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HEAT TRANSFER IN GRANULAR BEDS IN RADIATIVE HEAT SUPPLY

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UDC 532.5

The basic regularities of stationary heat transfer throughout the space of an infiltrated granular bed in radiative heat supply in cocurrent-flow (solar collector 1) and counterflow (solar collector 2) regimes have been investigated within the framework of a two-temperature model. The boundary layer of the third kind for the skeleton of particles at exit from the bed has been formulated; this condition allows for the degree of turbulence of the heat-transfer-agent flow. A quasihomogeneity criterion making it possible to evaluate the thermal state of a two-phase system has been introduced. The approximation dependences for calculation of the active-portion length, the bed's resistance, the solar-collector efficiency, and the average relative phase-temperature difference have been established.

Keywords: *granular bed, quasihomogeneity criterion, cocurrent flow, counterflow, radiative heat supply, bed's resistance, degree of attenuation of radiation, degree of turbulence, heat-transfer agent.*

Introduction. Flow of a liquid or a gas (heat-transfer agent) through a granular bed has been much studied. This problem has been the focus of numerous works (see, e.g., [1, 2]). However, the case of the heat exchange of a heat-transfer agent transparent to radiation and with a skeleton of translucent particles, on which the radiative heat flux is incident, is still not clearly understood, although it is by far of greater practical interest (different solar collectors, transpiration-cooling systems, etc.).

It is common practice to represent heat transfer in a granular bed within the framework of a two-temperature model, which makes it possible to describe in detail phase-temperature fields. In exceptional cases of stationary heat transfer (e.g., when heat release in the bed is rather small) the difference of the phase temperatures is relatively small and we can use a one-temperature (quasihomogeneous) approximation. With allowance for the simplicity of description of heat-transfer processes it is reasonable to start the analysis precisely with this.

One-Temperature Model. The equation of stationary heat conduction and the corresponding boundary conditions in a one-dimensional case have the form

$$c_f J_f \frac{dT}{dx} = \frac{d}{dx}\left(\lambda \frac{dT}{dx}\right) + Q_k(x)\,; \tag{1}$$

$$x = 0\,, \quad c_f J_f (T - T_0) = \lambda \frac{dT}{dx}\,; \tag{2}$$

$$x = H\,, \quad \frac{dT}{dx} = 0\,. \tag{3}$$

System (1)–(3) describes the case of heat supply to the bed's inlet (cocurrent-flow scheme, Fig. 1a) when $k = 1$ and to the bed's outlet (counterflow scheme, Fig. 1b) when $k = 2$. The first case will arbitrarily be called "solar collector 1," whereas the second case will be called "solar collector 2." We establish the form of the functions $Q_k(x)$, taking into account that the incident radiation is absorbed not completely by the particles at the boundary of the bed. Part of the radiation penetrates deep into the bed and is absorbed by the rows of particles that follow. The penetration

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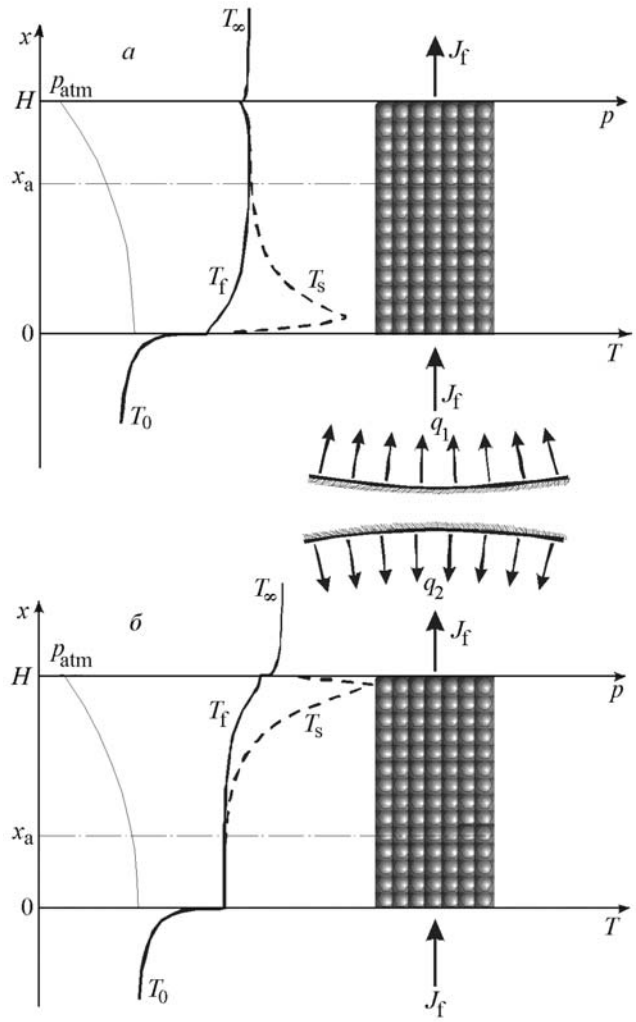

Fig. 1. Coordinate system, direction of the heat flux and the heat-transfer-agent flow, and character of distribution of the phase temperatures and the pressure: a) solar collector 1 (cocurrent flow); b) solar collector 2 (counterflow).

depth of the radiation is dependent on the properties of the particles (Fig. 2) [3]. As is seen, the functions $Q_k(x)$ can be represented in the form

$$Q_1(x) = A_1 \exp\left(-B\frac{x}{d}\right), \quad Q_2(x) = A_2 \exp\left(-B\frac{H-x}{d}\right). \tag{4}$$

The coefficients A_1 and A_2 are determined from the conditions

$$A_1 \int_0^\infty \exp\left(-B\frac{x}{d}\right)dx = q_1, \quad A_2 \int_0^\infty \exp\left(-B\frac{H-x}{d}\right)dx = q_2. \tag{5}$$

For Q_1 and Q_2, with account for (5), we obtain

$$Q_1(x) = \frac{q_1 B}{d}\exp\left(-B\frac{x}{d}\right), \quad Q_2(x) = \frac{q_2 B}{d}\exp\left(-B\frac{H-x}{d}\right). \tag{6}$$

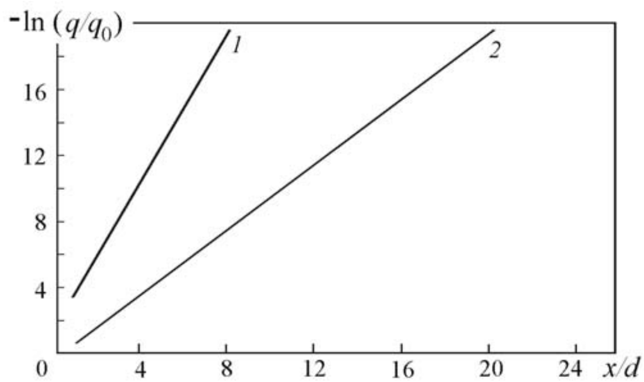

Fig. 2. Radiation intensity vs. depth of penetration into the granular bed [3]: 1) ε_s = 0.9 and 2) 0.1. q, W/m^2.

Solar Collector 1. Setting λ = const for the sake of simplicity, we represent (1)–(3) for k = 1 in dimensionless form

$$\frac{d\theta}{d\xi} = \frac{1}{\mathrm{Pe}} \frac{d^2\theta}{d\xi^2} + \overline{Q}_1 \, ; \qquad (7)$$

$$\xi = 0 \, , \;\; \theta = \frac{1}{\mathrm{Pe}} \frac{d\theta}{d\xi} \, ; \qquad (8)$$

$$\xi = 1 \, , \;\; \frac{d\theta}{d\xi} = 0 \, . \qquad (9)$$

We note that conditions (8) and (9) are the classical Danckwerts conditions [1]. The solution of (7)–(9), with account for (4) and (6), has the form

$$\theta(\xi) = \overline{q}_1 B^* \left(\frac{1}{B^* + \mathrm{Pe}} - \frac{1}{B^*} \right) \left(\exp(-B^*\xi) + \frac{B^*}{\mathrm{Pe}} \exp(-B^* - \mathrm{Pe}(1-\xi)) - \left(1 + \frac{B^*}{\mathrm{Pe}} \right) \right) . \qquad (10)$$

Calculations from (10) are given in Fig. 3A.

Solar Collector 2. System (1)–(3) for k = 2 will be written in dimensionless form as

$$\frac{d\theta}{d\xi} = \frac{1}{\mathrm{Pe}} \frac{d^2\theta}{d\xi^2} + \overline{Q}_2 \, ; \qquad (11)$$

$$\xi = 0 \, , \;\; \theta = \frac{1}{\mathrm{Pe}} \frac{d\theta}{d\xi} \, ; \qquad (12)$$

$$\xi = 1 \, , \;\; \frac{d\theta}{d\xi} = 0 \, . \qquad (13)$$

The solution of (11)–(13), with account for (4) and (6), has the form

$$\theta(\xi) = \overline{q}_2 \left(1 - \frac{B^*}{B^* + \mathrm{Pe}} \right) \left(\exp(B^*\xi) + \frac{B^*}{\mathrm{Pe}} - 1 - \frac{B^*}{\mathrm{Pe}} \exp(B^* - \mathrm{Pe}(1-\xi)) \right) \exp(-B^*) \, . \qquad (14)$$

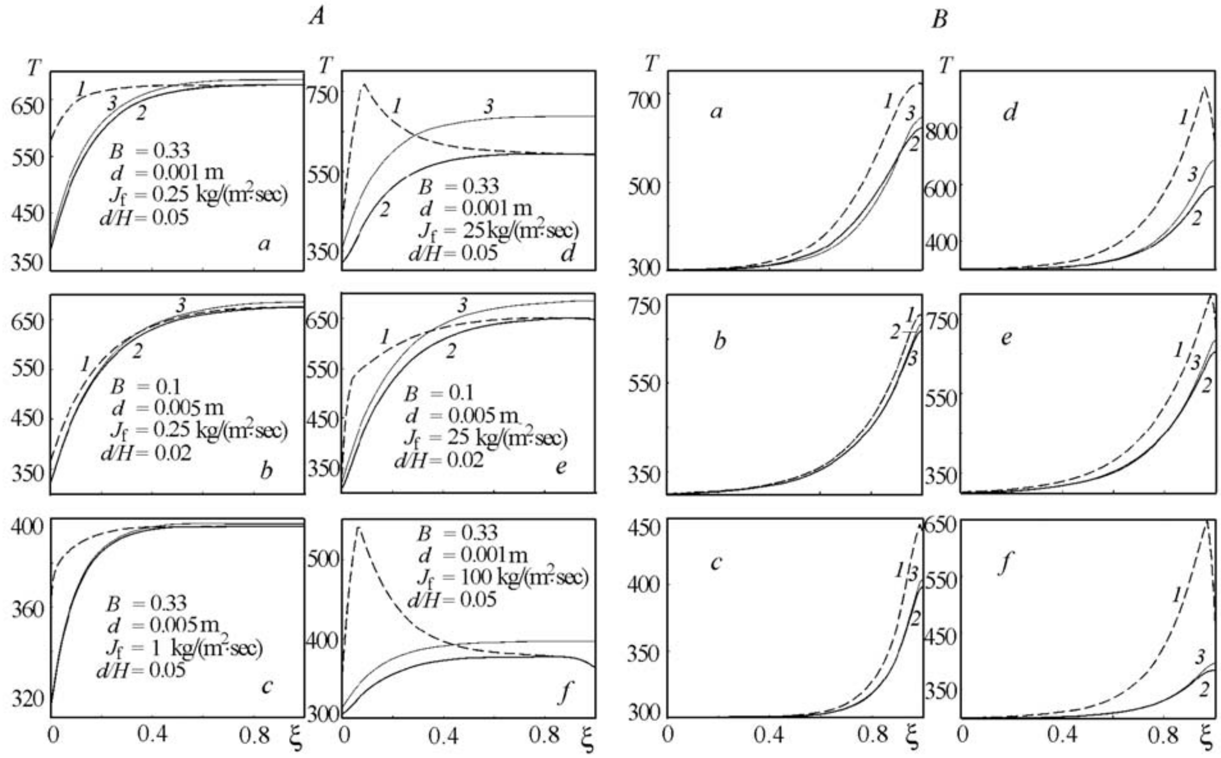

Fig. 3. Quantities T_s, T_f, and T vs. dimensionless coordinate ξ for Tu = 0.15 (A, solar collector 1; B, solar collector 2): a, b, and c) $q_1(q_2) = 10^5$ and d, e, and f) 10^7 W/m^2; 1) T_s; 2) T_f; 3) T. T, K.

Figure 3B shows the functions $T(\xi)$ calculated from (14).

Two-Temperature Model. To describe the hydrodynamics and heat transfer within the heat-releasing bed under stationary conditions we use the system of equations (the heat-transfer agent is gas)

$$c_f J_f \frac{dT_f}{dx} = \frac{d}{dx}\left(\varepsilon \lambda_f \frac{dT_f}{dx}\right) + \frac{6(1-\varepsilon)\alpha}{d}(T_s - T_f), \tag{15}$$

$$0 = \frac{d}{dx}\left((1-\varepsilon)\lambda_s \frac{dT_s}{dx}\right) + \frac{6(1-\varepsilon)\alpha}{d}(T_f - T_s) + Q_k(1-\varepsilon). \tag{16}$$

$$\rho_f v_f \frac{dv_f}{dx} = -\frac{dp}{dx} - 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_f u_f}{d^2} - 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_f u_f^2}{d}, \tag{17}$$

$$p = \rho_f R T_f. \tag{18}$$

Representation of the force of friction of the gas against the particles in (17) is based on the well-known Ergun equation [1]. The gas is assumed to be ideal. Expressions for α, ρ_f, and μ_f have been given in [4]; those for λ_f and λ_s, in [5]. The value of Q_k is determined by formulas (4), in which A_k values are calculated from (6). The system of equations (15)–(18) is solved with the following boundary conditions:

$$x = 0, \quad c_f J_f (T_f - T_0) = (1-\varepsilon)\lambda_s \frac{dT_s}{dx} + \varepsilon \lambda_f \frac{dT_f}{dx}; \tag{19}$$

$$(1-\varepsilon)\,\lambda_s \frac{dT_s}{dx} = \alpha_0\,(T_s - T_0)\;; \tag{20}$$

$$x = H\,,\quad \frac{dT_f}{dx} = 0\;; \tag{21}$$

$$(1-\varepsilon)\,\lambda_s \frac{dT_s}{dx} = \alpha_H\,(T_f - T_s)\;; \tag{22}$$

$$p = p_{atm}\,. \tag{23}$$

The difference of the coefficient α_H in (22) from α_0 that is usually used in this condition [6, 7] is due to the following two circumstances. The first circumstance is due to the use of the quantity $T_f(H)$ instead of the quantity T_∞ which is the temperature of the heat-transfer agent away from the bed's outlet (see Fig. 1) and is assumed in accordance with the classical boundary conditions of the third kind [8]. With account for this temperature, (22) will take the form

$$(1-\varepsilon)\,\lambda_s \frac{dT_s}{dx} = \overset{*}{\alpha}_H\,(T_\infty - T_s)\,. \tag{24}$$

Using the evident relation

$$x = H\,,\quad (1-\varepsilon)\,\lambda_s \frac{dT_s}{dx} = c_f J_f\,(T_f - T_\infty) \tag{25}$$

and substituting T_∞ determined from (25) into (24), we obtain condition (22) with the coefficient

$$\alpha_H = \frac{\overset{*}{\alpha}_H}{1 + \dfrac{\overset{*}{\alpha}_H}{c_f J_f}}\,. \tag{26}$$

The second circumstance leading to the difference of α_H from α_0 is due to the use of $\overset{*}{\alpha}_H$ instead of $\overset{0}{\alpha}_H$ in (24). This is because the flow of the heat-transfer agent out of the bed has the degree of turbulence Tu ≠ 0, whereas $\overset{0}{\alpha}_H$ refers to the case of heat exchange with an unperturbed flow for Tu = 0. Using the relation (given in [9]) which connects $\overset{*}{\alpha}_H$ to $\overset{0}{\alpha}_H$ for air

$$\overset{*}{\alpha}_H = \overset{0}{\alpha}_H\,(1 + 0.09\,(\mathrm{Re}_H \cdot \mathrm{Tu})^{0.2})\,, \tag{27}$$

we obtain the final formula for calculating α_H:

$$\alpha_H = \psi \overset{0}{\alpha}_H\,, \tag{28}$$

where

$$\psi = \frac{1 + 0.09\,(\mathrm{Re}_H \cdot \mathrm{Tu})^{0.2}}{1 + \overset{0}{\alpha}_H \dfrac{1 + 0.09\,(\mathrm{Re}_H \cdot \mathrm{Tu})^{0.2}}{c_f J_f}}\,. \tag{29}$$

When $\mathrm{Re}_H \ll 1$ we have $\psi = 1.64\ \mathrm{Re}_H^{0.5}$ (for $\overset{0}{\alpha}_H = 0.5 c_f J_f \mathrm{Re}_H^{-0.5} \mathrm{Pr}^{-0.6}$ [10]); when $\mathrm{Re}_H \gg 1$ we have $\psi = 0.09\ (\mathrm{Re}_H \mathrm{Tu})^{0.2}$.

Thus, system (15)–18) with boundary conditions (19)–(23) is a mathematical model of hydrodynamic and heat-transfer processes in granular beds in radiative heat supply in the regimes of cocurrent flow ($k = 1$) and counterflow ($k = 2$).

Reduction to a Dimensionless Form. System (15)–(23) in dimensionless form will be

$$\frac{d\theta_f}{d\xi} = \frac{d}{d\xi}\left(\frac{1}{\mathrm{Pe_f}}\frac{d\theta_f}{d\xi}\right) + \frac{6(1-\varepsilon)H}{d}\mathrm{St}(\theta_s - \theta_f)\,; \tag{30}$$

$$0 = \frac{d}{d\xi}\left(\frac{1}{\mathrm{Pe_s}}\frac{d\theta_s}{d\xi}\right) + \frac{6(1-\varepsilon)H}{d}\mathrm{St}(\theta_f - \theta_s) + \overline{Q}_k(1-\varepsilon)\,; \tag{31}$$

$$\overline{J}_f\rho_f'\frac{d}{d\xi}\left(\frac{1}{\rho_f'}\right) = -D\frac{dp'}{d\xi} - 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\mathrm{Re} - 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\mathrm{Re}^2\,; \tag{32}$$

$$\rho_f' = \frac{p'}{\theta_f + 1}\,; \tag{33}$$

$$\xi = 0\,,\quad \theta_f = \frac{1}{\mathrm{Pe_f}}\frac{d\theta_f}{d\xi} + \frac{1}{\mathrm{Pe_s}}\frac{d\theta_s}{d\xi}\,; \tag{34}$$

$$\frac{1}{\mathrm{Pe_s}}\frac{d\theta_s}{d\xi} = \mathrm{St_0}\theta_s\,; \tag{35}$$

$$\xi = 1\,,\quad \frac{d\theta_f}{d\xi} = 0\,; \tag{36}$$

$$\frac{1}{\mathrm{Pe_s}}\frac{d\theta_s}{d\xi} = \psi\mathrm{St}_H^0(\theta_f - \theta_s)\,; \tag{37}$$

$$p' = 1\,. \tag{38}$$

From the form (30)–(38), we can infer that the dimensionless hydrodynamic and thermal characteristics of the granular bed are functions of the following complexes and simplexes:

$$\Gamma = f\left(\mathrm{Pe_f}, \mathrm{Pe_s}, \mathrm{St}, \mathrm{St_0}, \psi, \overline{q}_k, D, \overline{J}_f, \mathrm{Re}, \frac{H}{d}, B\right), \tag{39}$$

where Γ is one of the functions θ_f, θ_s, p', and ρ_f'. Since the first five complexes are functions of Re, Pr, and Tu, the dependence (39) is equivalent to the following one:

$$\Gamma = f\left(\mathrm{Re}, \mathrm{Tu}, \overline{q}_k, D, \overline{J}_f, \frac{H}{d}, B\right). \tag{40}$$

The complexity of the system of dimensionless numbers in (40) is that Re, D, and $\overline{J}_f$ are not constant and depend on the temperature T_f and pressure. Taking account of this fact, we can recommend, for generalization of calculated and experimental results, the following equation in which the complexes are independent of T_f and p:

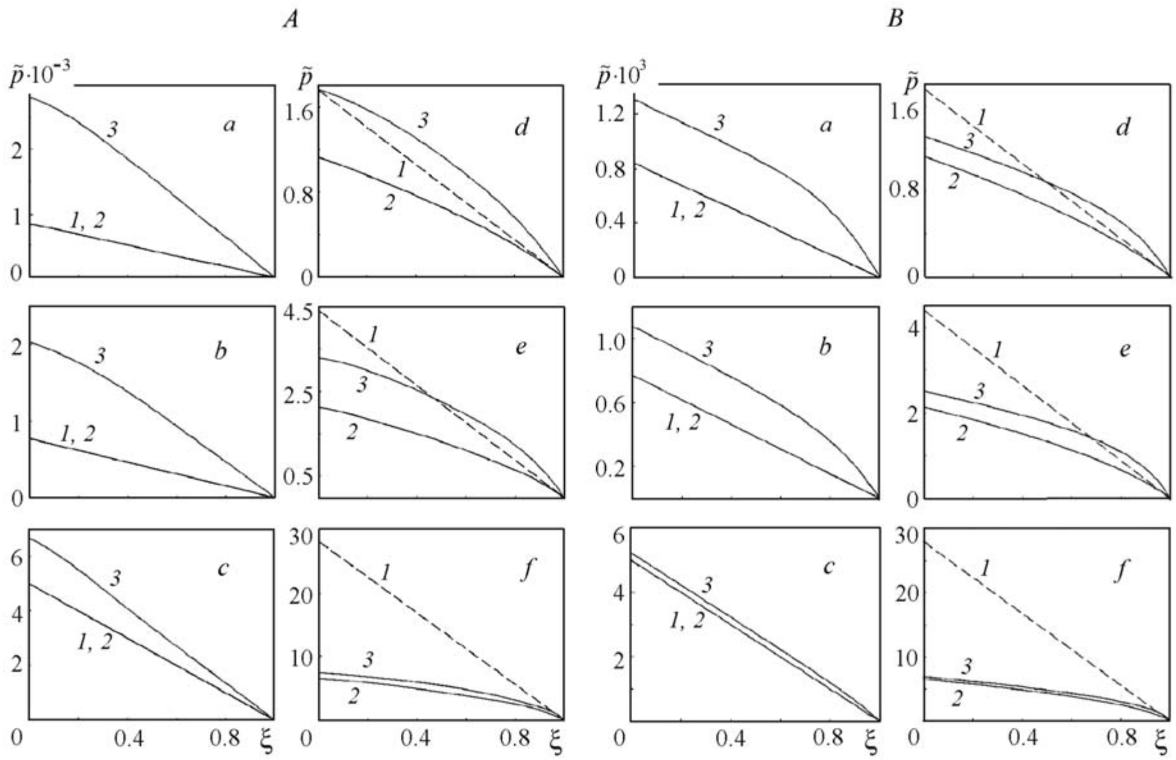

Fig. 4. Pressure difference vs. dimensionless coordinate ξ for Tu = 0.15 (A, solar collector 1; B, solar collector 2): a, b, and c) $q_1(q_2) = 10^5$ and d, e, and f) 10^7 W/m^2; 1) calculation from the Ergun formula (46); 2) calculation from (47); 3) numerical calculation. The regimes are the same, as those in Fig. 3. $\tilde{p}$, atm.

$$\Gamma = f\left(\mathrm{Re}_0, \mathrm{Tu}, \bar{q}_k, D_0, \bar{J}_{f0}, \frac{H}{d}, B\right), \qquad (41)$$

or, combining $\bar{q}_k$ and H/d, we obtain

$$\Gamma = f\left(\mathrm{Re}_0, \mathrm{Tu}, (QH)_k, D_0, \bar{J}_{f0}, \frac{H}{d}, B\right).$$

Analysis of the Obtained Results. *Solar Collector 1.* Figure 3A plots T_s and T_f versus the dimensionless coordinate. The same figure shows the functions $T(\xi)$ determined by formula (10). The quantity $(J_f)_{min}$ is evaluated from the balance condition

$$(J_f)_{min} \cong \frac{q_1}{c_f (T_{cr} - T_0)},$$

in which T_{cr} is taken to be 800 K. From a comparison of the phase temperatures T_s and T_f to the quantity T calculated from the one-temperature model (1)–(3) [formula (10)], it is clearly seen that the functions $T_f(\xi)$ and $T(\xi)$ are close in form. At the same time, $T_s(\xi)$ significantly differs from $T(\xi)$ as a rule, as far as the value and the form of the functional dependence are concerned. This is, probably, due to the similarity of the equations and boundary conditions for T_f and T and to the significant difference, from them, of the equation and boundary conditions for T_s.

The length of the active zone x_a (see Fig. 1) is determined from the condition $(\theta_s - \theta_f) \geq 0.01$. For calculating it, we obtain the dependence

$$\frac{x_a}{H} = 4\,\frac{d}{H}\,B^{-0.85}\,\mathrm{Re}_0^{0.04}\,. \tag{42}$$

where $0.1 < B < 0.33$, $13.6 < \mathrm{Re}_0 < 54{,}000$, and $15 < \frac{H}{d} < 100$.

The optimum length of solar collector 1, which is determined from the condition $x_a/H \approx 1$, follows from (42):

$$\frac{H_{1\mathrm{opt}}}{d} = 4B^{-0.85}\,\mathrm{Re}_0^{0.04}\,. \tag{43}$$

An important characteristic of the granular bed is its resistance, which is dependent on many factors, including the heat-release power. Generalization of the calculated data (Fig. 4) leads to the following dependence:

$$\frac{\Delta p_1}{(\Delta p)_E^{\mathrm{mod}}} = 3.35\bar{q}_1^{\,0.35} B^{0.04} \mathrm{Re}_0^{-0.085}\,, \tag{44}$$

where

$$(\Delta p)_E^{\mathrm{mod}} = p_{\mathrm{atm}}\sqrt{1 + 2\,(\Delta p)_E / p_{\mathrm{atm}}} - 1\,; \tag{45}$$

$0.1 < B < 0.33$, $13.6 < \mathrm{Re}_0 < 54{,}000$, and $0.03 < \bar{q}_1 < 1.33$.

Formula (45) obtained in [11] allows for the compressibility of the gas and describes the resistance of an isothermal granular bed on the basis of the Ergun formula [1]

$$\frac{(\Delta p)_E}{H} = \frac{\mu_{f0}^2}{d^3 \rho_{f0}}\left(150\,\frac{(1-\varepsilon)^2}{\varepsilon^3}\,\mathrm{Re}_0 + 1.75\,\frac{(1-\varepsilon)}{\varepsilon^3}\,\mathrm{Re}_0^2\right). \tag{46}$$

As is clear from Fig. 4, for low rates of flow of the heat-transfer agent (small total pressure differences), calculations from the Ergun formula (46) virtually coincide with p values computed from the formula [11]

$$\frac{\tilde{p}}{p_{\mathrm{atm}}} = \sqrt{1 + 2\,\frac{(\Delta p)_E}{p_{\mathrm{atm}}}\,(1-\xi)} - 1\,, \tag{47}$$

which allows only for the influence of the gas compressibility. As the flow rate of the heat-transfer agent increases, $p(\xi)$ values determined by (47) approach the numerical solution. It is precisely this circumstance that has been allowed for in using expression (45), which corresponds to (47) at $\xi = 0$ for generalization of the calculated values of pressure in the form (44).

The specific power consumed by pumping the heat-transfer agent is determined, with account for (44), as

$$N_1 = \frac{\Delta p_1 J_f}{\rho_0} = \frac{J_f}{\rho_{f0}}\,\frac{\Delta p_1}{\left(\frac{\Delta p_1}{p_{\mathrm{atm}}} + 1\right)}\,. \tag{48}$$

We note that in (48), the bed length is calculated from formula (43).

An important characteristic determining the operating efficiency of the solar collector as a heat exchanger is its efficiency, which is computed from the formula

$$\eta_1 = 1 - \frac{N_1}{q_1} = 1 - \frac{\Delta p_1}{(\Delta p_1 + p_{\mathrm{atm}})}\,\tilde{q}_1^{\,-1}\,. \tag{49}$$

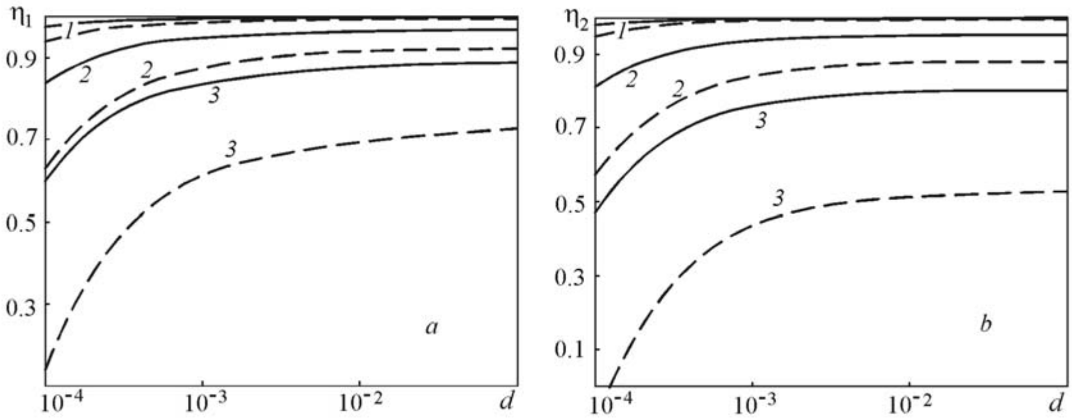

Fig. 5. Solar-collector efficiency vs. particle diameter: a) solar collector 1; b) solar collector 2: 1) J_f = 1; 2) 3, and 3) 5 kg/(m^2·sec); solid curves, B = 0.33; dashed curves, B = 0.1. $q_k = 10^5$ W/m^2. d, m.

Figure 5a shows results of calculating from (49) which make it possible to select the optimum particle diameters in different regimes. The influence of the parameter B on η_1 is related to the substantial dependence of $H_{1\text{opt}}$ on B, which is involved in the expression of Δp_1 by $(\Delta p)_E^{\text{mod}}$.

The relative phase-temperature difference averaged over the bed Θ_1 (when $H \cong H_{1\text{opt}}$) is determined by the relation

$$\Theta_1 = 2 \left\langle \frac{T_s - T_f}{T_s + T_f} \right\rangle = 0.75\,(QH)_1^{0.83}\,. \tag{50}$$

Solar Collector 2. Figure 3B shows results of calculating the fields of temperature T_s, T_f, and T. To calculate the size of the active zone and the effective (working) length of the apparatus when the active zone occupies the entire volume of the bed, we obtain dependences analogous to (42) and (43):

$$\frac{x_a}{H} = 5.25\,\frac{d}{H}\,B^{-0.85}\,\text{Re}_0^{0.014}\,, \tag{51}$$

$$\frac{H_{2\text{opt}}}{d} = 5.25\,B^{-0.85}\,\text{Re}_0^{0.014}\,, \tag{52}$$

where $0.1 < B < 0.33$, $13.6 < \text{Re}_0 < 54{,}000$, and $15 < \frac{H}{d} < 100$.

Generalization of the calculations of the pressure difference, just as in the case of solar collector 1 (Fig. 4B), yields

$$\frac{\Delta p_2}{(\Delta p)_E^{\text{mod}}} = 1.7\bar{q}_2^{\,0.08} B^{-0.05} \text{Re}_0^{-0.02} \left(\frac{H}{d}\right)^{-0.09}\,, \tag{53}$$

where $0.1 < B < 0.33$, $13.6 < \text{Re}_0 < 54{,}000$, and $0.03 < \bar{q}_2 < 1.33$.

The specific power consumed by pumping the heat-transfer agent, with account for (53), is

$$N_2 = \frac{\Delta p_2 J_f}{\rho_0} = \frac{J_f}{\rho_{f0}}\,\frac{\Delta p_2}{\left(\dfrac{\Delta p_2}{p_{\text{atm}}} + 1\right)}\,. \tag{54}$$

We obtain, for the efficiency, a formula analogous to (49):

$$\eta_2 = 1 - \frac{N_2}{q_2} = 1 - \frac{\Delta p_2}{(\Delta p_2 + p_{atm})} \tilde{q}_2^{-1} . \quad (55)$$

The calculations from (55) are shown in Fig. 5b.

The relative phase-temperature difference average over the bed Θ_2 (when $H \cong H_{2opt}$) is determined by a relation analogous to (50):

$$\Theta_2 = 0.65 \, (QH)_2^{0.83} . \quad (56)$$

Quasihomogeneity Criterion. To calculate the parameter $\Theta_3 = \frac{\langle T_s - T_f \rangle}{T_0}$, we have obtained [4], for the heat-releasing bed with Q = const, the dependence

$$\Theta_3 = 0.25 \, (QH)_3^{0.73} . \quad (57)$$

Comparing (50), (56), and (57) we can draw the conclusion on the significant role of the criteria $(QH)_1$, $(QH)_2$, and $(QH)_3$ in evaluating the degree of difference of the phase temperatures in one heat-exchange regime or another. Taking this into account, we can formulate a rather universal criterion:

$$(QH)_k = \frac{W_k d}{c_f J_f T_0} , \quad (58)$$

where W_k is the average heat-release power in unit volume of the bed; $W_1 = \frac{q_1}{H}$ is solar collector 1, $W_2 = \frac{q_2}{H}$ is solar collector 2, and $W_3 = Q(1 - \varepsilon)$ is the heat-releasing bed with Q = const.

The complex $(QH)_k$ determining the value of the relative phase-temperature difference can be called the quasihomogeneity criterion of a two-phase system, which makes it possible to determine the thermal state of the granular bed (degree of difference of the phase temperatures) on the basis of the existing conditions. Clearly, evaluation of $(QH)_k$ enables us to judge the possibility of using a simple one-temperature model. In [4], it has been shown from (57) that if Θ_3 = 0.01 is taken as the upper bound, it is allowable to use (1)–(3) for description of heat exchange in the heat-releasing granular bed for $(QH)_3 < 0.01$. As follows from (50) and (56), the one-temperature model can be used for $(QH)_k < 0.005$ (k = 1 and 2) in the case of solar collectors 1 and 2.

Conclusions. We have formulated the boundary condition of the third kind (22), which allows for the degree of turbulence of the flow of the heat-transfer-agent out of the granular bed. The dimensionless dependences for calculation of the size of the active zone of solar collector 1 (42) and solar collector 2 (51) have been obtained. The effective lengths of the beds in which the active zone occupies the entire volume of solar collector 1 (43) and solar collector 2 (52) have been determined. The dependences for calculation of the resistance of the bed and the efficiency of heat exchangers — solar collector 1 ((44) and (49)) and solar collector 2 ((53) and (55)) — have been obtained. The universal quasihomogeneity criterion of the heat-releasing bed (58), which makes it possible to evaluate the thermal state of the two-phase system on the basis of the existing conditions, has been formulated.

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NOTATION

B, index of attenuation of radiation: $B^* = BH/d$; c_f, specific heatof the heat-transfer agent at constant pressure, J/(kg·K); d, particle diameter, m; $D = p_{atm} d^3 \rho_f/(H\mu_f^2)$; $D_0 = p_{atm} d^3 \rho_{f0}/(H\mu_{f0}^2)$; H, length of the granular bed, m; $J_f = \rho_f u$, mass flow rate of the heat-transfer agent, kg/(m^2·sec); $\bar{J}_f = J_f^2 d^3/(\varepsilon^2 H \mu_f^2)$; $\bar{J}_{f0} = J_f^2 d^3/(\varepsilon^2 H \mu_{f0}^2)$; $\mathrm{Pe}_f = \frac{c_f J_f H}{\lambda}$, $\mathrm{Pe} = \frac{c_f J_f H}{\varepsilon \lambda_f}$, and $\mathrm{Pe}_s = \frac{c_f J_f H}{(1 - \varepsilon)\lambda_s}$, Péclet number; $\mathrm{Pr} = \frac{c_f \mu_f}{\lambda_f^0}$, Prandtl number; p, pressure, Pa; $p' = p/p_{atm}$, Pa; $\tilde{p}$ =

$p - p_{atm}$, Pa; q_k, incident radiation flux (k = 1, at entry into the bed, k = 2, at exit from the bed), W/m^2; $\bar{q}_k = \frac{q_k}{c_f J_f T_0}$; $\tilde{q}_k = \frac{q_k \rho_{f0}}{J_f p_{atm}}$; Q_k = heat-release power (k = 1 and 2), W/m^3; $\bar{Q}_k = \frac{Q_k H}{c_f J_f T_0}$; $(QH)_k = \frac{W_k d}{c_f J_f T_0}$, quasihomogeneity criterion; R, gas constant, m^2/(sec^2·K); $\mathrm{Re} = \frac{J_f d}{\mu_f}$, $\mathrm{Re}_0 = \frac{J_f d}{\mu_{f0}}$, Reynolds numbers; $\mathrm{St} = \frac{\alpha}{c_f J_f}$, $\mathrm{St}_0 = \frac{\alpha_0}{c_f J_f}$, and $\mathrm{St}_H = \frac{\alpha_H}{c_f J_f}$, Stanton numbers; T, temperature, K; T_0, inlet temperature of the heat-transfer agent, K; Tu, degree of turbulence; u, filtration rate of the heat-transfer agent, m/sec; v_f, gas velocity in the gaps between particles, m/sec; W_k, average heat-release power, W/m^3; x, longitudinal coordinate, m; x_a, length of the active portion, m; α, coefficient of interphase heat exchange, W/(m^2·K); α_0 and α_H, coefficients of heat exchange of the heat-transfer agent with the skeleton of particles for x equal to 0 and to H, W/(m^2·K); ε, porosity; ε_s, emissivity factor of particles; $\theta = (T - T_0)/T_0$; Θ, average-over-the bed (for $H \cong H_{1opt}$) relative difference of phase temperatures; λ_f and λ_s, coefficients of longitudinal thermal conductivity of the heat-transfer agent and the skeleton of particles, W/(m·K); λ_f^0, molecular thermal conductivity of the heat-transfer agent, W/(m·K); μ_f, dynamic viscosity of the heat-transfer agent, kg/(m·sec); μ_{f0}, dynamic viscosity of the heat-transfer agent at the temperature T_0, kg/(m·sec); ρ_f, density of the heat-transfer agent, kg/m^3; ρ_{f0}, density of the heat-transfer agent at atmospheric pressure and the temperature T_0, kg/m^3; $\rho_f' = \rho_f/\rho_{f0}$ and ρ_0, density of the heat-transfer agent at $p = p_0$, $T_f = T_0$, kg/m^3; $\xi = x/H$. Subscripts: a, active; atm, atmospheric; cr, critical; E, calculation from the Ergun formula (46); f, heat-transfer agent; opt, optimum; s, particles; 0, at entry; H, at exit; mod, modified.

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