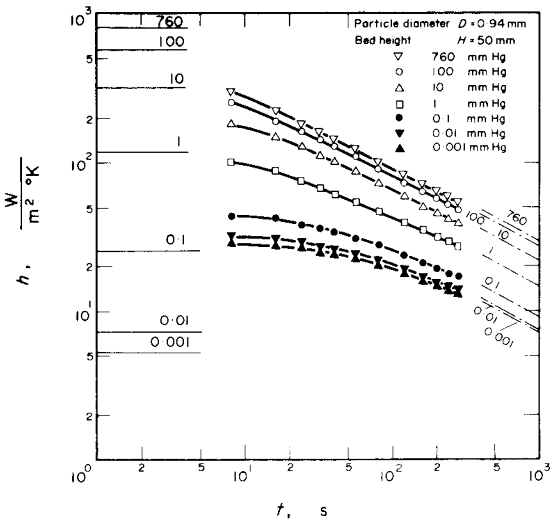

FIG. 5. Experimental data and theoretical prediction of heat-transfer coefficients h vs contact time t at various pressures for packed beds for 0·94 mm bronze spheres.

figures the maximum heat-transfer coefficients according equation (5) are indicated by full lines. The coefficients were calculated with an accommodation coefficient of $\gamma = 0{\cdot}9$ and an emissivity for the radiation of $\varepsilon = 0{\cdot}95$. At the right side of the figures the Fourier law according equation (3) is represented by dotted lines. The heat conductivity λ_b for the bed was calculated using the formulae given by Zehner and Schlünder [4], see Appendix.

During the experiments no fully developed temperature profiles were obtained, so that equation (4) is not applicable.

One can see from the Figs. 3 and 4 that the experimental data are in good agreement with the predicted ones for polystyrene and glass spheres. The experimental data for bronze spheres, however, are higher than the predicted ones. The discrepancies show to be worst at low pressure and short contact time. At a pressure of 0·001 mm Hg heat should be transferred only by radiation according the second term in equation (5), which yields

$$h = h_{\max} = 0{\cdot}04 \quad \varepsilon . C\left(\frac{T_m}{100}\right)^3 \cong 5\,\mathrm{W/m^2K}$$

at room temperature ($T_m = 300\,\mathrm{K}$). While this value was observed indeed with nonmetallic spheres, the value obtained with bronze spheres is roughly five times larger (25 W/mK).

(4) The observed phenomenon, that heat transfer and heat conduction in packed beds of metal spheres are always better than predicted by correlations, which fit very well with experimental data obtained from packed beds of nonmetallic spheres, is not quite a new one. The usual explanation is, that the spheres are not perfectly round, and giving pure solid heat paths providing additional heat transfer through the solid phase. In the case of poor conductors, this additional heat path is of minor significance, but with very good conductors as metal particles, this contribution will become important. From steady-state heat-transfer or heat-conduction experiments, which were performed many times before, one cannot decide, whether this explanation is true or not. From the unsteady state heat-transfer experiments, however, one can learn, that the additional amount of heat which is transferred to the metallic packing under vacuum is independent of the contact time! If the explanation given in Fig. 6 was true, this additional amount of heat should decrease with the contact time according the Fourier theory, applied to the pure metallic heat path.

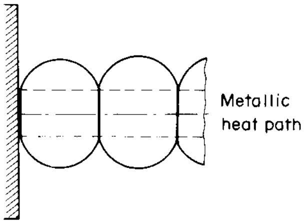

FIG. 6. Metallic heat path caused by a non spherical shape of the particles.

Since this was not observed, one has to conclude, that the additional heat path is not allowed to have any heat capacity. There must exist an additional heat-transfer mechanism having the characteristics of a radiation process. Since the law of radiation by electromagnetic waves is well known and under no circumstances can explain the observed high heat-transfer rates, one has to postulate another mechanism.

The hypothesis introduced now is, that there is an additional heat transfer caused by an electron transfer due to the so called "tunnel effect", which means, that a certain amount of the free electrons in the metal phase are allowed to bridge a certain vacuum gap between two metal bodies. The energy of the free electrons in the metal phase is very close to the Fermi energy E_f while the energy barrier preventing the electrons from escaping the metal phase is E_e, as shown in Fig. 7. If δ denotes the width of the gap between the two bodies the probability for electrons penetrate this gap can be calculated by applying the laws of quantum mechanics, which yield [5]:

$$D = \frac{1}{1 + \frac{1}{4}\left(K + \frac{1}{K}\right)^2 \sinh^2\left(\frac{\delta}{\Lambda_e}\right)} \tag{7}$$

with

$$K = \frac{E_e}{E_f} \quad \text{and} \quad \Lambda_e = \frac{h^*}{\sqrt{(2m_e E_e)}} \tag{8}$$

h^* is Planck's constant, m_e the mass of an electron and E_e the height of the energy barrier. Λ_e is the

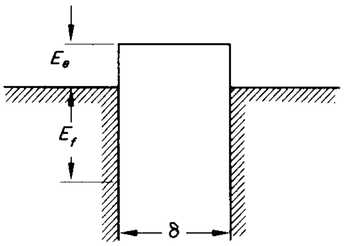

FIG. 7. Fermi energy and energy barrier for electrons tunnelling the gap δ between two metallic bodies.

de Broglie wave length of an electron having the energy E_e. Usually E_f is between 3 and 7 eV, while E_e is between 1 and 5 eV. E_e can be lowered by thin oxide layers at the metal surface. Assuming K to be unity one obtains D as a function of δ/Λ_e as shown in Table 1.

Table 1.

$\frac{\delta}{\Lambda_e}$	D
0	1
1	0,42
2	0,07

Assuming furthermore that for bronze spheres as used in the experiments with a slight surface oxidation E_e is about 1 eV the de Broglie wave length becomes 12 Å. Since the crystal lattice spacing is about 5 Å the spheres of the packing would be welded together when approaching to within that distance.

Since on the other hand the contact of the particles in the experiments was fully reversible, the minimum distance between the spheres (and between the spheres and the plate, respectively) must have been at least two to three times the crystal lattice spacing. But this still gives a distance tunnelling electrons can penetrate. The heat flux due to such an electron flux depends on quite a number of parameters, which are difficult to be determined. The model of a perfect sphere in contact with a perfect smooth wall, which turned out to be surprisingly successful to predict the heat transfer by conduction (equation 5), certainly will not be a realistic one to describe gap widths of some Angström. It seems to be more reasonable, that the gap width of this order of magnitude corresponds to the size and geometrical structure of the surface roughness. A second parameter is the influence of a thin oxide layer, which presumably covered the spheres as well as the heated wall. A third one may be another layer of adsorbed material at the surfaces, such as H_2O or other substances. Some quantum mechanical calculations are being carried out at present based on several models and simplifications. To obtain additional information the electrical resistance of the packed bed will be measured also.

Summing up one can say, that there are three mechanisms of heat transfer involved, when heating a packed bed of metallic particles being in contact with a hot wall:

1. Conduction
2. Radiation
3. Electron transfer.

The heat transfer by conduction is controlled by the Fourier mechanism as well as by the Knudsen mechanism. The Fourier mechanism is predominant at high and normal pressure while the Knudsen mechanism is prevailing at low pressure. Under high vacuum only radiation according the Stefan–Boltzmann mechanism accounts for the heat transfer as far as nonmetallic packings are concerned, but in addition also heat transfer by electron transfer occurs with metallic packing. The latter mechanism gives rise to transfer rates being much larger (e.g. five times) than those caused by the Stefan–Boltzmann radiation. The electron transfer mechanism arises, when the ratio of the characteristic gap width to the de Broglie wave length of electrons tunnelling the surface energy barrier is in the order of unity.

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APPENDIX

Calculation of the apparent heat conductivity of the packed bed, see [4]:

$$\frac{\lambda_b}{\lambda_g} = [1-\sqrt{(1-\psi)}]\left(\frac{1}{1+Kn^*/\psi}+\psi Nu_r\right)+\sqrt{(1-\psi)}\,\frac{\lambda_b'}{\lambda_g}$$

$$\frac{\lambda_b'}{\lambda_g} = \frac{2}{N-M}\left\{\frac{\left[N-(1+Kn^*)\dfrac{\lambda_g}{\lambda_s}\right]B}{(N-M)^2}\ln\frac{N}{M}-\frac{B-1}{N-M}(1+Kn^*) - \frac{B+1}{2B}\,\frac{\lambda_s}{\lambda_g}\,[1-(N-M)-(B-1)Kn^*]\right\}$$

$$M = B\left[\frac{\lambda_g}{\lambda_s}+Kn^*\left(1+\mathrm{N}u_r\frac{\lambda_g}{\lambda_s}\right)\right];$$

$$N = \left(1+Nu_r\frac{\lambda_g}{\lambda_s}\right)(1+Kn^*)$$

$$B = 1{\cdot}25\left(\frac{1-\psi}{\psi}\right)^{10/9}, \qquad Kn^* = \frac{2\sigma}{d}\left(\frac{2}{\gamma}-1\right),$$

$$Nu_r = \frac{0{\cdot}04\,C_s}{\dfrac{2}{\varepsilon}-1}\left(\frac{T}{100}\right)^3\frac{d}{\lambda_g}.$$

TRANSFERT THERMIQUE DE PAROIS CHAUFFEES A DES LITS FIXES DE PARTICULES METALLIQUES POUR DIFFERENTES PRESSIONS

Résumé—En se basant sur des résultats expérimentaux, on établit l'hypothèse que le transfert thermique d'une paroi métallique chaude à un lit fixe de sphères métalliques est gouverné par trois mécanismes: la conduction moléculaire, le rayonnement électromagnétique et le transfert électronique. Le troisième mécanisme peut développer des flux de chaleur plus importants que ceux qui proviennent du second.

WÄRMEÜBERTRAGUNG VON BEHEIZTEN WÄNDEN AN METALLISCHE FÜLLKÖRPERBETTEN BEI VERSCHIEDENEN DRÜCKEN

Zusammenfassung—Auf der Basis experimenteller Ergebnisse wird die Hypothese aufgestellt, daß der Wärmeübergang von einer beheizten Metallwand an ein Füllkörperbett aus metallischen Kugeln durch drei Übertragungsmechanismen beherrscht wird: molekulare Leitung, elektromagnetische Strahlung und Elektronenübertragung. Letztere kann Wärmeströme bewirken, die viel größer sind als die der Strahlung.

ПЕРЕНОС ТЕПЛА ОТ НАГРЕТЫХ СТЕНОК К ПЛОТНЫМ СЛОЯМ МЕТАЛЛИЧЕСКИХ ЧАСТИЦ ПРИ РАЗЛИЧНЫХ ДАВЛЕНИЯХ

Аннотация — На основе экспериментальных результатов построена гипотеза о том, что перенос тепла от нагретой металлической стенки к плотному слою металлических частиц определяется тремя механизмами: молекулярной проводимостью, электромагнитным излучением и переносом электронов. Третий механизм может вызвать тепловые потоки, которые значительно больше порожденных электромагнитным излучением.