In order to explain the suitability of formula (1) also for other processes taking place in a fluidized bed, Fig. 4 graphically shows the dependence of the degree of saturation of air by water vapor a^Z on the height of the fluidized bed H for different values of n and μ. The curve constructed according to formula (1) is also plotted on this graph.

It can be seen from Fig. 4 that the curve plotted according to formula (1) is close to the curves constructed for processes taking place in the wetted fluidized bed without heat evolution ($\mu = 0$) over the whole height of the bed H. In the presence of significant heat evolution, a significant difference can be seen between the path of the curves (in the direction of increase of a^Z) for a given height H and the curve obtained by formula (1). However, for values of $a^Z > 0.95$, all the curves practically coincide. Thus, we may assume that formula (1) can be used for estimating the height of the active zone h^Z_{az} for a wide circle of heat- and mass-exchange processes taking place in a wetted fluidized bed.

NOTATION

H, total height of fluidized bed, m; Z_0, Θ_0, humidity and temperature of the air at the inlet to the apparatus, kg/kg and °C; Z_∞, Θ_∞, humidity and temperature of the air at the outlet from the fluidized bed of infinite height; T, temperature of particles in the fluidized bed, °C; μ, quantity of heat evolved per 1 kg of assimilated moisture; g_C, mass flow rate of air, kg/m^2·h; F, surface area of particles in the fluidized bed, 1/m; α, β, coefficients of heat- and mass-exchange, respectively; P_0, atmospheric pressure, atm; w, linear velocity of air, m/sec; coefficients of Eq. (1): $K_1 = 0.36 \cdot 10^4$; K_2, shape factor of particles, equal to 1/6 for the case of spheres; K_3, ratio of the gas constants of the vapor supplied to the fluidized bed of liquid and fluidizing agent, equal to 0.622 in the case of water vapor and air; HB, dimensionless complex, where $B = \beta F P_0 / g_C$.

LITERATURE CITED

1. N. I. Gel'perin, V. G. Ainshtein, and V. B. Kvasha, Principle of Fluidizing Technology [in Russian], Khimiya, Moscow (1967).
2. V. F. Volkov, V. I. Churkin, et al., Khim. Prom-st', No. 9 (1967).
3. V. F. Volkov, G. I. Shishkin, V. V. Ukhlov, and T. G. Zhugrina, Inzh.-Fiz. Zh., 24, No. 3 (1973).
4. V. V. Ukhlov, G. I. Shishkin, and V. F. Volkov, Teor. Osn. Khim. Tekhnol., 5, No. 5 (1971).
5. Ya. Tsiborovskii and A. Seletskii, Zh. Prikl. Khim., 31, No. 4 (1958).

FORCED-CONVECTION HEAT TRANSFER IN POROUS MEDIUM WITH JOULE–THOMSON EFFECT

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The heat-conduction effect on the thermal field of the throttle effect is investigated close to the boundary of a porous medium at low pressure gradients.

A thermal field is considered in two semiinfinite media, one of which is impenetrable and the other of which is a porous medium; in the latter a fluid motion takes place accompanied by the Joule–Thomson effect. Such a problem arises when thermal fields are investigated in collector-carriers of oil and gas [1] or in various installations for studying and utilizing the Joule–Thomson effect. A wide range of heat-exchange problems on the boundary of two different throttle fluids can be reduced to the above problem.

It is known that the heat-conduction effect due to fluid motion is small [2]. A low pressure gradient arises in the direction of convection so that the derivative of temperature due to throttling is small; the latter

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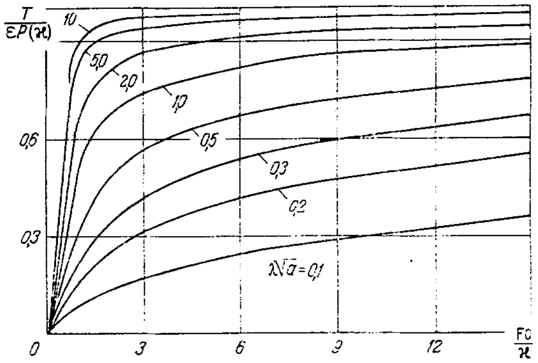

Fig. 1

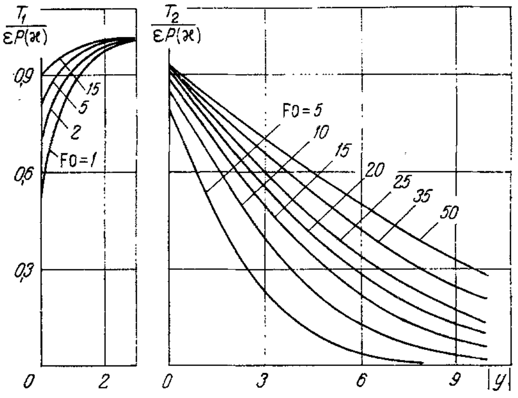

Fig. 2

Fig. 1. Relative temperature $T/\varepsilon P(\varkappa)$ versus $\mathrm{Fo}/\varkappa$ for $y = 0$ for linear pressure profile $P(\varkappa) = c\varkappa$.

Fig. 2. Relative temperature $T_{1,2}/\varepsilon P(\varkappa)$ versus y for linear pressure profile.

enables one to neglect heat conduction due to throttling in an impenetrable medium. It is assumed that instantaneous heat exchange takes place between the skeleton of porous medium and the throttling fluid [3].

The problem can therefore be formulated mathematically as

$$a_1 \frac{\partial^2 T_1}{\partial z^2} - u\left[\frac{\partial T_1}{\partial x} + \varepsilon \frac{\partial P}{\partial x}\right] = \frac{\partial T_1}{\partial t}, \; z<0, \; x>0, \; t>0, \tag{1}$$

$$a_2 \frac{\partial^2 T_2}{\partial z^2} = \frac{\partial T_2}{\partial t}, \; z>0, \; t>0, \; x>0 \tag{2}$$

with the boundary conditions

$$T_1|_{z=0} = T_2|_{z=0}; \quad \lambda_1 = \frac{\partial T_1}{\partial z}\Big|_{z=0} = \lambda_2 \frac{\partial T_2}{\partial z}\Big|_{z=0} \tag{3}$$

and the initial condition

$$T_{1,2}|_{t=0} = 0. \tag{3'}$$

In the dimensionless form it becomes

$$\frac{\partial^2 T_1}{\partial y^2} = \frac{\partial T_1}{\partial \varkappa} + \varepsilon \frac{\partial P}{\partial \varkappa} + \frac{\partial T_1}{\partial \mathrm{Fo}}; \; y<0, \; \varkappa>0, \; \mathrm{Fo}>0; \tag{4}$$

$$\frac{\partial^2 T_2}{\partial y^2} = \frac{\partial T}{\partial \mathrm{Fo}}; \; y>0, \; \mathrm{Fo}>0; \tag{5}$$

$$T_1|_{y=0} = T_2|_{y=0}; \quad \lambda \frac{\partial T_1}{\partial y}\Big|_{y=0} = \frac{\partial T_2}{\partial y}\Big|_{y=0}; \quad T_{1,2}|_{\mathrm{Fo}=0} = 0. \tag{6}$$

In the above one has

$$\mathrm{Fo} = \frac{at}{R^2}; \; \varkappa = \frac{xa}{uR^2}; \; y = \frac{z}{R}; \; a = \frac{a_2}{a_1}; \; \lambda = \frac{\lambda_1}{\lambda_2}. \tag{7}$$

In the Laplace—Carson transform space,

$$v_{1,2} = pq \int_0^\infty d\,\mathrm{Fo} \int_0^\infty \exp(-p\,\mathrm{Fo} - q\varkappa)\, T_{1,2}(y, \varkappa, \mathrm{Fo})\, d\varkappa, \tag{8}$$

the problem (4)-(6) is transformed into

$$\frac{\partial^2 v_1}{\partial y^2} = (q+p)\, v_1 + \varepsilon q P(q); \tag{9}$$

$$\frac{\partial^2 v_2}{\partial y^2} = \frac{p}{a} v_2; \tag{10}$$

$$v_1|_{y=0} = v_2|_{y=0}; \quad \lambda \frac{\partial v_1}{\partial y}\Big|_{y=0} = \frac{\partial v_2}{\partial y}\Big|_{y=0}. \tag{11}$$

The solution of the system (9)-(10) is given by the expressions

$$v_1 = -\frac{\varepsilon q P(q)}{p+q} + c_1 \exp[-\sqrt{p+q}\,|y|]; \tag{12}$$

$$v_2 = c_2 \exp\left[-\sqrt{\frac{p}{a}}\, y\right]. \tag{13}$$

To find the coefficients c_1 and c_2 one obtains from the conditions (11)

$$v_1 = -\frac{\varepsilon q P(q)}{p+q}\left[1 - \frac{\frac{1}{\lambda}\sqrt{\frac{p}{a}}\exp(-|y|\sqrt{q+p})}{\frac{1}{\lambda}\sqrt{\frac{p}{a}} + \sqrt{p+q}}\right]; \; y<0; \tag{14}$$

$$v_2 = -\frac{\varepsilon q P(q)}{p+q}\left[\frac{\sqrt{p+q}\exp\left(-y\sqrt{\frac{p}{a}}\right)}{\frac{1}{\lambda}\sqrt{\frac{p}{a}} + \sqrt{p+q}}\right]; \; y>0. \tag{15}$$

To obtain inverse transforms of the solutions (14)-(15) one can use the well-known operational relations [4] by analogy with one of the problems in [5]:

$$T_1 = -\frac{2\varepsilon}{\sqrt{\pi}} \int_0^{\varkappa} \frac{\partial P(\varkappa-\varkappa')}{\partial \varkappa} \eta(\mathrm{Fo}-\varkappa') \int_0^{\varkappa} \exp(-s^2)\, \mathrm{erf}\left(\frac{|y|}{2\sqrt{\varkappa'}} + s\lambda\sqrt{a}\sqrt{\frac{\mathrm{Fo}-\varkappa'}{\varkappa'}}\right) ds\, d\varkappa'; \tag{16}$$

$$T_2 = -\frac{\varepsilon}{\pi} \int_0^{\varkappa} \frac{\partial P(\varkappa-\varkappa')}{\partial \varkappa} \eta(\mathrm{Fo}-\varkappa') \int_0^{\mathrm{Fo}-\varkappa'} \sqrt{\frac{\varkappa'}{a\lambda^2\tau}} \cdot \frac{1}{\tau + \frac{\varkappa'}{a\lambda^2}}\, \mathrm{erfc}\left(\frac{y}{2\sqrt{\mathrm{Fo}-\varkappa'-\tau)a}}\right) d\tau\, d\varkappa'. \tag{17}$$

It can be shown that the expression thus obtained satisfies all the conditions of the problem (16)-(17). To verify the correctness of the solution, two particular cases are considered:

a) if $P(\varkappa) = 0$ (constant pressure in porous medium), then (16)-(17) imply the trivial result of $T_{1,2} = 0$;

b) for $u \to \infty$ one obtains from (16) by substituting $\varkappa' = x'a/uR^2$

$$T_1 = -\varepsilon \int_0^{x} \frac{\partial P(x-x')}{\partial x} dx' = -\varepsilon P(x). \tag{18}$$

Substituting $\varkappa' = xa/uR^2$; $\tau = \tau'/u$, one obtains from (17) for $u \to \infty$

$$T_2 = -\varepsilon P(x)\, \mathrm{erfc}\left(\frac{y}{2\sqrt{a\mathrm{Fo}}}\right). \tag{19}$$

The expression (19) is identical with the solution of the heat-propagation problem in the half-space where constant temperature is maintained at the boundary. This is obvious, since with the rate of convective heat transfer increasing one can neglect in a porous medium the effect of heat emission on temperature. Integrating (16) or (17) in the case of y = 0 and for the linear pressure profile $[P(\varkappa) = c\varkappa]$, an expression is obtained which describes the temperature at the boundary of the porous medium:

$$-\frac{T}{\varepsilon P(\varkappa)} = \begin{cases} \dfrac{\lambda\sqrt{a}}{1+\lambda\sqrt{a}}\dfrac{\mathrm{Fo}}{\varkappa}; \quad \mathrm{Fo}<\varkappa; \\ \dfrac{2}{\pi}\left(\dfrac{\mathrm{Fo}}{\varkappa}\right)\left\{\mathrm{arctg}\left(\lambda\sqrt{a}\sqrt{\dfrac{\mathrm{Fo}}{\varkappa}-1}\right)\Big/\left(\dfrac{\mathrm{Fo}}{\varkappa}\right) - \dfrac{\lambda\sqrt{a}}{1-\lambda^2 a}\left[\mathrm{arctg}\sqrt{\dfrac{\mathrm{Fo}}{\varkappa}-1} - \lambda\sqrt{a}\right.\right. \\ \left.\left.\times\, \mathrm{arctg}\left(\lambda\sqrt{a}\sqrt{\dfrac{\mathrm{Fo}}{\varkappa}-1}\right)\right] + \dfrac{\lambda\sqrt{a}}{\lambda\sqrt{a}+1} \times \dfrac{\pi}{2}\right\}; \\ \mathrm{Fo}>\varkappa. \end{cases} \tag{20}$$

In Fig. 1 the results of the calculations are shown of the relative temperature at the boundary of the porous medium in accordance with (20). To compute the temperature of the porous and impenetrable media a program was prepared for the evaluation of the integrals (16)-(17) on the BÉSM-4M electronic computer. In Fig. 2 the results of these calculations are shown verified for the particular case (Fig. 1).

It can be seen from the graphs that the time of reaching steady temperature at the boundary of the porous medium depends strongly on the relation between the thermophysical properties of the porous (with a filler) medium and the impenetrable medium. The highest possible value of $\lambda\sqrt{a}$ should be chosen to reduce the time.

NOTATION

t, time; x, z, coordinates; T_1, T_2, a_1, a_2, λ_1, λ_2, temperatures, thermal diffusivities, and thermal conductivities in penetrable and impenetrable half-spaces; u, rate of convective heat transfer by fluid; ε, Joule–Thomson coefficient; $P(\varkappa)$, pressure distribution in porous medium; R, characteristic length; $\eta(x) = \begin{cases} 1, & x > 0; \\ 0, & x < 0. \end{cases}$

LITERATURE CITED

1. I. L. Dvorkin et al., Oil Economy [in Russian], No. 12 (1974).
2. A. V. Lykov, Heat and Mass Exchange. Handbook [in Russian], Énergiya, Moscow (1972).
3. É. B. Chekalyuk, Thermodynamics of Oil Beds [in Russian], Nedra, Moscow (1965).
4. V. A. Ditkin and A. G. Prudnikov, Handbook of Operational Calculus [in Russian], Vysshaya Shkola, Moscow (1965).
5. L. I. Rubinshtein, Temperature Fields in Oil Beds [in Russian], Nedra, Moscow (1972).

LOCAL REBINDER CRITERION (NUMBER) OF MOIST DISPERSED SOLIDS

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The results of an analytical and experimental determination of the local Rebinder number of moist dispersed solids are presented. The manner in which the number varies with the properties of the dispersed solids to which it applies is established.

Many experimental and analytical investigations have been applied to the determination of the Rebinder number, a quantity which is employed in calculating rates of drying by the Lykov equation [1] and is defined by the expression

$$\mathrm{Rb} = \frac{c_q}{r} \cdot \frac{d\bar{u}}{d\bar{t}} \tag{1}$$

[1-5]. In all the investigations of which we are aware, however, the Rb number which has been studied has been that characterizing the behavior of the dispersed solid as a whole (the so-called integrated Rb number). In a number of problems relating to the theory of drying it is nevertheless important to know the "local" Rebinder number Rb* relating to an elementary volume of the drying material. A knowledge of the local Rb number is required in the drying of multilayered porous materials and also when calculating heat and mass flows inside the material, which determine the quality of drying (in respect of cracking, shrinkage, local overheating, etc.).

This paper will be devoted to certain properties of the local Rb* number and its relationship to the integrated Rb number.

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