Journal of Engineering Physics and Thermophysics, Vol. 81, No. 4, 2008

HEAT AND MASS TRANSFER IN POROUS AND DISPERSION MEDIA

THERMOMECHANICS OF A HEAT-RELEASING GRAINED LAYER

Yu. S. Teplitskii and V. I. Kovenskii UDC 532.5

From the point of view of the model of an infiltrative grained layer the influence of the heat release and compressibility of the gas on the resistance of the layer has been investigated. In the isothermal case, with account for the gas compressibility, the range of applicability of the known Ergan formula $\left(\frac{\Delta p}{p_{atm}}\right)_E \le 1$ *has been established. We have developed an engineering technique for calculating the resistance of the heat-releasing grained layer taking into account the simultaneous influence of the pressure and temperature on the gas density and viscosity.*

Introduction. As is known, the influence of thermal processes on the hydrodynamics of a layer can be significant, which under certain conditions leads to a radical change in the flow conditions [1–3]. From the practical point of view, of great importance is the investigation of the influence of the heat release on the resistance of a granular layer, largely determining the efficiency of a particular technical device.

To describe flows in grained layers, one usually uses the filtration theory based on the modified Darcy law, which in the elementary case at ρ_f = constant reduces to the equations [1]

$$-\frac{dp}{dx} = A\mu_f u + B\rho_f u^2 \,, \quad \frac{dv}{dx} = 0 \,. \tag{1}$$

Since ρ_f is a constant, the first equation of (1) is easily integrated and for the layer resistance we obtain

$$\frac{\Delta p}{h} = A\mu_f u + B\rho_f u^2 \,. \tag{2}$$

The best known variant of dependence (2) is the Ergan formula [4]

$$\frac{\Delta p}{h} = 150\,\frac{(1-\varepsilon)^2}{\varepsilon^3}\,\frac{\mu_f u}{d^2} + 1.75\,\frac{(1-\varepsilon)}{\varepsilon^3}\,\frac{\rho_f u^2}{d} \,, \tag{3}$$

which yields for the coefficients A and B the values

$$A = 150\,\frac{(1-\varepsilon)^2}{\varepsilon^3}\,\frac{1}{d^2} \,, \quad B = 1.75\,\frac{(1-\varepsilon)}{\varepsilon^3}\,\frac{1}{d} \,. \tag{4}$$

The Ergan formula describes experimental data on the resistance of grained layers composed of particles of compact form (balls, cylinders, tablets, etc.) in regimes where the dependences $\rho_f(p, T_f)$ and $\mu_f(T_f)$ can be neglected.

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. 4, pp. 637–645, July–August, 2008. Original article submitted January 21, 2007.

1062-0125/08/8104-0659©2008 Springer Science+Business Media, Inc.

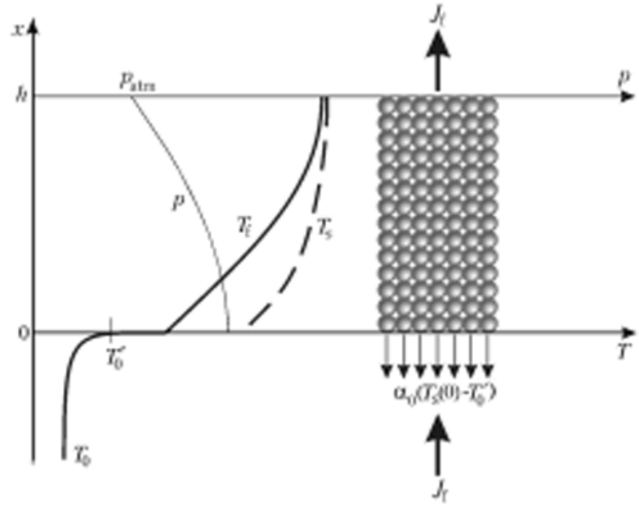

Fig. 1. Character of the phase temperature and pressure distribution inside the heat-releasing grained layer in the accepted coordinate system.

In [1], an analysis of the thermomechanical processes in a heat-releasing grained layer in the isobaric approximation (the gas density depends only on T_f) without account for the heat conductivity of phases was performed. For the calculation of the layer resistance, the expression

$$\frac{\rho_{f0}}{J_f^2}\Delta p = \hat{Q} + \frac{2}{5}\bar{\alpha}_1\left((1+\hat{Q})^{5/2}-1\right) + \bar{\alpha}_2\,(1+\hat{Q}/2) \tag{5}$$

was obtained. It permits estimating the influence of the heat release on the Δp value under the above assumptions.

The aim of the present work was to perform an analysis of the phenomenon in the general case, without any severe limitations on the physical and regime parameters of the grained layer.

Formulation of the Problem. To describe the stationary longitudinal heat transfer and the pressure distribution inside the heat-releasing layer (Fig. 1), we use the system of equations [1]

$$\varepsilon\rho_f v T_f \frac{dS}{dx} = \frac{d}{dx}\left(\varepsilon\lambda_f \frac{dT_f}{dx}\right) + \frac{6\,(1-\varepsilon)\,\alpha}{d}\,(T_s - T_f) + F_x u\,, \tag{6}$$

$$0 = \frac{d}{dx}\left((1-\varepsilon)\,\lambda_s \frac{dT_s}{dx}\right) + \frac{6\,(1-\varepsilon)\,\alpha}{d}\,(T_f - T_s) + Q\,(1-\varepsilon)\,, \tag{7}$$

$$\rho_f v \frac{dv}{dx} = -\frac{dp}{dx} - F_x\,, \tag{8}$$

$$p = \rho_f R T_f\,, \tag{9}$$

where F_x, a differential analog of (3), is used. Let us make use of the known thermodynamic relation [5]

$$dS = \frac{c_p}{T_f}\,dT_f - \left(\frac{\partial V_f}{\partial T_f}\right)_p dp\,. \tag{10}$$

In view of (8), (9) and the relation $V_f = 1/\rho_f$, Eq. (6) will take the form

$$\rho_f c_p u \frac{dT_f}{dx} = \frac{d}{dx}\left(\varepsilon\lambda_f \frac{dT_f}{dx}\right) + \frac{6(1-\varepsilon)\,\alpha}{d}(T_s - T_f) - \rho_f \varepsilon v^2 \frac{dv}{dx} . \tag{11}$$

It should be noted that the last term in (11) describes the action of the heat outflow, whose power increases with increasing x ($\frac{dv}{dx} > 0$, since the gas expands in the filtration process). At higher speeds of filtration the influence of this outflow can lead to a deformation of the temperature fields in the layer.

Equations (7)–(9) and (11) are considered at the following boundary conditions (with allowance for the gas preheating [6]):

$$x = 0: \qquad c_p J_f (T_f - T_0) = \varepsilon\lambda_f \frac{dT_f}{dx} + (1-\varepsilon)\,\lambda_s \frac{dT_s}{dx} , \tag{12}$$

$$(1-\varepsilon)\,\lambda_s \frac{dT_s}{dx} = \alpha_0 (T_s - T_0') ; \tag{13}$$

$$x = h: \qquad p = p_{atm} , \quad \frac{dT_f}{dx} = \frac{dT_s}{dx} = 0 . \tag{14}$$

With the use of the trivial relation

$$(1-\varepsilon)\,\lambda_s \frac{dT_s}{dx}\bigg|_{x=0} = c_p J_f (T_0' - T_0) \tag{15}$$

condition (13) will acquire the form

$$x = 0: \qquad (1-\varepsilon)\,\lambda_s \frac{dT_s}{dx} = \frac{\alpha_0}{1 + \frac{\alpha_0}{c_p J_f}} (T_s - T_0) . \tag{16}$$

Determination of the Model Parameters. In analyzing system (7)–(9), (11)–(14), the correct choice of the coefficients α, α_0, λ_f, λ_s is essential.

Heat-transfer coefficients. The interphase heat-transfer coefficient is calculated by the formulas [7]

$$\mathrm{Nu} = \frac{\alpha d}{\lambda_f^0} = \begin{cases} 0.4\left(\frac{\mathrm{Re}}{\varepsilon}\right)^{2/3} \mathrm{Pr}^{1/3} , & \frac{\mathrm{Re}}{\varepsilon} > 200 ; \\ 1.6 \cdot 10^{-2}\left(\frac{\mathrm{Re}}{\varepsilon}\right)^{1.3} \mathrm{Pr}^{1/3} , & \frac{\mathrm{Re}}{\varepsilon} \le 200 . \end{cases} \tag{17}$$

The heat-transfer coefficient α_0 defining the preheating intensity is found from the dependence [8]

$$\mathrm{St}_0 = \frac{\alpha_0}{c_p J_f} = 0.5\mathrm{Re}_0^{-0.5}\mathrm{Pr}^{-0.6} . \tag{18}$$

Heat-transfer coefficients of phases. In the literature, there are no uniform recommendations for calculating the parallel thermal conductivity of phases λ_f and λ_s. To analyze them, let us use the trivial relation

$$\lambda_x^{\text{c-c}} = \varepsilon\lambda_f + (1-\varepsilon)\,\lambda_s^{\text{c-c}} , \tag{19}$$

relating the heat conductivity coefficients of phases to the effective thermal conductivity of the layer λ_x^{c-c}. For the calculation of the latter, many empirical dependences exist. Note the most reliable dependence [4]

$$\lambda_x^{c\text{-}c} = \tilde{\lambda} + 0.5 c_p \rho_f u d\,, \tag{20}$$

where $\tilde{\lambda}$ can be determined by the formula [9]

$$\frac{\tilde{\lambda}}{\lambda_f^0} = 1 + \frac{(1-\varepsilon)\left(1 - \dfrac{\lambda_f^0}{\tilde{\lambda}_s}\right)}{\dfrac{\lambda_f^0}{\tilde{\lambda}_s} + 0.28\varepsilon^{0.63(\lambda_f^0/\tilde{\lambda}_s)^{-0.18}}}\,. \tag{21}$$

As is seen, for the calculation of λ_f and λ_s^{c-c} there is only one equation (19) with λ_x^{c-c} determined by (20) and (21). Therefore, additional model notions on the mechanism of heat transfer in a two-phase system are needed.

In [4], the analogy between the convective heat and mass transfer was used. For the basis, the known dependence for the parallel diffusion coefficient of the gas impurity

$$D_x = 0.3 D_f^0 + 0.5 u d \tag{22}$$

was used. In accordance with (2.2), for λ_f

$$\lambda_f = 0.5 c_p \rho_f \frac{u}{\varepsilon} d \tag{23}$$

was assumed. Then from (19) and (20) follows the formula for λ_s^{c-c}

$$\lambda_s^{c\text{-}c} = \frac{\tilde{\lambda}}{1-\varepsilon}\,. \tag{24}$$

In [10], the no-flow zones near the contact point between particles were assigned to the phase of the frame of particles, and for λ_f and λ_s^{c-c} the equations

$$\lambda_f = \lambda_f^0 + 0.03 c_p \rho_f u d\,, \tag{25}$$

$$\lambda_s^{c\text{-}c} = 12\lambda_f^0 + 0.85 c_p \rho_f u d \tag{26}$$

were obtained. In view of (25) and (26) at $\varepsilon = 0.4$ Eq. (19) takes the form

$$\lambda_x^{c\text{-}c} = 7.6\lambda_f^0 + 0.52 c_p \rho_f u d\,. \tag{27}$$

As the calculations show, for λ_x^{c-c} (27) gives values fairly close to those determined by (20).

Analyzing the systems of coefficients (23)–(26), we observe the following:

1) both systems for the homogeneous model give approximately equal values of the parallel heat conductivity λ_x^{c-c};

2) system (23), (24) does not take into account the molecular heat conductivity of the gas in the expressions for λ_f;

3) system (25), (26) does not comply with the requirements of analogy of the processes of convective heat and mass transfer and contains no thermal characteristics of particles.

Therefore, we took, as the basis, system (23), (24) with the addition of the molecular heat conductivity coefficient in λ_f and the corresponding correction in λ_s^{c-c}:

$$\lambda_f = \lambda_f^0 + 0.5 c_p \rho_f \frac{u}{\varepsilon} d \,, \tag{28}$$

$$\lambda_s^{c\text{-}c} = \frac{\tilde{\lambda} - \varepsilon \lambda_f^0}{1 - \varepsilon} \,. \tag{29}$$

The gross heat conductivity coefficient of the framework of particles is calculated by the formula

$$\lambda_s = \lambda_s^{c\text{-}c} + \lambda_r \,, \tag{30}$$

where the radiation component is [11, 12]

$$\lambda_r = \frac{0.3024}{\kappa + \sigma} \left(\frac{T_s}{100} \right)^3 . \tag{31}$$

Reduction to Dimensionless Form. Let us write system (7)–(9), (11)–(14) in the dimensionless form:

$$\frac{d\theta_f}{d\xi} = \frac{d}{d\xi} \left(\frac{1}{\text{Pe}_f} \frac{d\theta_f}{d\xi} \right) + \frac{1}{\text{Pe}} (\theta_s - \theta_f) - \frac{J_f^2}{c_p \varepsilon^2 \rho_f^2 (\theta_f + 1) T_0} \left(\frac{d\theta_f}{d\xi} - \frac{\theta_f + 1}{p'} \frac{dp'}{d\xi} \right), \tag{32}$$

$$0 = \frac{d}{d\xi} \left(\frac{1}{\text{Pe}_s} \frac{d\theta_s}{d\xi} \right) + \frac{1}{\text{Pe}} (\theta_f - \theta_s) + \hat{Q} \,, \tag{33}$$

$$\hat{J}_f \rho_f' \frac{d}{d\xi} \left(\frac{1}{\rho_f'} \right) = - D \frac{dp'}{d\xi} - 150 \frac{(1 - \varepsilon)^2}{\varepsilon^3} \text{Re} - 1.75 \frac{1 - \varepsilon}{\varepsilon^3} \text{Re}^2 \,, \tag{34}$$

$$\rho_f' = \frac{p'}{\theta_f + 1} \,. \tag{35}$$

The boundary conditions are

$$\xi = 0: \qquad \theta_f = \frac{1}{\text{Pe}_f} \frac{d\theta_f}{d\xi} + \frac{1}{\text{Pe}_s} \frac{d\theta_s}{d\xi} \,; \tag{36}$$

$$\theta_s = 6 (1 - \varepsilon) \frac{\text{Pe}_0 h}{\text{Pe}_s d} \frac{d\theta_s}{d\xi} (1 + \text{St}_0) \,; \tag{37}$$

$$\xi = 1: \qquad p' = 1 \,, \quad \frac{d\theta_f}{d\xi} = \frac{d\theta_s}{d\xi} = 0 \,. \tag{38}$$

For $\mu_f = \mu_{f0}(\theta_f + 1)^{0.75}$ [6] Eq. (34) in view of (35) can be given in a form more convenient for analysis

$$p' \frac{d}{d\xi}\left(\frac{\theta_f + 1}{p'}\right) = -\frac{\varepsilon^2 \mathrm{Re}_{sd}^2}{\gamma \mathrm{Re}_0^2} p' \frac{dp'}{d\xi} - \frac{h}{d}\left(150 \frac{(1-\varepsilon)^2}{\varepsilon} \frac{(\theta_f + 1)^{1.75}}{\mathrm{Re}_0} + 1.75 \frac{1-\varepsilon}{\varepsilon} (\theta_f + 1)\right). \tag{39}$$

Consider special cases allowing integration of (39).

Resistance of the Grained Layer in the Isothermal Case. At $\theta_f = 0$ (39) will have the form

$$p' \frac{d}{d\xi}\left(\frac{1}{p'}\right) = -\frac{\varepsilon^2 \mathrm{Re}_{sd}^2}{\gamma \mathrm{Re}_0^2} p' \frac{dp'}{d\xi} - \frac{h}{d}\left(150 \frac{(1-\varepsilon)^2}{\varepsilon} \frac{1}{\mathrm{Re}_0} + 1.75 \frac{1-\varepsilon}{\varepsilon}\right). \tag{40}$$

Let us integrate (40) from ξ to 1:

$$\ln\left(1 + \frac{p(\xi) - p_{atm}}{p_{atm}}\right) = -\frac{\varepsilon^2 \mathrm{Re}_{sd}^2}{2\gamma \mathrm{Re}_0^2}\left(1 - \left(1 + \frac{p(\xi) - p_{atm}}{p_{atm}}\right)^2\right) - \frac{h}{d}\left(150 \frac{(1-\varepsilon)^2}{\varepsilon} \frac{1}{\mathrm{Re}_0} + 1.75 \frac{1-\varepsilon}{\varepsilon}\right)(1-\xi). \tag{41}$$

For $\mathrm{Re}_{sd}^2/\mathrm{Re}_0^2 >> 1$ in (41) neglect of $\ln\left(1 + \frac{p(\xi) - p_{atm}}{p_{atm}}\right)$ is admissible. Then for the calculation of the layer resistance we obtain a simple dependence

$$\frac{p(\xi) - p_{atm}}{p_{atm}} \cong \sqrt{1 + 2\left(\frac{\Delta p}{p_{atm}}\right)_E (1-\xi)} - 1, \tag{42}$$

where $\left(\frac{\Delta p}{p_{atm}}\right)_E = \frac{\gamma \mathrm{Re}_0^2}{\mathrm{Re}_{sd}^2 \varepsilon^2} \frac{h}{d}\left(150 \frac{(1-\varepsilon)^2}{\varepsilon} \frac{1}{\mathrm{Re}_0} + 1.75 \frac{1-\varepsilon}{\varepsilon}\right)$ is a dimensionless writing of the Ergan formula for $\rho_f = \rho_{f0}$:

$$\frac{\Delta p}{h} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{J_f \mu_{f0}}{d^2 \rho_{f0}} + 1.75 \frac{1-\varepsilon}{\varepsilon^3} \frac{J_f^2}{d \rho_{f0}}. \tag{43}$$

As is seen, even in the isothermal case, in the layer, generally speaking, a nonlinear pressure profile is formed. At small values of $\left(\frac{\Delta p}{p_{atm}}\right)_E$ (42) will describe the pressure profile in the layer

$$\frac{p(\xi) - p_{atm}}{p_{atm}} \approx \left(\frac{\Delta p}{p_{atm}}\right)_E (1-\xi). \tag{44}$$

To calculate the total differential pressure in the layer, from (42) at $\xi = 0$ it follows that

$$\frac{\Delta p}{p_{atm}} \cong \sqrt{1 + 2 \frac{\gamma \mathrm{Re}_0^2}{\mathrm{Re}_{sd}^2 \varepsilon^2} \frac{h}{d}\left(150 \frac{(1-\varepsilon)^2}{\varepsilon} \frac{1}{\mathrm{Re}_0} + 1.75 \frac{1-\varepsilon}{\varepsilon}\right)} - 1 \tag{45}$$

or

$$\frac{\Delta p}{p_{atm}} \cong \sqrt{1 + 2 \frac{h}{p_{atm}}\left(150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu_f u}{d^2} + 1.75 \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho_f u^2}{d}\right)} - 1.$$

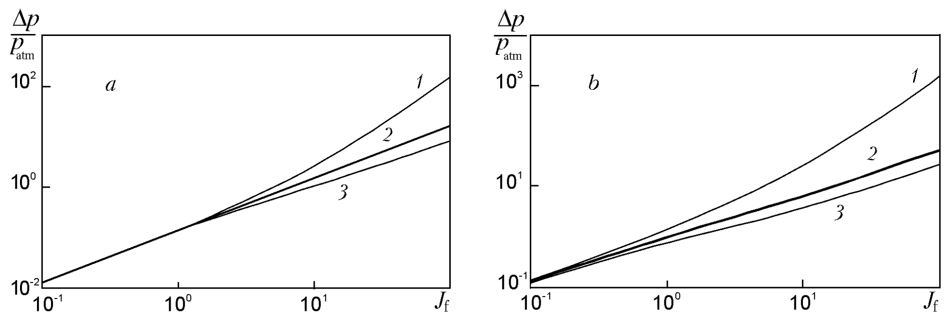

Fig. 2. Differential pressure in the grained layer (isothermal case): a) h/d = 100; b) 1000; 1) calculation by the Ergan formula (43); 2) calculation by (41) and 45); 3) calculation by the Ergan formula (43) with substitution of ρ_{f0} by $\rho_f(p_0)$. $d = 10^{-4}$ m. J_f, kg/(m^2·sec).

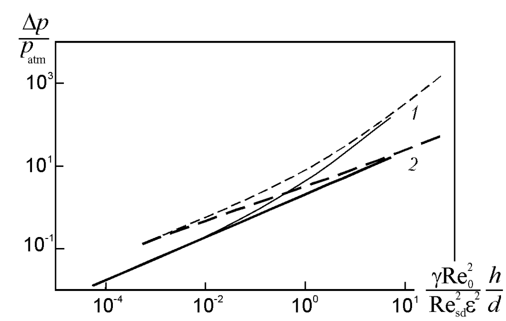

Fig. 3. Dimensionless differential pressure in the isothermal grained layer versus the complex $(\gamma \mathrm{Re}_0^2/\mathrm{Re}_{sd}{}^2\varepsilon^2$ (h/d): 1) calculation by the Ergan formula (43); 2) calculation by (41) and (45); h/d = 100 — solid lines; h/d = 1000 — dashed lines. $d = 10^{-4}$ m.

Figure 2 presents the results of the calculation of the differential pressure on the whole of the layer $\Delta p/p_{atm}$ by (41) at $\xi = 0$ and (45), as well as by the Ergan formula (43) and by the same formula at $\rho_f = \rho_f(p_0)$. It is seen that the exact solution of (41) practically coincides with the approximate solution of (45). Calculations by the Ergan formula for various densities of the gas give curves markedly differing from one anther and from the solutions of (41) and (45) (Fig. 2). As is seen, the calculation of the layer resistance by the Ergan formula, where the influence of pressure on the gas density is neglected, can lead to great errors at $\left(\frac{\Delta p}{p_{atm}}\right)_E > 0.1$. This conclusion holds as well for other analogous formulas obtained from the modified Darcy equation (e.g., the one used in (5)) in using them to calculate the resistance of a gas-blown layer when the differential pressure on the layer becomes comparable to the output pressure. The generalization of the results obtained is given in Fig. 3.

Resistance of the Grained Layer in the "Isobaric" Case. At $p' = 1$ (this is justified to some extent for thin layers) Eq. (39) assumes the form

$$\frac{d\theta_f}{d\xi} = -\frac{\varepsilon^2 \mathrm{Re}_{sd}^2}{\gamma \mathrm{Re}_0^2}\frac{dp'}{d\xi} - \frac{h}{d}\left(150\,\frac{(1-\varepsilon)^2}{\varepsilon}\frac{(\theta_f+1)^{1.75}}{\mathrm{Re}_0} + 1.75\,\frac{1-\varepsilon}{\varepsilon}(\theta_f+1)\right). \tag{46}$$

Following [1], we neglect the terms containing λ_f and λ_s in (6) and (7). Adding (32) and (33) for sufficiently large $\hat{Q}$, we obtain

$$\frac{d\theta_f}{d\xi} \approx \hat{Q}\,. \tag{47}$$

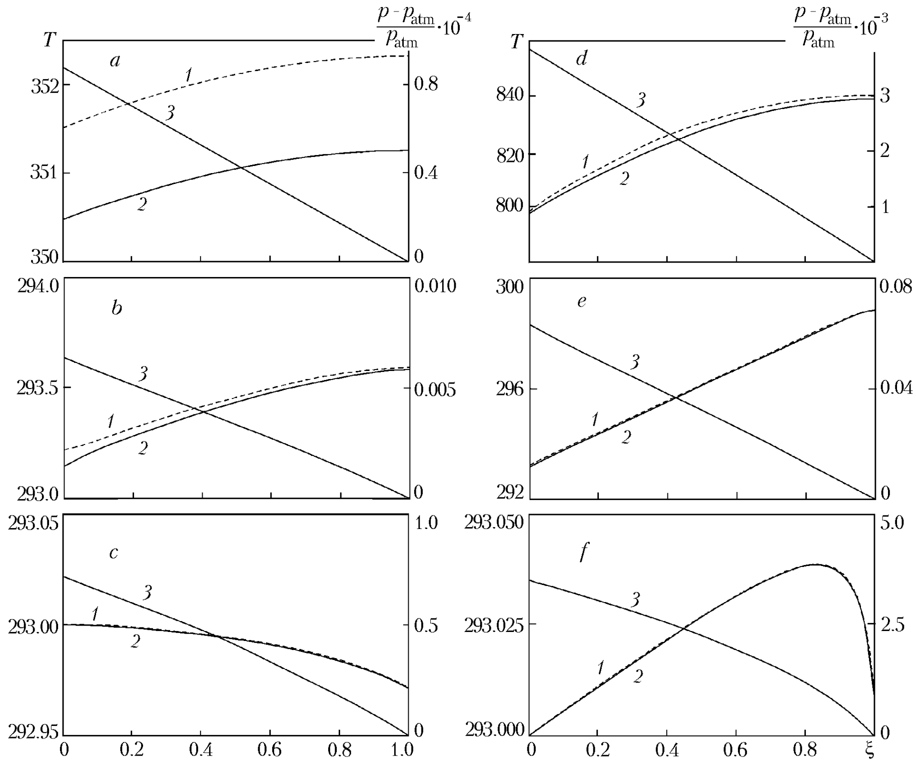

Fig. 4. Temperature and pressure profiles in the grained layer: a, b, c) h/d = 100; d, e, f) 1000; a, d) $J_f = 5 \cdot 10^{-4}$ kg/(m^2·sec); b, e) $5 \cdot 10^{-2}$; c, f) 5; 1) T_s; 2) T_f; 3) $(p - p_{atm})/p_{atm}$. $Q = 5 \cdot 10^3$ W/m^3, $d = 10^{-4}$ m.

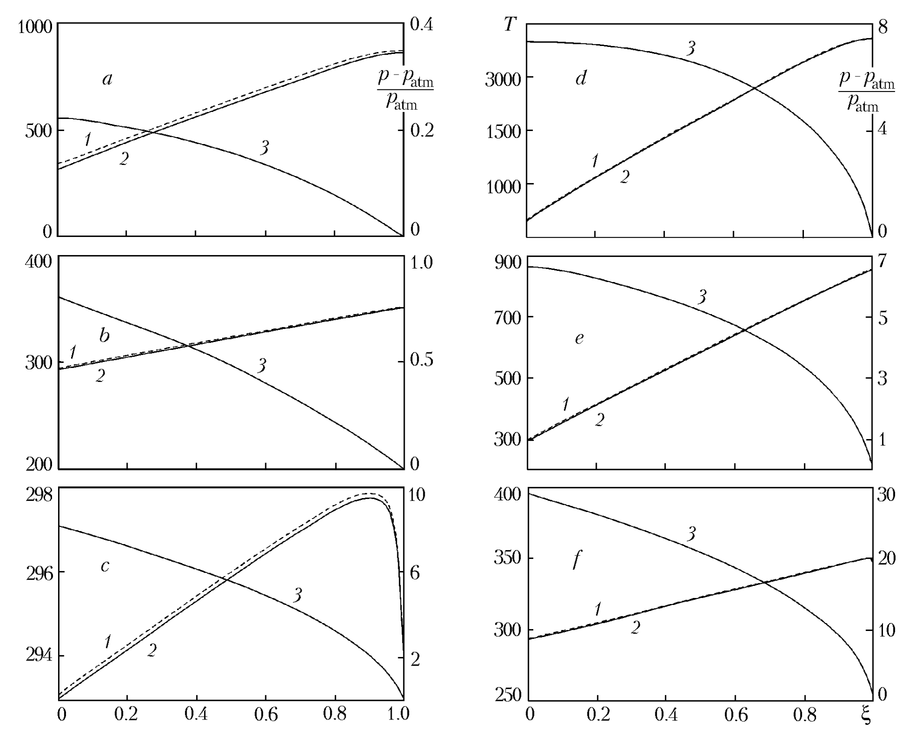

Fig. 5. Temperature and pressure profiles in the grained layer: a, b, c) h/d = 100; d, e, f) 1000; a, d) J_f = 0.5 kg/(m^2·sec); b, e) 50; 1) T_s; 2) T_f; 3) $(p - p_{atm})/p_{atm}$. $Q = 5 \cdot 10^7$ W/m^3, $d = 10^{-4}$ m.

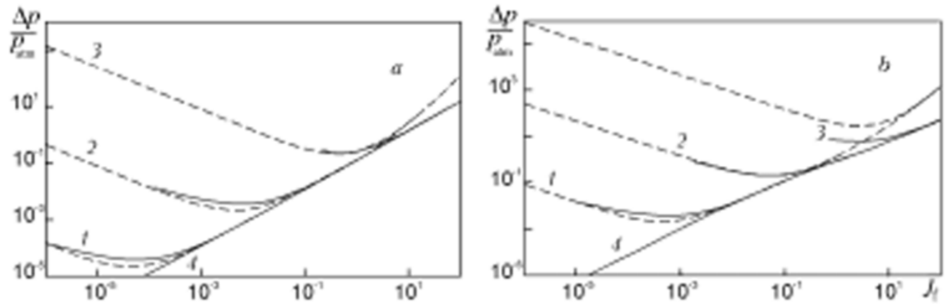

Fig. 6. Pressure differential in the grained layer (general case): a) h/d = 100; b) 1000; 1) Q = $5{\cdot}10^3$ W/m^3; 2) $5{\cdot}10^5$; 3) $5{\cdot}10^7$; 4) calculation by (45); dashed lines — calculation by (48), solid lines — numerical calculation. $d = 10^{-4}$ m. J_f, kg/(m^2·sec).

The solution of (47) with the boundary condition $\theta_f(0) = 0$ following from (36) has the form $\theta_f = \hat{Q}\xi$. The integration of (46) with respect to ξ from 0 to 1 in view of the solution of (47) yields an expression analogous to (5):

$$\frac{\rho_f^0}{J_f^2}\Delta p = \hat{Q} + \frac{h}{d}\frac{1-\varepsilon}{\varepsilon}\frac{1}{\hat{Q}}\left(\frac{54.5\,(1-\varepsilon)}{\mathrm{Re}_0}\left((1+\hat{Q})^{2.75}-1\right)+0.87\left((1+\hat{Q})^2-1\right)\right). \tag{48}$$

Resistance of the Grained Layer (general case). The layer resistance is influenced by the thermal processes and the pressure dependence of the gas density. Therefore, to determine Δp, one has to solve the complete system of equations (32)–(38). Figures 4 and 5 show the calculated phase temperature and pressure profiles for various values of J_f, Q, and h. As is seen, with increasing Q the pressure profile in the layer becomes essentially nonlinear. Note that the calculations of T_f, T_s, and p made for various λ_f and λ_s^{c-c} (Eqs. (25), (26) and (28), (29), respectively), turned out to be very close.

Figure 6 shows the dependences $\Delta p/p_{atm}$ obtained as a result of the numerical solution and by Eqs. (45) and (48). The given curves make it possible to determine the value of the flow rate $\tilde{J}_f$ at which Δp in the heat-releasing layer begins to coincide with the pressure differential value in the isothermal layer (curves 4). It should also be noted that at $J_f < \tilde{J}_f$ the calculations by (48) practically coincide with the numerical solution. As is seen from Fig. 6, at $J_f < \tilde{J}_f$ Δp can be calculated by (48), and at $J_f \geq \tilde{J}_f$ by (45). To determine $\tilde{J}_f$, we have obtained a simple relation

$$\hat{Q}\,(\tilde{J}_f) = \frac{Q\,(1-\varepsilon)\,h}{\tilde{J}_f c_p T_0} = 0.024\left(\frac{h}{d}\right)^{0.2}. \tag{49}$$

Note that the extreme character of the dependence $\Delta p(J_f)$ points to the existence of two J_f values corresponding to two stationary regimes of filtration at $\Delta p > \Delta p_{min}$. In [3], it has been shown that the regime with a lower flow rate is unstable. The system either slowly goes from this state to the stable stationary regime or is heated with no limit.

CONCLUSIONS

1. On the basis of the analogy of convective heat and mass transfer, dependences for calculating the parallel heat conductivity of phases (28), (29) have been obtained.

2. In the isothermal case, the account of the gas compressibility has made it possible to establish the range of applicability of the known Ergan formula $\left(\frac{\Delta p}{p_{atm}}\right)_E \leq 0.1$. At $\left(\frac{\Delta p}{p_{atm}}\right)_E > 0.1$ in the layer an essentially nonlinear pressure profile (42) is formed. In this case, to calculate the layer resistance, a simple relation (45) has been obtained.

3. For the isobaric case where the pressure dependence of the gas density can be neglected, formula (48) taking into account the influence of the heat release on the layer resistance has been obtained.

4. Relation (49) has been obtained for calculating the gas flow rate $\tilde{J}_f$ at which Δp in the heat-releasing layer begins to coincide with the differential pressure value in the isothermal case. At $J_f < \tilde{J}_f$ Δp can be calculated by (48), and at $J_f \geq \tilde{J}_f$ — by (45).

The obtained relations (45), (48), (49) have a simple form and are convenient for use in engineering practice.

NOTATION

c_v and c_p, specific heat capacities of gas at constant volume and pressure, respectively, J/(kg·K); d, particle diameter, m; D_f^0, molecular diffusion coefficient of the gas, m^2/sec; $D = p_{atm}d^3\rho_f/(h\mu_f^2)$; F_x, resistance force acting from the side of the flow on particles in a unput volume of the layer, N/m^3; h, height of the grained layer, m; $J_f = \rho_f u$, mass flow of the gas, kg/(m^2·sec); $\hat{J}_f = J_f^2 d^3/(\varepsilon^2 h \mu_f^2)$; $\mathrm{Pe}_0 = c_p J_f d/(6\alpha_0 h(1-\varepsilon))$, $\mathrm{Pe} = c_p J_f d/(6\alpha h(1-\varepsilon))$, $\mathrm{Pe}_f = c_p J_f h/(\varepsilon\lambda_f)$, $\mathrm{Pe}_s = c_p J_f h/((1-\varepsilon)\lambda_s)$, Peclet numbers; Pr, Prandtl number; p, pressure, Pa; p_0, pressure at the inlet to the layer, Pa; $\Delta p = p_0 - p_{atm}$; $p' = p/p_{atm}$; Q, heat release power, W/m^3; $\hat{Q} = Q(1-\varepsilon)h/(c_p J_f T_0)$; $\mathrm{Re} = J_f d/\mu_f$, $\mathrm{Re}_0 = J_f d/\mu_{f0}$, $\mathrm{Re}_{sd} = u_{sd} d\rho_{f0}/\mu_{f0}$, Reynolds numbers; R, gas constant, m^2/(sec^2·K); S, entropy, J/K; $\mathrm{St}_0 = \dfrac{\alpha_0}{c_p J_f}$, Stanton number; T_0, inlet gas temperature, K; T_0', gas temperature at $x \to 0$, K; T_f and T_s, temperature of gas and particles, K; u , gas filtration speed, m/sec; $u_{sd} = \sqrt{\gamma p_{atm}/\rho_{f0}}$, velocity of sound, m/sec; v, gas velocity in interparticle gaps, m/sec; x, coordinate, m; α, interphase heat transfer coefficient, W/(m^2·K); α_0, heat transfer coefficient between the framework of particles on the inflowing gas, W/(m^2·K); $\bar{\alpha}_1 = 633(1-\varepsilon)\varepsilon\mu_{f0}h/(J_f\hat{Q}d^2)$; $\bar{\alpha}_2 = 3\varepsilon(1-\varepsilon)h/(2\psi d)$; $\gamma = c_p/c_v$; $\xi = x/h$; ε, porosity; $\theta_f = (T_f - T_0)/T_0$; $\theta_s = (T_s - T_0)/T_0$; κ, absorption coefficient of the dispersion medium, 1/m; λ_f^0, molecular heat conductivity of the gas, W/(m·K); λ_f and λ_s, effective parallel heat conductivities of the gas and the framework of particles, respectively, W/(m·K); $\tilde{\lambda}_s$, heat conductivity of the particle material, W/(m·K); λ_x^{c-c}, effective parallel heat conductivity of the dispersion layer, W/(m·K); λ_r, radiation heat capacity of the dispersion layer, W/(m·K); μ_f, dynamic gas viscosity, kg/(m·sec); μ_{f0}, dynamic gas viscosity at T_0, kg/(m·sec); ρ_f, gas density, kg/m^3; ρ_{f0}, gas density at p_{atm} and T_0, kg/m^3; $\rho_f' = \rho_f/\rho_{f0}$; σ, scattering coefficient of the dispersion medium, 1/m; ψ, minimum relative flow section. Superscripts: 0, molecular; c-c, conductive-convective; subscripts: 0, inlet value; atm, atmospheric; E, calculation by the Ergan formula at ρ_{f0} and μ_{f0}; f, gas; r, radiation; s, particles; sd, sound; v, at constant volume.

REFERENCES

1. M. A. Gol'dshtik, *Transfer Processes in a Granular Layer* [in Russian], Inst. Teplofiziki SO AN SSSR, Novosibirsk (1984).
2. V. P. Maslov, V. P. Myasnikov, and V. G. Danilov, *Mathematical Modeling of the Accident Unit of the Chernobyl Nuclear Power Station* [in Russian], Nauka, Moscow (1988).
3. V. A. Levin and N. A. Lutsenko, Gas flow through a porous heat-releasing medium with allowance for the temperature dependence of the gas viscosity, *Inzh.-Fiz. Zh.*, **79**, No. 1, 35–40 (2006).
4. M É. Aérov, O. M. Todes, and D. A. Narinskii, *Apparatuses with a Stationary Granular Layer* [in Russian], Khimiya, Leningrad (1979).
5. I. K. Kikoin and A. K. Kikoin, *Molecular Physics* [in Russian], Fizmatgiz, Moscow (1962).
6. Yu. S. Teplitskii and V. I. Kovenskii, On the setting of boundary and conjugation conditions for problems of heat transfer in granular layers on the basis of a two-temperature model, *Inzh.-Fiz. Zh.*, **79**, No. 6, 98–106 (2006).
7. N. I. Gel'perin, V. G. Ainshtein, and V. B. Kvasha, *Principles of the Fluidization Technique* [in Russian], Khimiya, Moscow (1967).

8. E. M. Seliverstov, *Investigation and Development of Methods for Calculating Penetrating-Cooling Systems for the Blades of High-Temperature Gas Turbines*, Author's Abstract of Candidate's Dissertation (in Engineering), Moscow (2004).
9. N. I. Gel'perin and V. G. Ainshtein, Heat transfer, in: I. F. Davidson and D. Harrison (Eds.), *Fluidization* [in Russian], Khimiya, Moscow (1974), pp. 414–470.
10. Yu. Sh. Matros, V. I. Lugovskoi, B. L. Ogarkov, and V. B. Nakrokhin, Heat transfer in a blown stationary granular layer, *Teor. Osnovy Khim. Tekhnol.*, **12**, No. 2, 291–294 (1978).
11. E. M. Sparrow and R. D. Cess, *Radiation Heat Transfer* [Russian translation], Énergiya, Moscow (1977).
12. V. I. Kovenskii, On the calculation of the radiative characteristics of a concentrated dispersive medium, in: *Investigation of Heat- and Mass Transfer in Apparatuses with Dispersed Systems* [in Russian], ITMO AN BSSR, Minsk (1991), pp. 10–15.