concentration of the solid phase on the axis of the jet and on the boundary of the jet; ε_k, ε_d, kinematic coefficient of turbulent viscosity of the gas phase and the coefficient of turbulent diffusion of the solid phase; $\varkappa$, jet coefficient; and ρ and ρ_s, density of the gas and of the solid particles.

LITERATURE CITED

1. Yu. A. Buevich and G. A. Minaev, Jet Pseudofluidization [in Russian], Moscow (1980).
2. N. A. Shakhova, Inzh.-Fiz. Zh., 14, No. 1, 61-69 (1968).
3. G. A. Minaev, "Investigation of local fluidization zones in a granulator with a pseudo-fluidized bed," Author's Abstract of Candidate's Dissertation, Technical Sciences, Moscow (1969).
4. G. N. Abramovich, Theory of Turbulent Jets [in Russian], Fizmatgiz, Moscow (1960).
5. N. A. Shakhova and V. K. Lukashev, Teor. Osn. Khim. Tekhnol., 9, No. 2, 234-240 (1975).
6. N. A. Shakhova, G. N. Lastovtseva, and V. K. Lukashev, Heat and Mass Transfer [in Russian], Vol. 5, Part 1, Kiev (1972), pp. 113-117.
7. G. N. Abramovich and T. A. Girshovich, Dokl. Akad. Nauk SSSR, 212, No. 3, 573-576 (1973).
8. R. Busroid, Flow of Gases with Suspended Particles [in Russian], Moscow (1975).
9. G. A. Minaev, Khim. Prom'shlennost', No. 6, 456-459 (1975).
10. A. P. Vostokov, M. V. Vas'kin, and L. S. Aksel'rod, Chemical Machine Building [in Russian], No. 9, Moscow (1978), pp. 123-128.

HEAT TRANSFER IN A VIBRATING-ROTATING BED OF DISPERSED MATERIAL

N. V. Antonishin, V. V. Lushchikov, and G. F. Puchkov

UDC 536.242:532.546

The results of studies of heat transfer between a surface and a bed are presented. The experimental results are compared with calculations based on a two-temperature model. It is shown that the computational results are in satisfactory agreement with the experiments.

In heat-treatment of dispersed materials (heating, drying, thermal decomposition, baking, cooling) it is often not desirable to blow through the bed because of the high hydraulic resistance of the bed, removal of particles of the material, etc. For this reason, apparatus with mixers are used increasingly more often [1-3]. They have the significant drawback that their heat-transfer coefficients and the mixing rates of the components are relatively low. In order to intensify the heating and mixing of the dispersed materials, a new method for moving the dispersed materials was proposed: a vibrating-rotating dispersed bed [4]. A vibrating-rotating bed differs from a vibrating-fluidized bed, which is similar, in that there are no vibrating structures, which greatly complicate the technological equipment when the large sizes which, as a rule, are preferable in practice, are used.

A vibrating-rotating bed is created in the apparatus with the help of an activator, placed at the bottom of the bed. As the activator rotates it turns the blade fastened on its top surface, and the blade is continuously sweeping particles and raises up part of the bed. As a result of the interaction of the activator with the dispersed material the particles begin to rotate relative to the axis of the chamber and oscillate in the vertical plane [5]. Structures of this type are distinguished by their structural simplicity and high operating reliability.

Both large (2-5 mm) and fine (0.01 mm) particles of their mixtures in any ratio can be equally well heat-treated in such an apparatus. The moisture content of the loaded material has virtually no effect on the motion of the particles, and in spite of the intensive mixing even the finely dispersed materials create virtually no dust, which makes cumbersome dust extractors and filters unnecessary. When dispersed materials are dried in a vibrating-rotating

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 51, No. 3, pp. 444-449, September, 1986. Original article submitted June 14, 1985.

0022-0841/86/5103-1075$12.50

TABLE 1. Characteristics of the Materials Studied

Particle material	Fraction composition d, μm	Density ρ, kg/m³	Porosity ε	Form of particles
Magnesite	20—50	3100	0,58	Irregular, rough
	63—100	3100	0,54	Same
	100—160	3100	0,53	»
	160—200	3100	0,52	»
	200—315	3100	0,52	»
	315—400	3100	0,51	Irregular
	400—630	3100	0,50	Same
	630—1000	3100	0,48	»
Quartz sand				
	100—160	2500	0,46	Irregular
	160—200	2500	0,45	Same
	200—315	2500	0,43	Irregular, smooth
	630—1000	2500	0,41	Same
Corundum	20—50	4000	0,54	Irregular, sharp-angled
	50—63	4000	0,53	Same
	100—160	4000	0,52	»

bed, in most cases, there is no need to use external heat sources. Self-heating of the particles owing to friction creates a highly uniform temperature throughout the entire volume of the heat-treated material [5, 6]. It is quite easy to set up a vibrating-rotating bed in a vacuum, which is in many cases necessary in order to achieve a high degree of drying. The results achieved with the use of vibrating-rotating bed for drying are published in [7, 8]. All this gives a basis for expecting that apparatus with a vibrating-rotating bed will be widely used in industry.

Quite extensive information on heat transfer in mixed beds of dispersed material has been published in the literature, but the results, as a rule, are presented in the form of empirical relations, which cannot be used for the calculation of new apparatus. It should be noted that the values of the coefficients of heat transfer in dispersed beds of different type are practically the same under similar conditions of motion of the particles and groups of particles. This suggests that it is possible to relate, with an accuracy which is adequate for engineering calculations, the intensity of heating to some parameter characterizing the mobility of particles or groups of particles, as in the case of a dense moving bed [9, 10].

Because of the diverse applications of vibrating-rotating beds it is important to study the conditions of heat transfer not only from a wall bounding the bed but also from surfaces submerged in it. Table 1 presents the characteristics of the dispersed materials used in the experiments.

The measurement procedure and the apparatus used are analogous to those described in [11]. The absolute error in the measurement of the heat-transfer coefficient did not exceed ±5.2 W/(m²·K) for a cylindrical heater and ±14.1 W/(m²·K) for a heater placed in the wall of the chamber.

Figures 1-3 show the characteristic dependences of the intensity of heating in a vibrating-rotating bed versus the rate of rotation of the activator.

We shall describe the heat transfer between the surface and the vibrating-rotating bed on the basis of a two-temperature model of heat transfer in a dense layer of dispersed material [10]. We shall neglect heat conduction along the framework formed by the particles and the change in the enthalpy of the continuous phase.

To simplify the problem we assume that the heating surface is flat, and its temperature is constant. Then the system of equations of heat flow in the bed of dispersed material can be written in dimensionless form as follows:

$$\frac{\partial^2 \Theta_1}{\partial \xi^2} = A^2 (\Theta_1 - \Theta_2),$$
$$\frac{\partial \Theta_2}{\partial \mathrm{Fo}} = A^2 (\Theta_1 - \Theta_2). \qquad (1)$$

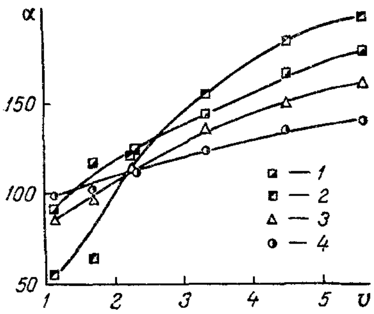

Fig. 1

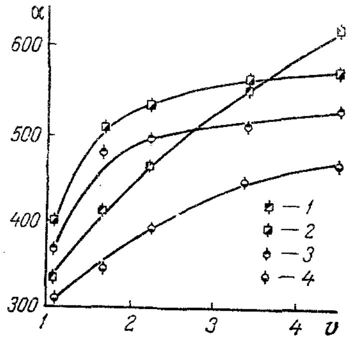

Fig. 2

Fig. 1. Coefficients of heat transfer between a wall and the bed versus the rate of rotation of the activator. The layer material is magnesite, d_{av} = 35 μm (1), 80 (2), 180 (3), 515 (4). α, W/(m²·K); v, m/sec.

Fig. 2. Coefficients of heat transfer between a wall and the bed versus the rate of rotation of the activator with full exchange of particles. The bed material is magnesite, d_{av} = 35 μm (1), 80 (2), 130 (3), 255 (4).

Here

$$\Theta_i = \frac{t_i - t_0}{t_w - t_0}\ (i = 1,\ 2);\ \ \xi = \frac{x}{d};\ \ \mathrm{Fo} = \frac{\lambda_{eff}\,\tau}{c_2\rho_2(1-\varepsilon)\,d^2};$$

$$A = \sqrt{\mathrm{Nu}^* Sd};\ \ \mathrm{Nu}^* = \frac{\alpha^* d}{\lambda_{eff}}.$$

Since the determining dimension is the diameter of the particles of the dispersed material, the quantity $L = \ell/d$ is large ($L \geqq 40$). For this reason, we shall study the problem for a semibounded mass.

In the measurement of the heat-transfer coefficients between the surface and the vibrating-rotating bed; the temperature difference between the heating surface and the core of the bed was maintained constant. Taking this into account, we assume the following boundary conditons:

$$\Theta_2(\xi,\ 0) = 0;\ \Theta_1(0,\ \mathrm{Fo}) = 1;\ \Theta_1(\xi,\ \mathrm{Fo})|_{\xi\to\infty} = 0. \tag{2}$$

We shall solve the system of equations (1) with the boundary conditions (2) with the help of the Laplace transformation. As a result, the dimensionless heat-transfer coefficient at the boundary of the surface and the bed of dispersed material has the form

$$\mathrm{Nu}(0,\ \mathrm{Fo}) = A\exp\left(-\frac{A^2\,\mathrm{Fo}}{2}\right) I_0\left(\frac{A^2\,\mathrm{Fo}}{2}\right). \tag{3}$$

In generalizing the results on heat transfer between the surface and the bed there arises the problem of selecting the residence time of the particles in the bed at the surface. We shall assume that the residence time of the particles at the heating surface is described by a gamma distribution, which is used to represent the nonnegative quantities or values, with a known lower limit [12]:

$$f(\mathrm{Fo}) = \frac{\mathrm{Fo}^{\mu}}{\Gamma(\mu+1)\,\mathrm{Fo}_\beta^{\mu+1}}\exp\left(-\frac{\mathrm{Fo}}{\mathrm{Fo}_\beta}\right). \tag{4}$$

Integrating (3), using the distribution function (4), we obtain the average dimensionless heat-transfer coefficient

$$\overline{\mathrm{Nu}}(0,\ \mathrm{Fo}_\beta) = \frac{A}{\Gamma(\mu+1)\,\mathrm{Fo}_\beta^{\mu+1}}\int_0^\infty \mathrm{Fo}^{\mu}\exp\left[-\left(\frac{1}{\mathrm{Fo}_\beta} - \frac{A^2}{2}\right)\mathrm{Fo}\right] I_0\left(\frac{A^2\,\mathrm{Fo}}{2}\right) d\,\mathrm{Fo}. \tag{5}$$

After the integral is calculated [13] the expression (5) assumes the following form:

$$\overline{\mathrm{Nu}}(0,\ \mathrm{Fo}_\beta) = \frac{A}{(1+A^2\,\mathrm{Fo}_\beta)^{\frac{\mu+1}{2}}} P_\mu\left(\frac{1}{2}\ \ \frac{2+A^2\,\mathrm{Fo}_\beta}{\sqrt{1+A^2\,\mathrm{Fo}_\beta}}\right), \tag{6}$$

where $P_\mu(x)$ are Legendre polynomials.

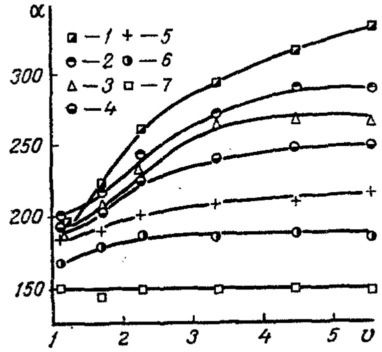

Fig. 3. Coefficients of heat transfer between a cylindrical heater and the bed versus the rate of rotation of the activator. The bed material is magnesite, d_{av} = 80 μm (1), 130 (2), 180 (3), 255 (4), 355 (5), 515 (6), 815 μm (7).

Investigations of the hydrodynamics of pseduofluidized beds shows that there is a preferable residence time for particles at the heating surface [14-17]. Therefore, the distribution function (4) must pass through a maximum, which is possible only when $\mu > 0$.

When $\mu = 1$ the expression (6) assumes the form

$$\overline{\mathrm{Nu}}(0,\ \mathrm{Fo}_\beta) = \frac{A}{2}\ \frac{2 + A^2\,\mathrm{Fo}_\beta}{(1 + A^2\,\mathrm{Fo}_\beta)^{3/2}}. \tag{7}$$

The expressions for $\overline{\mathrm{Nu}}(0,\ \mathrm{Fo}_\beta)$ with $\mu > 1$ are more complicated and do not give significant advantages in generalizing the experimental data.

The formula (7) contains an unknown dimensionless parameter A. For small values of Fo_β, $\overline{\mathrm{Nu}}(0,\ \mathrm{Fo}_\beta)$ is independent of this quantity and can be written as $\overline{\mathrm{Nu}} = A$. As is evident from Fig. 4, in our case $A \approx 0.7$.

The residence time of the particles β in the heating zone was calculated using the expression (7) using values of $\overline{\mathrm{Nu}}$ taken from experiment and the known characteristics of the dispersed bed. The values of a_{eff} and λ_{eff} were calculated using the formulas presented in [18]. The porosity was assumed to equal the porosity of the dense bed. The values of β obtained were averaged for different materials under the same heating conditions. After averaging, the residence time of the particles in the heating zone depends on the velocity of the activator, the character of the flow of particles around the heating and the configuration and location of the heater. It was convenient to characterize the different mobility of the bed at the gboundary with the heating surface by by the value β_{opt}, obtained for maximum heat-transfer coefficients. In this case β_{opt} takes into account the form and location of the heater in the bed.

Analysis enabled distinguishing three of the most characteristic cases:

1) intensive mixing, β does not exceed the time of one revolution of the activator, β_{opt} = 0.2 sec;

2) the heating surface is submerged in the vibrating-rotating bed, β_{opt} = 0.8 sec; and,

3) weak mixing, rod-like motion of the material is observed at the wall, β_{opt} = 1.9 sec.

The last case is most often observed at a wall at the top of the bed and when several activators are arranged in a series [19]. The dependence of the residence time β on the linear velocity of the activator for the conditions indicated above was obtained in the form

$$\beta = \frac{\beta_{opt}}{0{,}13 + 0{,}17v}. \tag{8}$$

This enabled generalizing the experimental data (Fig. 4) over a wide range of variation of the thermophysical properties of the particles of the dispersed material (see Table 1) and under the heating conditions studied above (Figs. 1-3) with a spread not exceeding 17%. The maximum deviations from the universal curve are obtained for conditions when the effect of the curvature of the heating surface becomes appreciable.

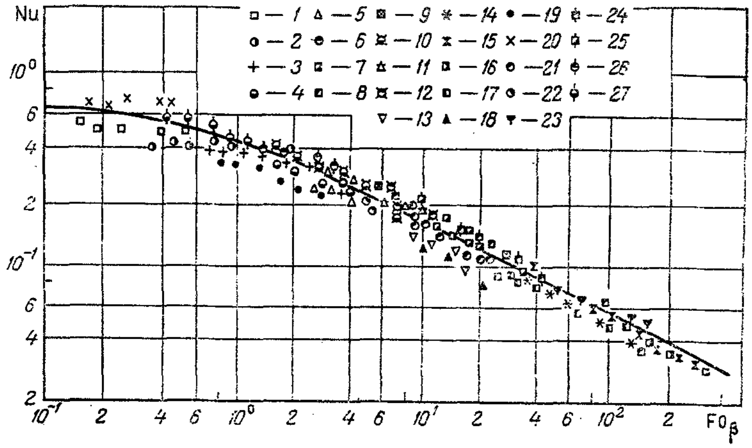

Fig. 4. Universal dependence of $\overline{Nu}$ in a rotating-vibrating bed on Fo_β: 1-15) within a magnesite bed, d_{av} = 815 μm (1), 515 (2), 355 (3), 255 (4), 180 (5), 130 (6), 80 (7), 35 (8); quartz sand, d_{av} = 815 μm (9), 255 (10), 180 (11), 120 (12); corundum, d_{av} = 130 μm (13), 55 (14), 35 (15); 16-23) at the wall, magnesite bed, d_{av} = 35 μm (16), 80 (17), 180 (18), 515 (19); quartz sand, d_{av} = 130 μm (20), 180 (21), 255 (22); corundum, d_{av} = 65 μm (23); 24-27) at the wall, scraper, magnesite bed, d_{av} = 35 μm (24), 80 (25), 130 (26), 255 (27); the curves shows the values computed using Eq. (7).

Analysis of the results obtained shows that the proposed model, relating the intensity of heating to the residence time of the particles near the heating surface, correctly describes the heating mechanism in the vibrating-rotating bed under diverse conditions.

Since the heating mechanism is similar in dispersed beds of different types, the approach developed here could be useful for the analysis and calculation of the intensity of heating irrespective of the method used for mixing the material in one or another apparatus.

NOTATION

t, Θ, dimensional and dimensionless temperature; x, ξ, dimensional and dimensionless coordinates; τ, time; λ, coefficient of thermal conductivity; c, heat capacity; ρ, density; ε, porosity; S, surface area of the particles per unit volume; ℓ, transverse distance from the heating surface to the core of the bed; d, diameter of the particles; d_{av}, average diameter of the particles; v, velocity of the activator; α, heat-trasfer coefficient; $Nu = \alpha d/\lambda_{eff}$, Nusselt's number; β, $Fo_\beta = \lambda_{eff}\beta/c_2\rho_2(1-\varepsilon)d_{av}^2$, average dimensional and dimensionless residence time of the particles in the heating zone; Γ(x), gamma function; $I_0(x)$, a modified Bessel function of the first kind of order zero. Indices: 1, continuous phase; 2, dispersed phase; *, interphase heat transfer; 0, initial value; w, value at the wall; and eff, effective value.

LITERATURE CITED

1. F. Strenk, Mixing and Apparatus with Mixers [in Russian], Leningrad (1977).
2. J. Botterill, Heat Transfer in a Pseudofluidized Bed [in Russian], Moscow (1980), pp. 29-299.
3. A. M. Lastovtsev, A. M. Khval'nov, and Yu. I. Makarov, Khim. Prom'yshlennost', No. 11, 35-38 (1962).
4. N. V. Antonishin, V. S. Nikitin, O. G. Martynov, and G. F. Puchkov, Minsk (1976), Vol. 6, pp. 260-265.
5. N. V. Antonishin, V. S. Nikitin, O. G. Martynov, and G. F. Puchkov, Vestsi Akad. Nauk BSSR, Ser. Fiz.-Energ. Navuk, No. 2, 63-67 (1977).
6. O. G. Martynov, Investigation of Transport Processes in Dispersed Systems [in Russian], Minsk (1981), pp. 152-156.
7. O. G. Martynov and V. S. Nikitin, Vestsi Akad. Nauk BSSR, Ser. Fiz.-Energ. Navuk, No. 2, 69-74 (1983).
8. O. G. Martynov, G. I. Kovenskii, T. E. Fruman, and V. P. Borisenko, Inzh.-Fiz. Zh., 42, No. 3, 435-437 (1982).
9. O. M. Todes, N. V. Antonishin, L. E. Simchenko, and V. V. Lushchikov, Inzh.-Fiz. Zh., 18, No. 5, 815-822 (1970).

10. N. V. Antonishin and V. V. Lushchikov, Investigation of Transport Processes in Dispersed Systems [in Russian], Minsk (1981), pp. 113-129.
11. G. F. Puchkov, Heat and Mass Transfer in Dispersed Systems [in Russian], Minsk (1982), pp. 29-33.
12. N. Johnson and F. Lyon, Statistics and Planning of Experiments in Engineering and Science. Data Processing Methods [Russian translation], Moscow (1980), pp. 147-148.
13. A. P. Prudnikov, Yu. A. Byuchkov, and O. I. Marichev, Integrals and Series. Special Functions [in Russian], Moscow (1983).
14. E. N. Ziegler, L. B. Koppel, and W. T. Brazelton, Ind. Eng. Chem. Fundam., 3, No. 4, 324-328 (1964).
15. N. N. Prokhorenko and N. B. Kondukov, Inzh.-Fiz. Zh., 12, No. 1, 62-67 (1967).
16. V. A. Kirakosyan and A. P. Baskakov, Izv. Akad. Nauk SSSR, Energet. Transport, No. 5, 172-176 (1972).
17. N. I. Syromyatnikov and V. M. Kulikov, Inzh.-Fiz. Zh., 23, No. 6, 998-1000 (1972).
18. N. I. Gel'perin, V. G. Ainshtein, and A. V. Zaikovskii, Khim. Prom'yshlennost', No. 6, 18-26 (1966).
19. N. V. Antonishin, M. A. Geller, and G. F. Puchkov, Inzh.-Fiz. Zh., 40, No. 2, 264-270 (1981).

MASS TRANSFER UNDER CONDITIONS OF FILTRATION IN A RANDOMLY INHOMOGENEOUS MEDIUM

Yu. A. Buevich

UDC 532.546

Dispersion phenomena occurring under conditions of filtration in a medium whose porosity and permeability are homogeneous and isotropic random fields are studied. The effective coefficients of hydraulic resistance and the dispersion of the impurity are calculated, and the averaged equations of filtration and convective diffusion are derived.

Dispersion effects in filtration flows are attributed, as a rule, to convective dispersion, owing to the interaction and mixing of elementary streams, appearing in a flow in a criss-crossed pore space, and to hindered molecular diffusion of the impurity in pores [1, 2]. These phenomena are in equal measure characteristic also of macroscopically homogeneous materials, whose porosity and permeability are independent of the coordinates, and of inhomogeneous materials, when the indicated characteristics form random or determinate fields.

The nonuniformity of the properties of a porous medium lead to the appearance of a unique spatially fluctuating motion of the liquid, superposed on the average filtrational flow and called in [3] filtrational pseudoturbulence. The correlation properties of the corresponding random velocity field are studied in [3, 4], and in application to a flow in a closely packed granular bed in [5].

It is obvious that pseudoturbulent motion gives rise to the appearance of an additional convective dispersion of the impurity. Since the pseduoturbulent mixing length is of the order of the linear scale of the inhomogeneities and the latter is usually much larger than the internal structural scale (pore size), pseudoturbulent dispersion of the impurity in real inhomogeneous media often more important than dispersion caused by other mechanisms, even in cases when the amplitude of the fluctuations of the rate of filtration is relatively small, i.e., the inhomogeneity is weak.

Attempts have been made to study the indicated dispersion and to obtain an averaged equation of convective diffusion based on the assumptions that the flow of moles of liquid is a Markovian process and that A. N. Kolmogorov's equations, relating the impurity concentration to the moments of the random field of the fluctuations in the rate of filtration, are valid

A. M. Gor'kii Ural State University, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 51, No. 3, pp. 450-458, September, 1986. Original article submitted May 27, 1985.

 0022-0841/86/5103-1080$12.50