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NONSTEADY-STATE HEAT TRANSFER IN A HIGH-TEMPERATURE GRANULAR BED

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Specific features of heat transfer in a high-temperature granular bed are studied based on a two-region model which takes into account the existence of an elevated porosity area.

Investigations of nonteady-state heat transfer between a dispersed material and a surface, apart from the solution of purely applied problems, are also of great interest for elucidating the heat transfer mechanism in heterogeneous systems.

In recent years, significant advances have been made in describing heat transfer of concentrated dispersed systems with surfaces on the basis of a two-region model, allowing for the elevated filling porosity near a heat transfer surface [1]. In the present paper we apply this concept to simulate unsteady-state heat transfer in a high-temperature granular bed where radiation heat transfer becomes essential.

The problem of nongradient heating (cooling) of a vertical cylinder in a granular bed can be formulated as

$$\frac{\partial\theta_f}{\partial \mathrm{Fo}} = \tilde{\rho}\frac{1}{\xi}\frac{\partial}{\partial\xi}\left(\Lambda_f\xi\frac{\partial\theta_f}{\partial\xi}\right), \quad r^0 \leqslant \xi < r^0 + 1, \tag{1}$$

$$\frac{\partial\theta_s}{\partial \mathrm{Fo}} = a_0^0\frac{1}{\xi}\frac{\partial}{\partial\xi}\left(\Lambda_s\xi\frac{\partial\theta_s}{\partial\xi}\right), \quad r^0 + 1 < \xi \leqslant B, \tag{2}$$

$$\theta_f(0, \xi) = \theta_s(0, \xi) = 0; \ \theta_f(0, r^0) = 1; \ \frac{\partial\theta_s(\mathrm{Fo}, B)}{\partial\xi} = 0;$$

$$\theta_f(\mathrm{Fo}, r^0+1) = \theta_s(\mathrm{Fo}, r^0+1); \ \Lambda_f\frac{\partial\theta_f(\mathrm{Fo}, r^0+1)}{\partial\xi} -$$

$$-\sigma^{**}\left[\left(\theta_f(\mathrm{Fo}, r^0) + \frac{T_0}{T_w - T_0}\right)^4 - \left(\theta_f(\mathrm{Fo}, r^0+1) + \frac{T_0}{T_w - T_0}\right)^4\right] = \tag{3}$$

$$= \Lambda_s\lambda_0^0\frac{\partial\theta_s(\mathrm{Fo}, r^0+1)}{\partial\xi}; \ \frac{\partial\theta_f(\mathrm{Fo}, r^0)}{\partial \mathrm{Fo}} = \Lambda\frac{\partial\theta_f(\mathrm{Fo}, r^0)}{\partial\xi}.$$

The latter from the boundary conditions in (3) corresponds to nongradient heating (cooling) of a cylinder submerged into the bed.

The boundary-value problem of (1)-(3) was solved numerically for two different gas-solid systems (see Table 1). We used the implicit absolutely stable difference scheme [2] realized by the running-in trail method. Owing to the discontinuous variation in thermophysical characteristics of the medium at the gas-bed boundary, in order to retain the required accuracy of calculations, the following relation must be satisfied:

$$\frac{a_f\Delta t}{(\Delta r_1)^2} = \frac{a_s\Delta t}{(\Delta r_2)^2}, \tag{4}$$

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TABLE 1. Initial Data

Element of the system	Parameter	Variant	
		1	2
Bed	Radius, m	0.08	0.055
	Height, m	0.04	0.11
	Porosity	04	0.4
Detector (cylinder)		Copper	Nickel
	Radius, m	0.002	0.0035
	Heat capacity, J/(kg·K)	390	440
	Density, kg/m^3	8000	8900
Gas	Heat capacity, J/(kg·K)	1000	1000
	Density (at 0^{o}C), kg/m^3	1.29	1.29
	Velocity, m/sec	0	0
Particles (balls)		Glass	Slag
	Heat capacity, J/(kg·K)	750	800
	Density, kg/m^3	2600	2300
	Thermal conductivity, W/(m·K)	0.74	0.5

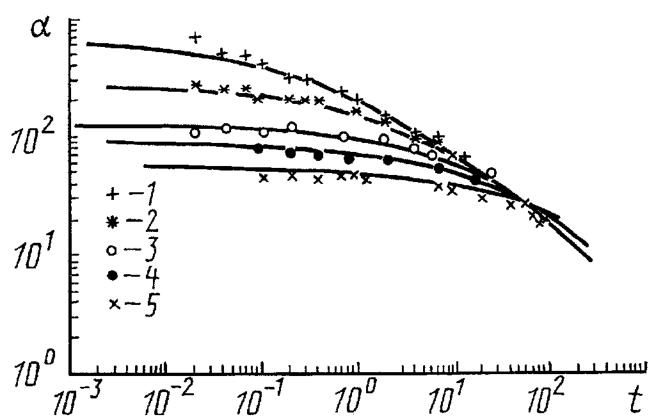


Fig. 1. Nonsteady-state heat transfer at room temperatures: 1,2,3,4,5) d = 0.39 mm; 0.93; 2.07; 3.05; 5.05 mm; T_0 = 299 K; T_w = 295 K; ε_w = 0.1; ε_s = 0.6. α, W/(m^2·K); t, sec.

where Δt, Δr_1, Δr_2 are the dimensional integration steps in time and in the coordinate r in the film and in the bed, respectively. Condition (4) establishes the relation between nondimensional digitization intervals in the bed and in the near-wall gaseous film. The thermal conductivity of the dispersed filling was calculated by the formula [3]

$$\lambda_s^0 = \lambda_f \left[1 + \frac{(1-\varepsilon)(1-\lambda_f/\lambda_s^*)}{\lambda_f/\lambda_s^* + 0{,}28\varepsilon^{0{,}63(\lambda_s^*/\lambda_f)^{0{,}18}}} \right], \tag{5}$$

and a linear interpolation in the form $\lambda_f = 0.024 + 6.38 \cdot 10^{-5} (T_f - 273)$, W/(m·K) was taken for the coefficient λ_f. Following [1], the gaseous film thickness $l_0 = 0.1$d. The radiant energy transfer inside the filling is considered in the contex of the "photon" thermal conductivity and is characterized by the corresponding effective coefficient λ_r. Assuming optical isotropy of the granular medium away from the boundaries, we calculate λ_r by the Rosseland formula [4]:

$$\lambda_r = \frac{16\sigma T_s^3}{3(\varkappa + \gamma)}. \tag{6}$$

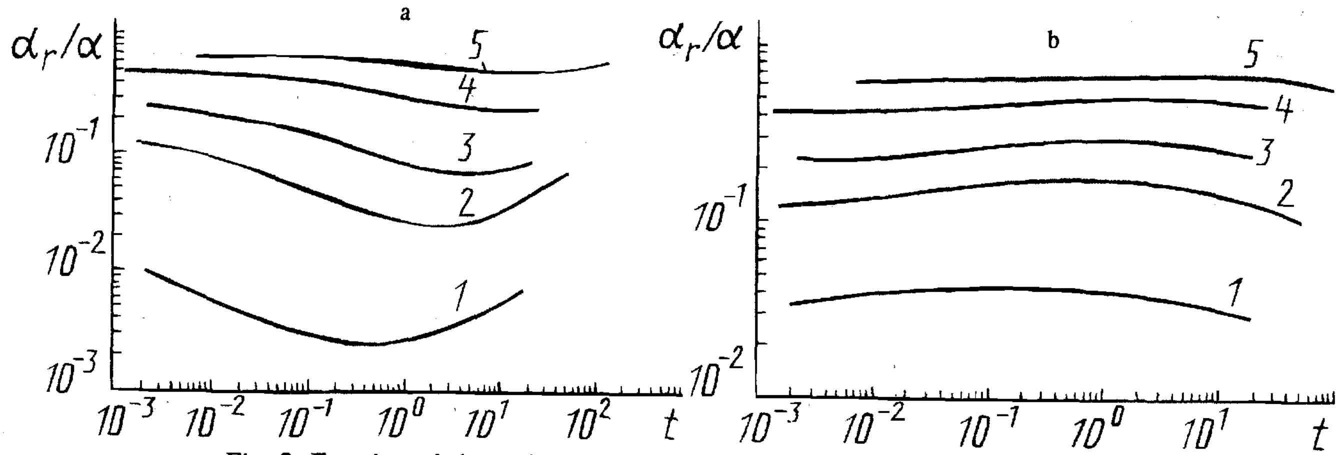


Fig. 2. Fraction of the radiant heat transfer component (1,2,3,4,5) d = 0.07, 0.39, 0.83, 2.23, and 5.05 mm; $\varepsilon_m = 0.8$ and $\varepsilon_s = 0.6$: a) $T_0 = 1773$ K; $T_w = 295$ K; b) 295 and 1773 K.

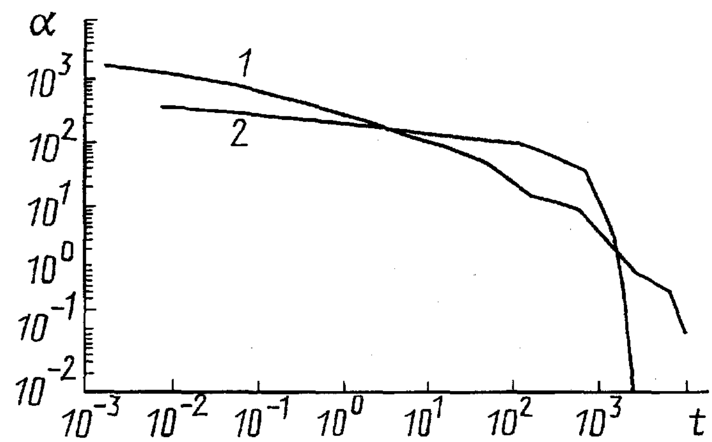


Fig. 3. Nonsteady-state heat transfer in a high-temperature granular bed: 1, 2) d = 0.39 and 5.05 mm; $T_0 = 1773$ K; $T_w = 295$ K; $\varepsilon_w = 0.8$; $\varepsilon_s = 0.6$.

The coefficients of absorption $\varkappa$ and scattering γ in (6) were predicted by the following formulas obtained from the solution to the transfer equation in the Schwarzschild-Schuster approximation for a plane-parallel bed and a spherical scattering indicatrix [4]:

$$\varkappa d = -\frac{1-R^*}{2(1+R^*)\,yN}\ln\frac{\sqrt{1-A^2}-1}{A},\qquad \gamma d = -\frac{2R^*}{(1-R^{*2})\,yN}\ln\frac{\sqrt{1+A^2}-1}{A},\tag{7}$$

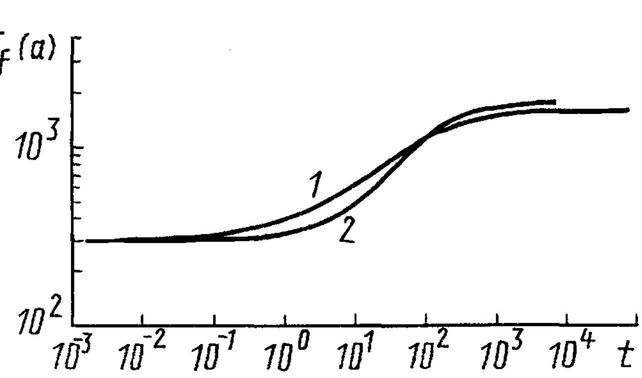
where

$$A = \frac{2R^*t^*}{(1-R^{*2})R^*};\quad y = \sqrt[3]{\frac{\pi}{6(1-\varepsilon)}}.$$

The reflecting R^* and transmitting t^* powers for a plane-parallel bed of particles of the dispersed material of N-rows thickness with porosity ε were determined by the model [5] for the prescribed degree of emissivity of particles ε_s.

The heat transfer coefficient was calculated by the formula

$$\alpha = -\lambda_f\,\frac{\partial T_f(a)}{\partial r}\Big/(T_f(a)-T_0) + \sigma^*\,[T_f^4(a)-T_f^4(a+l_0)]/(T_f(a)-T_0).\tag{8}$$



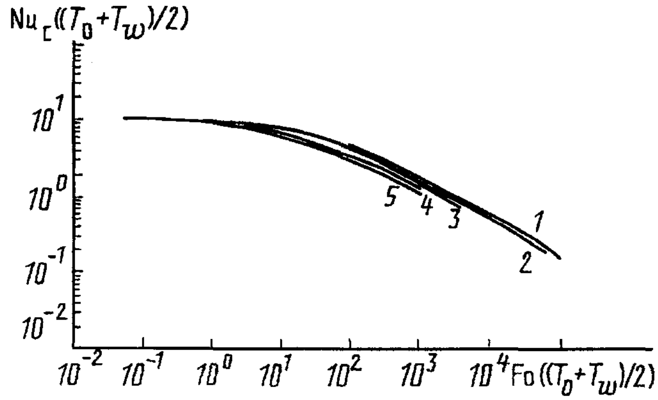


Fig. 4. Cylinder heating dynamics in a granular bed. Symbols are the same as in Fig. 3. $T_f(a)$, K.

Fig. 5. Nonsteady-state heat transfer in a high-temperature granular bed (a generalizing graph). Symbols are the same as in Fig. 2b.

Conductive Heat Transfer (the case of Moderate Temperatures). Figure 1 presents the results of the numerical experiment on heat transfer at room temperatures for system 1 (see Table 1) as well as the experimental data of [6], which quite satisfactorily coincide with the computational functions. Analysis of the results obtained showed that at sufficiently small times in the $\alpha(t)$ dependence there exists a stabilization section where α is virtually unchanged. With increase in particle diameter, this section grows with time. The values of the heat transfer coefficient in this region are well described by the relation $\alpha = 10\ \lambda_f/d$, which is equivalent to the equality $Nu = 10 = 1/K$, where $K = 0.1$ is the nondimensional thickness of the gaseous film. Thus, at the stabilization section, heat transfer is completely defined by contact thermal resistance (resistance of the gaseous film).

Conductive-Radiative Heat Transfer (the case of Elevated Temperatures). Figures 2-5 show the results of the numerical experiments for system 2 (see Table 1). As can be seen from Fig. 2, the radiative component contribution may be considerable (especially for coarse particles) and reaches 65%. The dependence of α_r/α on time is of an extremal character, and with increase in particle diameter it smooths out. Because of the inverse nature of the relation between the heat transfer coefficients in the beds of coarse and fine particles (Fig. 3), the cylinder heating time is practically independent of their diameter (Fig. 4). As with purely conductive heat transfer, the curves at small times have a stabilization section where $\alpha = 10\ \lambda_f((T_w+T_0)/2)/d$, i.e., $Nu_{con}=\alpha_{con}d/\lambda_f((T_w+T_0)/2)=10$ (Fig. 5). Thus, in the case of complex heat transfer too, the thermal resistance of the gaseous film, calculated at the determining temperature $(T_w+T_0)/2$, defines completely the conductive heat transfer component at the stabilized section.

NOTATION

$a_0^0=(a_s)_0/(a_f)_0$; $a_{f,s}$, horizontal thermal diffusivity; a, cylinder radius; $B = R/l_0$; C, specific heat; d, diameter of particles; $l_0 = 0.1d$, thickness of a gaseous film; L, height of a dispersed bed; $Fo = (a_f)_0 t/l_0^2$; $Nu = \alpha d/\lambda_f$; R, radius of a dispersed bed; r, coordinate; $r^0 = a/l_0$; t, time; T, temperature; T_0, initial temperature of a dispersed bed; α, heat transfer coefficient; ε, porosity; $\xi = r/l_0$; ρ, density; $\tilde{\rho} = (r_f)_0/\rho_f$; ε_w, emissivity of a heat transfer surface; ε_s, emissivity of particles; $\theta = (T-T_0)/(T_w-T_0)$; $\Lambda_f=\lambda_f/C_f(\rho_f)_0(a_f)_0$; $\Lambda_s=\lambda_s/\rho_s(1-\varepsilon)C_s(a_s)_0$; λ, horizontal thermal conductivity; $\lambda_0^0=(\lambda_s)_0/(\lambda_f)_0$; $\Lambda=2l_0\Lambda_f C_f(\rho_f)_0/aC_b\rho_b$; λ_s^0, thermal conductivity of dispersed filling; λ_s^*, thermal conductivity of the solid particle material; λ_f, thermal conductivity of gas; $\lambda_s=\lambda_s^0+\lambda_r$; $\sigma^{**}=\sigma^*(T_w-T_0)l_0/(\lambda_f)_0$; $\sigma^*=\sigma/(1/\varepsilon_w+1/\varepsilon_s^{0.485}-1)$; σ, Stefan-Boltzmann constant. Indices: b, heat exchanger material; c, conductive; f, gas; s, solid particles; r, radiative; $(\ )_0$ at $T = 0^oC$; w, heat transfer surface.

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