ABSTRACTS OF ARTICLES DEPOSITED AT VINITI*

A NEW METHOD OF THERMAL CALCULATION OF APPARATUS CONTAINING A FLUIDIZED BED OF LARGE-GRAIN PARTICLES

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As is known, the expression for the determination of the average temperature $\bar{T}(r, \tau_0)$ of large-grain particles leaving a fluidized-bed apparatus with complete intermixing of the material is obtained with allowance for the distribution of the particles with respect to the time they spend in the apparatus and has the form

$$\bar{T}(r, \tau_0) = \frac{1}{\tau_0} \int_0^\infty T(r, \tau) \exp(-\tau/\tau_0)\, d\tau. \qquad (1)$$

Equation (1) is essentially none other than a Laplace–Carson transform ($1/\tau_0 = S$) of the function $T(r, \tau)$ and, consequently, to determine $\bar{T}(r, \tau_0)$ it is sufficient to solve the differential equation of thermal conduction in transforms for a single particle. Thus, a laborious transition from the transform to the inverse transform $T(r, \tau)$ with subsequent integration by Eq. (1) turns out to be unnecessary, and the solution obtained by the proposed method has the form of a most simple algebraic expression which is the absolutely accurate sum of the infinite slowly converging series which results from the use of Eq. (1).

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TRANSIENT THERMAL PROCESSES IN TWO-STAGE THERMOELECTRIC BATTERIES

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A method is proposed for calculating transitional thermal regimes in two-stage thermoelectric batteries which allows one to study the dynamic properties of this kind of cooling devices in a wide range of variation of their parameters. In the mathematical model allowance is made for the temperature dependence of the sinks and sources of Peltier heat, the dissipation of Joule heat along the arms of the thermoelements and at the junction contacts, the heat capacity of the load on the working surface of the thermopile, the commutation plates, and the thermal junction, and heat exchange with the surrounding medium. It is assumed that Thomson heat and the temperature variation of the thermophysical characteristics of the material of the thermal arms can be ignored in the calculations.

The use of a Laplace transform allows one to convert from the initial description of the thermal processes in the thermopile stages, given by two thermal-conduction equations, to a system of three Volterra integral equations for the temperatures of the junctions and the thermal junction. The equations derived are easily integrated numerically by the iteration method, which allows one to calculate the temperature reaction of a thermopile for a broad class of functions describing the time variation of the supply current. The algorithm for the numerical solution is given.

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Data are presented on calculations of the reaction to a stepwise variation of the current in a thermopile with series supply of the stages. The variation in the temperatures of the cold and hot junctions and of the thermal junction is monotonic, and therefore the transitional curves are conveniently characterized by two parameters: the attainable temperature drop and the time of the transition process. The connection of these quantities with the thermopile parameters is studied in a wide range of variation of the latter.

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COMPLEX HEAT EXCHANGE IN THE PLANE-PARALLEL PROBLEM IN A GRAY MEDIUM

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An analytical solution of the problem of complex heat exchange in a gray medium is obtained in the Schwarzschild—Schuster approximation for radiation. The convective fluxes are found from the semiempirical theory of turbulence and the coefficient of friction is assumed to be weakly temperature-dependent. For a correct comparison of the roles of radiant and convective heat exchange the temperature of the upper boundary is not fixed but is determined from the condition of steadiness of the fluxes. The critical value of the optical thickness of the system, above which radiant heat exchange exceeds convective heat exchange, is estimated. For a flow velocity on the order of 10 m/sec and a temperature of 1100°C it comprises 0.03.

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HEAT AND MASS TRANSFER FROM A ROTATING CYLINDER WITH DEVELOPED TURBULENT FLOW

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For the case of turbulent flow around a cylinder when it is rotating in an unbounded space the nature of the dependence of the coefficient of hydrodynamic resistance on the Reynolds number is the same as in the universal law of resistance for smooth pipes. Assuming that in the case of rotation of the cylinder in the range of Re = 10^4–$6 \cdot 10^5$ the relative velocity profile coincides with the velocity distribution for turbulent flow in a round cylindrical pipe, and taking the "$^1/_7$ law" for the pipe, one can find the expression for the thickness of the hydrodynamic boundary layer:

$$\delta = 0.473\, r_1^{0.808}\, \omega_1^{-0.096}\, \nu^{0.096}. \tag{1}$$

The problem of heat and mass transfer was solved by the Kármán three-layer system. For the viscous sublayer ($\beta \leq 5$) we assumed that the coefficient of turbulent transfer is proportional to the fourth power of the distance from the surface; in the transition layer ($5 \leq \beta \leq 30$) the transfer of heat or mass was calculated on the basis of the Prandtl mixing-length theory; in the turbulent core ($\beta \geq 30$) we neglected molecular transfer.

The calculating expression for the determination of the coefficients of heat and mass transfer has the form

$$\mathrm{Nu} = \frac{0.168\,\mathrm{Re}^{0.89}\mathrm{Pr}}{K^*}, \tag{2}$$

where

$$K^* = 1.38\,\mathrm{Pr}^{0.75}\left(\ln\frac{25+55.2\,\mathrm{Pr}^{-0.25}+61\,\mathrm{Pr}^{-0.50}}{25-55.2\,\mathrm{Pr}^{-0.25}+61\,\mathrm{Pr}^{-0.50}}\right.$$

$$\left.+2\,\mathrm{arctg}\,\frac{55.2\,\mathrm{Pr}^{-0.25}}{61\,\mathrm{Pr}^{-0.5}-25}\right)+5\ln\frac{1+6\mathrm{Pr}}{1+\mathrm{Pr}}+2.50\ln 2.65\cdot 10^{-3}\,\mathrm{Re}^{0.79}. \quad (3)$$

From (2) and (3) with Pr = 1 we obtain

$$\mathrm{Nu} = \frac{0.168\,\mathrm{Re}^{0.89}}{10.90+2.50\ln 2.65\cdot 10^{-3}\,\mathrm{Re}^{0.79}}. \quad (4)$$

From Eqs. (2) and (3) with $\mathrm{Pr} \to \infty$ we get

$$\mathrm{Nu} = 0.0194\,\mathrm{Re}^{0.89}\,\mathrm{Pr}^{0.25}. \quad (5)$$

A comparison of the calculated results with experimental data on heat and mass transfer from a rotating cylinder showed that the mean-square deviation of the calculated Nusselt numbers from the experimental values does not exceed 7%.

NOTATION

r_1, radius of cylinder; δ, thickness of hydrodynamic boundary layer; ω_1, angular velocity; ν, coefficient of kinematic viscosity; β, dimensionless thickness of hydrodynamic boundary layer; $\mathrm{Re} = \omega_1 r_1^2/\nu$, Reynolds number; Nu, Nusselt number; Pr, Prandtl number.

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FLOW OF A NON-NEWTONIAN LIQUID IN THE CHANNEL OF A WORM PUMP UNDER CONDITIONS OF COMPLEX SHEAR WITH ALLOWANCE FOR SLIPPAGE

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The isothermal steady flow of an anomalously viscous liquid, which conforms to a power-law rheological equation, in the screw channel of a worm pump is analyzed in the report. Slippage of the liquid along the core of the screw is taken into account. A plane model of the screw channel is used in solving the problem.

The liquid begins to slip along the surface of the stationary plate (the core of the screw) as soon as the shear stresses at it reach the value of the external frictional stress τ_f. In this case,

$$\tau_{xz}^2|_{z=0} + \tau_{yz}^2|_{z=0} = \tau_f^2. \quad (1)$$

If the condition (1) begins to be satisfied at sufficiently small longitudinal pressure gradients A_x then a component of the velocity of liquid slippage appears in the positive direction of the X axis (the direction along the screw channel), while if the condition (1) begins to be satisfied at sufficiently large A_x then a component appears in the negative direction of the X axis. A component of the velocity of liquid slippage in the direction of the Y axis (across the screw channel) is possible only in the negative direction. But if $(\tau_{xz}^2|_{z=0}+\tau_{yz}^2|_{z=0}) < \tau_T^2$, then liquid slippage will be absent.

Through the joint solution of the rheological equation and the equations of motion, using the boundary conditions at the lower plate, expressions are obtained for the dimensionless velocities v_1 and v_2 of the liquid and the flow rate q_1:

$$v_1 = \frac{w_x}{V_0} = \frac{1}{\alpha}\int_0^{\zeta}\psi(\zeta - C_1)\,d\zeta + v_s\cos\varphi_1, \quad (2)$$

$$v_2 = \frac{w_y}{V_0} = \frac{a}{\alpha} \int_0^\zeta \psi(\zeta - C_2)\, d\zeta - v_S \sin\varphi_1,$$

$$q_1 = \frac{Q_x}{V_0 HS} = \int_0^1 v_1 d\zeta = \frac{1}{\alpha} \int_0^1 \psi(\zeta - C_1)(1-\zeta)\, d\zeta + v_S \cos\varphi_1. \quad (3)$$

Here $\alpha = (V_0/H)(B/HA_x)^{1/n}$; $\psi = [(\zeta - C_1)^2 + a^2(\zeta - C_2)^2]^{(1-n)/2n}$; $\zeta = z/H$; w_x and w_y are the true velocities of particles of liquid in the directions of the X and Y axes; V_0 is the peripheral velocity of the screw; H and S are the depth and width of the screw channel; Q_x is the true liquid flow rate; $v_S = w_S/V_0$ is the dimensionless velocity of liquid slippage; B and n are rheological constants of the liquid; φ_1 is the angle between the resultant shear stress at the lower plate (the resultant velocity of slippage w_S) and the positive direction of the X axis, i.e.,

$$\operatorname{ctg}\varphi_1 = \left(-\frac{\tau_{xz}}{\tau_{yz}}\right)\Bigg|_{z=0}. \quad (4)$$

Five unknowns enter into Eqs. (2) and (3): two arbitrary constants of integration C_1 and C_2, the ratio of pressure gradients $a = A_y/A_x$, and the quantities v_S and φ_1. The second pair of boundary conditions, the condition that the flow rate in the direction of the Y axis equals zero, and Eqs. (1) and (4) serve to find them.

As a result of a numerical analysis it is shown that the liquid flow rate increases while the power and the pressure drop decrease with a decrease in the external frictional stress. Expressions are obtained in a particular case for the determination of the character istics of the process in the complete absence of adhesion of the liquid to the surface of the screw.

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MEASUREMENT OF THE FLOW RATE OF SWIRLED STREAMS WITH NORMAL FLOWMETER NOZZLES

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The results of an experimental determination of the length of the section of hydrodynamic stabilization of swirled streams are presented and the effect of the rotation of the liquid on the flow-rate coefficient of normal flowmeter nozzles is shown.

The length of the section of swirl damping displays a weak dependence on the Reynolds number. An increase in the intensity of swirling of the stream at the inlet increases its damping length from 95D behind a swirler with $\varphi_S = 30°$ to 115D behind a swirler with $\varphi_S = 60°$.

When the flowmeter is mounted within the section of hydrodynamic stabilization it is necessary to allow for the effect of stream swirling on the flow-rate coefficient. Four normal flowmeter nozzles were studied at different distances from the swirling source. The maximum departure of the flow-rate coefficient from the standard value was 7.5% for a nozzle of modulus 0.6 with $\varphi_S = 60°$ at a distance of 16D from the swirling source. The effect of stream swirling on the flow-rate coefficient decreases with a decrease in the modulus of the constricting device.

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DETERMINATION OF THE FORM FACTOR OF A GRAIN ON THE EXAMPLE OF FLOW OVER CYLINDERS

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A number of investigators presume empirical dependences in which the dynamic form factor of a grain (the ratio of coefficients of resistance of the grain and a sphere) depends only on the Reynolds number and on its geometrical form factor. Such an approach is justified for rounded bodies (rolled river and sea sand, etc.) but gives important disagreement with experiment in the more general case. This is confirmed by the results of a study of the laws of free settling of graphite cylinders in glycerin. The calculation of the geometrical form factor and the determination of the dynamic form factors presents no difficulties for such isometric bodies. The test results show that even for the simplest cases of symmetrical flow over cylinders the relationship between the dynamic and geometrical form factors is found to be more complex than, for example, that proposed in the empirical equations of Pettijohn, Christiansen, et al. This difference is explained by the effect on the resistance of the spatial position of the body in the liquid and its relative elongation.

Through the introduction of a conditional dynamic form factor it was possible to obtain its unique dependence on the relative elongation of the cylinder and to connect this quantity with the geometrical form factor. Following V. P. Lyashchenko, the equations are reduced to a dimensionless criterial form.

The relationship obtained can be used approximately to determine the form factors of a grain. A simplifying factor in this case is the constancy in the ratio of the three mutually orthogonal dimensions of granulated materials, noted in a number of reports of I. V. Lavrov. A comparison of tests on the fall of cylinders and of grains of granulated ceramsite and schungesite in glycerin shows the possibility of analyzing the data in the reduced criterial form and the possibility of using such an approximate approach in practice.

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MOVEMENT OF MIXTURES THROUGH POROUS MEDIA WITH ALLOWANCE FOR HEAT RELEASE

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Numerical solutions of a quasilinear system of equations of the dynamics of sorption with allowance for heat release are analyzed. The system of equations consists of an equation of material balance with allowance for longitudinal mixing, an equation of diffusion kinetics of sorption with allowance for the diffusional transfer of sorbate molecules in the "free" space of pores of a porous grain and along the "surface" of pores of a porous grain, an equation of heat balance with allowance for the effective coefficient of longitudinal thermal diffusivity, an equation of diffusion kinetics of heat exchange within a porous grain, the boundary equations of continuity of the fluxes of material and heat at the outer surface of a porous grain, and the initial and boundary conditions. A difference system of the second order of accuracy is presented for the numerical integration of this system of equations. An exact and an approximate model system of equations of sorption dynamics for the Langmuir thermal equation are integrated numerically as an example. For a stepwise form of the thermal equation of sorption estimates are made of the width of the stationary front with finite values of the coefficients of heat and mass exchange. The necessary and sufficient conditions are obtained for the existence and uniqueness of solutions of the equations of nonisothermal ($m_2 \neq 0$) sorption dynamics for a thermal equation of arbitrary form.

If $h^{(1)}(q_0) \neq 0$ and $h^{(1)}(q^0) \neq 0$ then the sufficient conditions for the existence and uniqueness of solutions of the equations of sorption dynamics have the form

$$h^{(1)}(q_0) > 0, \quad h^{(1)}(q^0) < 0, \quad q_0 = q(y_0), \quad q^0 = q(y^0), \quad y_0 < y < y^0.$$
$$h^{(1)}(q) = \partial\varphi/\partial q + \partial\varphi/\partial T B - w, \qquad B = Qw(w-a)^{-1}, \tag{1}$$

where $y = z - wt$, w is the velocity of a traveling wave, $\varphi = f^{-1}$, and f is the thermal sorption function.

If $h^{(1)}(q_0) = h^{(1)}(q^0) = 0$, then the sufficient condition has the form

$$(q - q_0)\, h^{(2)}(q_0) > 0, \qquad (q - q^0)\, h^{(2)}(q^0) < 0, \qquad B_0 = Q\mu(\mu - a)^{-1},$$
$$h^{(2)}(q) = \partial^2\varphi/\partial q^2 + 2B_0\partial^2\varphi/(\partial q\partial T) + B_0^2\partial^2\varphi/\partial T^2, \tag{2}$$
$$w = \mu, \quad \mu_{1,2} = A \pm (A^2 - a\partial\varphi/\partial q)^{1/2}, \qquad A = 1/2\,[\partial\varphi/\partial q + Q\partial\varphi/\partial T + a].$$

If $h^{(1)}(q_0) = h^{(1)}(q^0) = h^{(2)}(q_0) = h^{(2)}(q^0) = 0$, then the sufficient condition has the form

$$h^{(3)}(q_0) > 0, \qquad h^{(3)}(q^0) < 0. \tag{3}$$

In the majority of practical cases one can be confined to the conditions (1)-(3).

If $h^{(1)}(q_0) = h^{(2)}(q_0) = \ldots = h^{(p)}(q_0) = h^{(1)}(q_0) = \ldots = h^{(p)}(q^0) = 0$, then one can obtain the sufficient conditions for $h^{(p+1)}(q_0)$ and $h^{(p+1)}(q^0)$ in a form analogous to (2) and (3). The method of constructing the functions $h^{(p)}(q)$ is presented in the report. The sufficient conditions for isothermal ($T = 0$) and nonadiabatic ($m_2 \neq 0$) sorption dynamics are found from the conditions (2) and (3) with $B = B_0 = 0$.

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NONSTEADY TEMPERATURE FIELD DURING HEATING AND DRYING OF A FLUIDIZED BED WITH THERMAL RADIATION

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The temperature distribution is analyzed in an apparatus for the heating and drying of a fluidized bed when the heat is supplied through the upper boundary by thermal radiation. For the drying in the second period the problem has the form (one-phase model)

$$\frac{\partial\theta}{\partial\,\mathrm{Fo}} = \frac{\partial^2\theta}{\partial y^2} - \mathrm{Pe}\,\frac{\partial\theta}{\partial y} - \mathrm{Po}\exp(-\mathrm{Pd\,Fo}); \tag{1}$$

$$\theta(y, 0) = 0; \qquad \frac{\partial\theta(0, \mathrm{Fo})}{\partial y} = \mathrm{Pe}\,\theta(0, \mathrm{Fo}); \tag{2}$$
$$\frac{\partial\theta(1, \mathrm{Fo})}{\partial y} = \mathrm{Ki}.$$

Here Fo, Pe, Po, Pd, and Ki are the Fourier, Peclet, Pomerantsev, Predvoditelev, and Kirpichev numbers, respectively; θ and y are the dimensionless temperature and dimensionless longitudinal coordinate.

The solution, obtained using a Laplace transformation with respect to Fo, is written as follows:

$$\frac{\theta}{\mathrm{Ki}} = \frac{\exp[-2b(1-y)]}{2b} - 2\exp[-b(1-y)]\sum_{n=1}^{\infty}\frac{(\mu_n\cos\mu_n y + b\sin\mu_n y)\,\mu_n\exp[-(b^2+\mu_n^2)\,\mathrm{Fo}]}{(b^2+\mu_n^2)\,[2\mu_n(b+1)\sin\mu_n - (b^2+2b-\mu_n^2)\cos\mu_n]}$$
$$+\frac{\mathrm{Po}}{2\mathrm{KiPd}} - \frac{\mathrm{Po}}{\mathrm{KiPd}}\,[1-\exp(by)\,\mathrm{ch}(py)]\exp(-\mathrm{PdFo}) - \frac{\mathrm{Po}\exp(by)\,(p\,\mathrm{sh}\,p + b\,\mathrm{ch}\,p)\,(p\,\mathrm{ch}\,py + b\,\mathrm{sh}\,py)\exp(-\mathrm{PdFo})}{\mathrm{KiPd}\,[(2b^2-\mathrm{Pd})\,\mathrm{sh}\,p + 2bp\,\mathrm{ch}\,p]}$$
$$-\frac{2\mathrm{Po}}{\mathrm{Ki}}\exp(by)\sum_{n=1}^{\infty}\frac{\mu_n(b\cos\mu_n - \mu_n\sin\mu_n)\,(\mu_n\cos\mu_n y + b\sin\mu_n y)}{(b^2+\mu_n^2)\,(\mathrm{Pd}-b^2-\mu_n^2)\,[2\mu_n(b+1)\sin\mu_n - (b^2+2b-\mu_n^2)\cos\mu_n]}\exp[-(b^2+\mu_n^2)\,\mathrm{Fo}]. \tag{3}$$

Here $b = Pe/2$, $p = \sqrt{b^2 - Pd}$; μ_n are the roots of the characteristic equation

$$\operatorname{tg} \mu = \frac{2\mu b}{\mu^2 - b^2}. \tag{4}$$

The convergence of the solution (3) is estimated and solutions are obtained for the cases of $b < \sqrt{Pd}$ and $b = \sqrt{Pd}$. From (3) an expression is obtained for the drying in the first period ($Pd = 0$), as well as for the mean temperature over the volume of the bed during drying in the first and second periods and for the temperature distribution during the heating of a dry bed ($Po = 0$).

A numerical example is given of the calculation of the heating of a dry fluidized bed of sand; it is shown that a relatively sharp temperature drop over the height of the bed is established for low fluidization numbers; the duration of the emergence into a steady mode is about 20 min. It is shown that the required number of terms of the series in Eq. (3) does not exceed eight.

The solutions obtained can also be used to calculate the temperature field of a porous plate containing sources (sinks) of heat which depend exponentially on time, with mixed boundary conditions of the second and third kinds, and with blowing of gas through the porous wall.

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