Journal of Engineering Physics and Thermophysics, Vol. 81, No. 5, 2008

ON THE THERMAL CONDUCTIVITY OF A BLOWN GRANULAR BED

V. I. Kovenskii and Yu. S. Teplitskii

UDC 532.5

Dependences for calculation of the effective thermal-conductivity coefficients of a granular bed and its constituent phases have been obtained by analogy with the processes of convective heat and mass transfer. The dependences involve simple and quite reliable formulas for calculation of the conductive thermal conductivity of an unblown bed and the radiative thermal conductivity of the skeleton of solid particles.

Introduction. In describing heat transfer in a granular bed, the most substantiated results are yielded by the two-temperature model of the process. In the case of small velocities of filtration of the gas the equations of thermal conductivity of phases without internal sources have, in cylindrical coordinates, the form

$$c_{\rm f}\rho_{\rm f}\varepsilon\frac{\partial T_{\rm f}}{\partial t}+c_{\rm f}\rho_{\rm f}u\frac{\partial T_{\rm f}}{\partial x}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\varepsilon\lambda_{\rm f}^{r}\frac{\partial T_{\rm f}}{\partial r}\right)+\frac{\partial}{\partial x}\left(\varepsilon\lambda_{\rm f}^{x}\frac{\partial T_{\rm f}}{\partial x}\right)+\frac{6\,(1-\varepsilon)\,\alpha}{d}\,(T_{\rm s}-T_{\rm f})\,, \tag{1}$$

$$c_{\rm s}\rho_{\rm s}\,(1-\varepsilon)\frac{\partial T_{\rm s}}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\,(1-\varepsilon)\,\lambda_{\rm s}^{r}\frac{\partial T_{\rm s}}{\partial r}\right)+\frac{\partial}{\partial x}\left((1-\varepsilon)\,\lambda_{\rm s}^{x}\frac{\partial T_{\rm s}}{\partial x}\right)+\frac{6\,(1-\varepsilon)\,\alpha}{d}\,(T_{\rm f}-T_{\rm s})\,. \tag{2}$$

Under the conditions where the difference of the phase temperatures is negligible ($T_{\rm f}\simeq T_{\rm s}=T$), model (1) and (2) becomes the one-temperature (quasihomogeneous) model

$$\left(c_{\rm f}\rho_{\rm f}\varepsilon+c_{\rm s}\rho_{\rm s}\,(1-\varepsilon)\right)\frac{\partial T}{\partial t}+c_{\rm f}\rho_{\rm f}u\frac{\partial T}{\partial x}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda^{r}\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial x}\left(\lambda^{x}\frac{\partial T}{\partial x}\right), \tag{3}$$

where we have

$$\lambda^{r}=\varepsilon\lambda_{\rm f}^{r}+(1-\varepsilon)\,\lambda_{\rm s}^{r}\,;\quad \lambda^{x}=\varepsilon\lambda_{\rm f}^{x}+(1-\varepsilon)\,\lambda_{\rm s}^{x}\,. \tag{4}$$

Relations (4) are seen to represent the equations of connection of the effective thermal-conductivity coefficients of the bed λ^r and λ^x to the thermal-conductivity coefficients of the phases.

When (1)–(3) are used in concrete calculations, it is important to have reliable information on the thermal-conductivity coefficients, which are the parameters of these models. The conductive-convective components λ^r and λ^x have been studied to a sufficient degree in the literature. We give the most substantiated formulas for calculation of these coefficients [1]:

$$\lambda_{\rm c-c}^{r}=\lambda_{\rm c}+0.1c_{\rm f}\rho_{\rm f}ud\,,\quad \lambda_{\rm c-c}^{x}=\lambda_{\rm c}+0.5c_{\rm f}\rho_{\rm f}ud\,. \tag{5}$$

It is difficult to calculate the radiative thermal conductivity because of the absence of simple commonly accepted recommendations similar to (5). The same is true for the thermal-conductivity coefficients of the phases $\lambda_{\rm f}^{r}$, $\lambda_{\rm f}^{x}$, $\lambda_{\rm s}^{r}$, and $\lambda_{\rm s}^{x}$.

A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus; email: kvi@hmti.ac.by. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 81, No. 5, pp. 956–962, September–October, 2008. Original article submitted April 27, 2007.

Coefficients of Conductive-Convective Thermal Conductivity of the Phases. Two connection equations (4) are insufficient to find four coefficients $\lambda^r_{\mathrm{f,c-c}}$, $\lambda^x_{\mathrm{f,c-c}}$, $\lambda^r_{\mathrm{s,c}}$, and $\lambda^x_{\mathrm{s,c}}$. Therefore, we must use additional model representations of the mechanism of transition in the two-phase system. We believe that the approach based on the analogy of convective heat and mass transfer and adopted in [1] is the most substantiated. The existing dependences were used for determination of the diffusion coefficients of the gas impurity in a granular bed [1]:

$$D^r = 0.3D_{\mathrm{f}} + 0.1ud\,, \quad D^x = 0.3D_{\mathrm{f}} + 0.5ud\,. \tag{6}$$

In accordance with (6), it was taken that

$$\lambda^r_{\mathrm{f,conv}} = 0.1c_{\mathrm{f}}\rho_{\mathrm{f}}\frac{u}{\varepsilon}d\,, \quad \lambda^x_{\mathrm{f,conv}} = 0.5c_{\mathrm{f}}\rho_{\mathrm{f}}\frac{u}{\varepsilon}d\,. \tag{7}$$

Equations (4) and (5) yielded

$$\lambda^r_{\mathrm{s,c}} = \lambda^x_{\mathrm{s,c}} = \lambda_{\mathrm{c}}/(1-\varepsilon)\,. \tag{8}$$

We note that thereafter Aérov et al. [1] illegitimately used expressions (7) as $\lambda^r_{\mathrm{f,c-c}}$ and $\lambda^x_{\mathrm{f,c-c}}$. With allowance for the molecular thermal conductivity of the gas and with account for Eqs. (4)–(5), the thermal-conductivity coefficients of the phases at low temperatures can be determined more correctly:

$$\lambda^r_{\mathrm{f,c-c}} = \lambda_{\mathrm{f}} + 0.1c_{\mathrm{f}}\rho_{\mathrm{f}}\frac{u}{\varepsilon}d\,, \quad \lambda^r_{\mathrm{s,c}} = \lambda^x_{\mathrm{s,c}} = \lambda_{\mathrm{s,c}} = \frac{\lambda_{\mathrm{c}} - \varepsilon\lambda_{\mathrm{f}}}{1-\varepsilon}\,, \quad \lambda^x_{\mathrm{f,c-c}} = \lambda_{\mathrm{f}} + 0.5c_{\mathrm{f}}\rho_{\mathrm{f}}\frac{u}{\varepsilon}d\,. \tag{9}$$

To calculate the conductive component of the unblown (for u = 0) bed, in the present work, we have obtained, by processing experimental data [2], the following compact formula:

$$\frac{\lambda_{\mathrm{c}}}{\lambda_{\mathrm{f}}} = \left(\frac{\lambda_{\mathrm{s}}}{\lambda_{\mathrm{f}}}\right)^{(1-\varepsilon)\left(\frac{\lambda_{\mathrm{s}}}{\lambda_{\mathrm{f}}}\right)^{-0.06}}\,. \tag{10}$$

Dependence (10) represents a more simple and accurate (mean error ≈4% for ε = 0.35–0.48) approximation compared to the formula

$$\frac{\lambda_{\mathrm{c}}}{\lambda_{\mathrm{f}}} = 1 + \frac{(1-\varepsilon)\,(1-\lambda_{\mathrm{f}}/\lambda_{\mathrm{s}})}{\lambda_{\mathrm{f}}/\lambda_{\mathrm{s}} + 0.28\varepsilon^{0.63(\lambda_{\mathrm{f}}/\lambda_{\mathrm{s}})^{-0.18}}} \tag{11}$$

proposed in [2] and much cited in the literature (mean approximation error ~15%).

Coefficient of Radiative Thermal Conductivity of the Bed Skeleton. A pile model [3, 4] allowing for the cooperative effects has been used as a tool of assessment of this parameter. The model was developed for calculation of the transfer of radiation in a homogeneous dispersive medium of optically large particles with their different concentration (from a packed bed to very rarefied systems $1-\varepsilon = 5\cdot10^{-3}$). Within the model's framework, the system of opaque gray spherical particles (uniformly distributed in space) with a diffusely reflecting surface is represented as a set (pile) of parallel plates (elementary layers in terms of the model) characterized by the coefficients of reflection r_{t}, transmission τ_{t}, and absorption ε_{t}. The above coefficients are determined using the auxiliary model [3] in which their calculation is reduced to solution of the problem on radiative transfer in a closed system formed by isothermal gray and black surfaces. When r_{t}, τ_{t}, and ε_{t} are known, the reflection, transmission, and absorption coefficients of a pile of k elementary layers are calculated from the following recurrence formulas:

$$r_n = r_{n-1} + \frac{\tau_{n-1}^2 r_t}{1 - r_{n-1} r_t} \quad (r_1 = r_t) , \tag{12}$$

$$\tau_n = \frac{\tau_{n-1}\tau_t}{1 - r_{n-1} r_t} \quad (\tau_1 = \tau_t) , \tag{13}$$

$$\varepsilon_n = 1 - r_n - \tau_n , \tag{14}$$

which allow for the multiple reflection of radiation between the elementary layers.

The emissivity factor and the reflection coefficient of the surface of an infinitely thick pile are determined as

$$R = \lim_{n \to \infty} r_n , \quad \varepsilon_b = 1 - R , \tag{15}$$

since $\tau_n \to 0$ for $n \to \infty$.

For description of the transfer of radiation in a packed bed one widely uses a continuous approximation [5] in which the disperse system is considered as a homogeneous scattering, absorbing, and radiating medium. In this case the bed is characterized by the indices of absorption κ, scattering σ_b, and attenuation $\kappa + \sigma_b$ and by the optical thickness $\tau_x = (\kappa + \sigma_b)x$, and the transfer equation is used to determine the radiant flux and the temperature profile. The appreciable optical thickness of the bed ($\tau_x >> 1$) makes it possible to consider the propagation of radiation as its diffusion [5] and to characterize the transport properties of the medium by the radiative thermal conductivity

$$\lambda_r = \frac{16}{3} \frac{\sigma}{\kappa + \sigma_b} T^3 . \tag{16}$$

As is seen from (16), assessment of the radiative thermal conductivity requires κ and σ_b values which can be calculated from certain model representations of a disperse system (with the pile model in this case). Comparing the expressions for the reflectivity and transmissivity of the plane-parallel bed of a closely packed gray granular medium, which have been established within the framework of the pile model and in the diffusion approximation of the transfer equation [6], we can obtain the following formulas:

$$\kappa d = -\frac{1 - R}{2(1 + R)} \ln \frac{\sqrt{1 + a^2} - 1}{a} , \quad \sigma_b d = -\frac{2R}{1 - R^2} \ln \frac{\sqrt{1 + a^2} - 1}{a} \tag{17}$$

(where $a = \frac{2R\tau_t}{(1 - R^2) r_t}$) making it possible to calculate the indices of absorption and scattering and hence the radiative thermal conductivity (16). The results of these calculations can be approximated by the approximate formula

$$\lambda_r = \frac{16}{3} \left(0.35 + 0.52\varepsilon_s^{0.85}\right) \sigma T^3 d = 4 \left(0.47 + 0.7\varepsilon_s^{0.85}\right) \sigma T^3 d = \left(1.87 + 2.77\varepsilon_s^{0.85}\right) \sigma T^3 d . \tag{18}$$

The mean approximation error amounts to 0.28% with a maximum error of 0.84%.

A great many formulas for calculation of the radiative thermal conductivity that are analogous to (18) and have been obtained from different models of radiation transfer in the bed are presented in the literature. To compare different dependences we represent (16), following [7], in the form

$$\lambda_r = 4\chi\sigma T^3 d , \tag{19}$$

where the factor χ reflects the model representations used in deriving the formula. Different expressions for this parameter are given in Table 1.

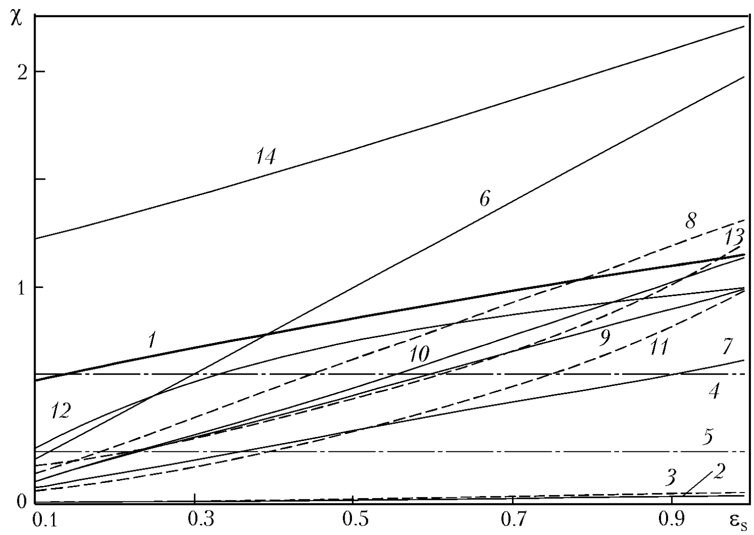

Fig. 1. Model parameter χ vs. emissivity factor of particles ε_s. Curve number corresponds to the formula number in Table 1.

TABLE 1. Formulas for the Model Parameter χ

No.	Parameter χ	Literature source	No.	Parameter χ	Literature source
1	$0.47 + 0.7\varepsilon_s^{0.85}$	(18)	9	ε_s	[15]
2	$0.0305\varepsilon_s$	[8]	10	$\dfrac{2\varepsilon_s}{2 - 0.264\varepsilon_s}$	[16]
3	$0.05\varepsilon_s^2$	[9]			
4	$\dfrac{8}{9}\dfrac{\varepsilon}{1-\varepsilon} = \dfrac{16}{27}\Big\|_{\varepsilon = 0.4}$	[10]	11	$\dfrac{2\varepsilon_s}{2 - 0.264\varepsilon_s}$	[17, 18]
5	$\dfrac{8}{9}\dfrac{\varepsilon^2}{1-\varepsilon} = \dfrac{6.4}{27}\Big\|_{\varepsilon = 0.4}$	[11]	12	$\dfrac{1}{1 + \dfrac{\varepsilon}{1-\varepsilon}\dfrac{1-\varepsilon_s}{2\varepsilon_s}} = \dfrac{1}{1 + \dfrac{2}{3}\dfrac{1-\varepsilon_s}{2\varepsilon_s}}\Bigg\|_{B = 0.1}$	[19]
6	$2\varepsilon_s$	[12]			
7	$\dfrac{\varepsilon_s\varepsilon}{1-\varepsilon} = \dfrac{2}{3}\varepsilon_s\Big\|_{\varepsilon = 0.4}$	[13]	13	$\dfrac{2B + \varepsilon_s(1-B)}{(2-\varepsilon_s)(1-B)} = \dfrac{0.2 + 0.9\varepsilon_s}{0.9(2-\varepsilon_s)}\Big\|_{B = 0.1}$	[20]
8	$\dfrac{1-(1-\varepsilon)^{2/3} + (1-\varepsilon)^{4/3}}{1-\varepsilon}\varepsilon_s = 1.325\varepsilon_s\big\|_{\varepsilon = 0.4}$	[14]	14	$\dfrac{\varepsilon_s + B}{1-B} = \dfrac{10}{9}(\varepsilon_s + 0.1)\Big\|_{B = 0.1}$	[21]

Figure 1 plots the model parameters χ as functions of the emissivity factors of particles ε_s; the dependences correspond to the formulas from Table 1. As is seen, the curve corresponding to (18) lies in the zone of "accumulation" of the dependences taken from the given literature. The dependence (12) from [19] is the closest to (18). It is significant that formula (18) is not empirical, and the pile model underlying it allows for the effect of collective inter-

TABLE 2. Packed-Bed Characteristics Used in the Experiments

No.	Literature source	Solid–gas	ε	d, mm	ε_s	$\tilde{\lambda}_s$, W/(m·K)	$T_{min} - T_{max}$, K
1	[22]	Alumina–air	0.36	2.77	$0.83 - 4\cdot10^{-4}(T - 300)$	$3.6 - 3\cdot10^{-3(}T - 300)$	350—1250
2	[22]	Alumina–air	0.38	6.64	$0.83 - 4\cdot10^{-4}(T - 300)$	$3.6 - 3\cdot10^{-3}(T - 300)$	350—1250
3	[22]	Alumina–air	0.37	0.96	$0.83 - 4\cdot10^{-4}(T - 300)$	$3.6 - 3\cdot10^{-3}(T - 300)$	350—1250
4	[22]	Aluminum–air	0.37	3.24	$0.043 + 3.4\cdot10^{-5}(T - 300)$	$220 - 0.036(T - 300)$	340—660
5	[22]	Aluminum–air	0.38	6.33	$0.043 + 3.4\cdot10^{-5(}T - 300)$	$220 - 0.036(T - 300)$	320—670
6	[22]	Glass–air	0.37	2.85	$0.95 - 6\cdot10^{-4}(T - 300)$	$1.2 + 6\cdot10^{-4}(T - 300)$	350—600
7	[22]	Glass–air	0.37	6.0	$0.95 - 6\cdot10^{-4}(T - 300)$	$1.2 + 6\cdot10^{-4}(T - 300)$	330—600
8	[22]	Glass–air	0.39	13.5	$0.95 - 6\cdot10^{-4}(T - 300)$	$1.2 + 6\cdot10^{-4}(T - 300)$	360—590
9	[23]	Alumina–air	0.4	6.0	$0.83 - 4\cdot10^{-4}(T - 300)$	$3.6 - 3\cdot10^{-3}(T - 300)$	310—950
10	[23]	Steel–air	0.4	11.0	0.8	$45 - 2\cdot10^{-2}(T - 473)$	413—1113
11	[23]	Cement clinker–air	0.4	0.18	0.54	2.5	440—930
12	[23]	Cement clinker–air	0.4	2.6	0.54	2.5	600—1110
13	[23]	Cement clinker–air	0.4	3.6	0.54	2.5	540—1060
14	[23]	Cement clinker–air	0.4	5.0	0.54	2.5	600—1130
15	[7]	Alumina–air	0.48	0.37	$0.83 - 4\cdot10^{-4}(T - 300)$	$3.6 - 3\cdot10^{-3}(T - 300)$	700—1250
16	[7]	Sand–air	0.43	0.45	0.63	$4.65 - 3.4\cdot10^{-3}(T - 550)$	620—1150
17	[7]	Sand–air	0.43	0.65	0.63	$4.65 - 3.4\cdot10^{-3}(T - 550)$	650—1200
18	[24]	Aluminum–air	0.4	50.0	0.1	167	300
19	[24]	Copper–helium	0.4	50.0	0.1	387	300

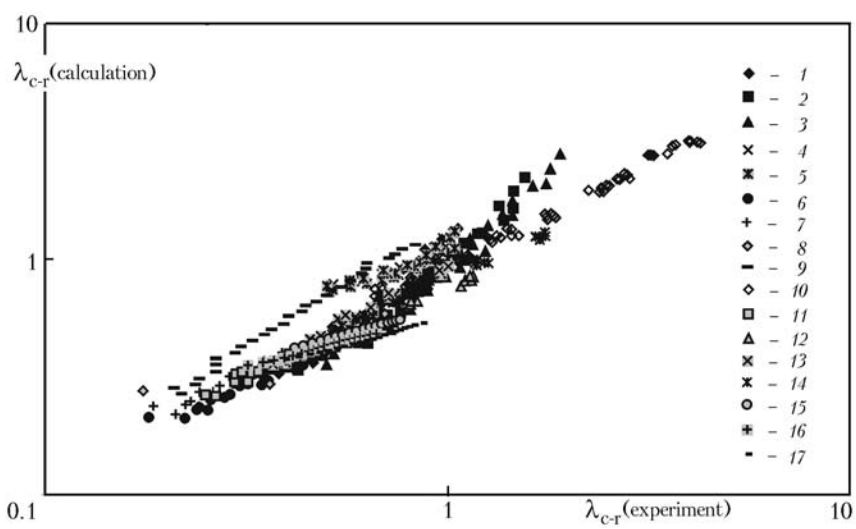

Fig. 2. Comparison of experimental data to the calculation from formula (21). Marker number corresponds to the line number in Table 2.

action of all particles, characteristic of concentrated systems. Therefore, (18) can serve as a certain reference point in the great number of the given recommendations (Table 1).

Coefficients of Effective Thermal Conductivity of the Bed. Since λ_r refers to the skeleton of particles, λ^r and λ^x with account for (5) can be represented as

$$\lambda^r = \lambda_{c-r} + 0.1 c_f \rho_f u d \,, \quad \lambda^x = \lambda_{c-r} + 0.5 c_f \rho_f u d \,, \tag{20}$$

TABLE 3. Effective Thermal-Conductivity Coefficients of a Blown Packed Bed

Constitutive formula	Coefficient
One-temperature model	
$\lambda^r = \lambda_{c-r} + 0.1 c_f \rho_f u d = \lambda^r_{c-c} + \lambda_r(1-\varepsilon)$	effective thermal conductivity of the bed across the flow
$\lambda^x = \lambda_{c-r} + 0.5 c_f \rho_f u d = \lambda^x_{c-c} + \lambda_r(1-\varepsilon)$	effective thermal conductivity of the bed along the flow
$\lambda_c = \lambda_f \left(\frac{\lambda_s}{\lambda_f}\right)^{(1-\varepsilon)\left(\frac{\lambda_s}{\lambda_f}\right)^{-0.06}}$	conductive thermal conductivity of an unblown bed
$\lambda^r_{c-c} = \lambda_c + 0.1 c_f \rho_f u d$	conductive-convective thermal conductivity of the bed across the flow
$\lambda^x_{c-c} = \lambda_c + 0.5 c_f \rho_f u d$	conductive-convective thermal conductivity of the bed along the flow
$\lambda_{c-r} = \lambda_c + \lambda_r(1-\varepsilon)$	conductive-radiative thermal conductivity of an unblown bed
Two-temperature model	
$\lambda^r_{f,c-c} = \lambda_f + 0.1 c_f \rho_f \frac{u}{\varepsilon} d$	conductive-convective thermal conductivity of the bed across the flow
$\lambda^x_{f,c-c} = \lambda_f + 0.5 c_f \rho_f \frac{u}{\varepsilon} d$	conductive-convective thermal conductivity of the bed along the flow
$\lambda_{s,c} = (\lambda_c - \varepsilon\lambda_f)/(1-\varepsilon)$	conductive thermal conductivity of the bed skeleton
$\lambda_r = \frac{16}{3}(0.35 + 0.52\varepsilon_s^{0.85})\sigma T_s^3 d$	radiative thermal conductivity of the bed skeleton
$\lambda_{s,c-r} = \lambda_{s,c} + \lambda_r$	conductive-radiative thermal conductivity of the bed skeleton
Connection of the one- and two-temperature models	
$\lambda^r = \varepsilon\lambda^r_{f,c-c} + (1-\varepsilon)\lambda_{s,c-r}$	effective thermal conductivity of the bed across the flow
$\lambda^x = \varepsilon\lambda^x_{f,c-c} + (1-\varepsilon)\lambda_{s,c-r}$	effective thermal conductivity of the bed along the flow

where

$$\lambda_{c-r} = \lambda_c + (1-\varepsilon)\,\lambda_r\,. \qquad (21)$$

The validity of formula (21) proposed for calculation of the conductive-radiative thermal conductivity of an unblown dense bed was checked by comparing to the experimental data presented in [7, 22–24]. The packed-bed parameters corresponding to experimental conditions are given in Table 2. We processed ~430 experimental points. A comparison of the experimental data to the calculations from formula (21) is presented in Fig. 2. The mean deviation of the calculated values from those experimental amounted to ~15% with a maximum deviation of 58%.

Thermal-Conductivity Coefficients of the Gas Phase and the Skeleton of Particles. With account for λ_r and (9), these quantities are determined as follows:

$$\lambda_f^r = \lambda^r_{f,c-c} = \lambda_f + 0.1 c_f \rho_f \frac{u}{\varepsilon} d\,,\quad \lambda_f^x = \lambda^x_{f,c-c} = \lambda_f + 0.5 c_f \rho_f \frac{u}{\varepsilon} d\,,\quad \lambda_s^r = \lambda_s^x = \lambda_{s,c-r} = \frac{\lambda_c - \varepsilon\lambda_f}{1-\varepsilon} + \lambda_r\,. \qquad (22)$$

Table 3 gives systematized results of determination of the effective thermal-conductivity coefficient of a blown granular bed.

Conclusions. The formulas obtained in the present work for the thermal-conductivity coefficients (20)–(22): 1) meet the requirements of similarity of the processes of convective heat and mass transfer; 2) satisfy the connection equations (4); 3) allow for all the basic mechanisms of heat transfer in the blown granular bed; 4) contain dependences (10) and (18) for calculation of λ_c and λ_r that are distinguished for their fairly substantiated character and simplicity. This enables us to recommend formulas (20)–(22) for use in mathematical modeling of concrete processes of heat transfer and in engineering practice.

NOTATION

c_f and c_s, specific heat of the gas at constant pressure and specific heat of the particle material respectively, J/(kg·K); d, particle diameter, m; D, effective diffusion coefficient, m^2/sec; D_f, molecular-diffusion coefficient of the gas, m^2/sec; r, radial coordinate (across the gas flow), m; R, reflection coefficient of an infinitely thick pile; r_t, reflection coefficient of an elementary layer of the pile; T_f and T_s, temperatures of the gas and particles, K; t, time, sec; u, filtration velocity of the gas, m/sec; x, vertical coordinate (along the gas flow), m; α, coefficient of interphase heat exchange, W/(m^2·K); ε, porosity of the bed; ε_b, emissivity factor of the bed; ε_t, absorption coefficient of an elementary layer of the pile; ε_s, emissivity factor of particles; κ, index of absorption, 1/m; λ, thermal conductivity, W/(m·K); λ_f and λ_s, molecular thermal conductivity of the gas and the particle material, W/(m·K); ρ_f and ρ_s, density of the gas and particles, kg/m^3; σ, Stefan–Boltzmann constant, W/(m^2·K^4); σ_b, index of scattering, 1/m; τ_t, transmission coefficient of an elementary layer of the pile; τ_x, optical thickness. Superscripts: r, across the gas flow; x, along the gas flow. Subscripts: b, bed; f, gas; s, particles; c, conductive; conv, convective; c–c, conductive-convective; r, radiative; c–r, conductive–radiative; t, elementary (thin) layer of the pile; min, minimum; max, maximum; n, number of elementary layers in the pile.

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