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WAVE MOTION OF POROUS PARTICLES IN A PULSATING GAS FLOW IN THE PRESENCE OF HEAT AND MASS TRANSFER WITH DEEPENING OF THE EVAPORATION ZONE

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Based on numerical solution of the dynamics equations of a monodisperse gas suspension with allowance for the interphase forces of aerodynamic drag, virtual masses, and the forces caused by nonstationary effects around particles, the influence of different forms of low-frequency harmonic and anharmonic oscillations of the gas on the motion of porous particles in the presence of heat and mass transfer accompanied by deepening of the evaporation zone has been investigated. The dependences of the solid-phase motion, kinetics of evaporation-zone deepening, and heat and mass transfer on the parameters of gas oscillations have been established. It is shown that on removal of free moisture, oscillations at certain parameters lead to enhancement of interphase heat and mass transfer.

The hydrodynamic and thermal conditions under which the phases interact in disperse systems exert a decisive influence on the intensity of heat- and mass-exchange processes and the efficiency of apparatuses. Nonstationary flows of a carrying phase and oscillations at certain parameters lead to enhancement of a number of technological processes (dissolution, extraction, drying, combustion, etc.). As a rule, the processes of heat and mass transfer in disperse media are energy consuming, and therefore an increase in their efficiency and economy of energy resources are presently pressing scientific-research problems. This places in the forefront the investigations aimed at creating efficient nonstationary, discrete-pulsed modes of energy input into disperse systems, wave and resonance modes of flow of a carrying phase with a large amplitude of velocity and pressure fluctuations.

In engineering, the oscillations of a carrying medium are produced by different devices. Among the most efficient generators of high-temperature, strongly pulsed gas flows are the pulse combustion chambers. Such nonstationary flows may be used to implement power-efficient technologies of drying and thermoprocessing of disperse materials and solutions [1–5].

The suspended state of a dispersed phase is provided by the forces of hydrodynamic drag. In the case of a constant velocity of particles, they experience the action of the forces attributable to a pressure gradient and to the differences between the velocities and densities of phases. When particles move in a pulsed mode, the above forces are supplemented with the forces caused by the unsteady-state character of the motion of phases. Ranking among them is the force of virtual masses due to inertial effects and the "hereditary" Basset force due to the nonstationary effects in the carrying phase (to the nonstationarity of the boundary layer around particles). A considerable number of investigations are known [5–14] in which the results of studying pulsed devices and the influence of harmonic pulsations of the carrying phase (gas and liquid) on the motion of particles and heat and mass transfer are given. It should be noted that, in the majority of cases, these results are valid only for the motion of single particles. The condition of the smallness of the volumetric concentration of particles is more restrictive in comparison with the absence of the interaction of particles, which for a monodisperse mixture can be limited by the value $\varepsilon_2 \leq 0.3$. It should be noted that the results of investigations of a pulsed motion of particles in liquids cannot be directly generalized to the case of motion and heat and mass transfer in a pulsed gas flow with a larger amplitude of velocity oscillations.

In [6], the influence of the parameters of harmonic oscillations of a gas on motion and interphase heat transfer has been investigated. In what follows, the wave motion of porous particles in an anharmonic oscillating gas flow

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and the influence of its parameters on heat and mass transfer accompanied by deepening of the zone of evaporation are studied.

We will consider a one-dimensional oscillating motion of a monodisperse mixture in the direction opposite to the action of the gravity force, provided that the carrying-phase (gas) velocity changes according to the periodic dependence

$$v_1 = \bar{v}_1' + v_1^{a'} \sin\left[2\pi\omega'\left(t - \frac{m}{\omega}\right)\right] \quad \text{for} \quad \frac{m}{\omega} \le 1 < \frac{m+\chi}{\omega},$$

$$v_1 = \bar{v}_1'' + v_1^{a''} \sin\left[2\pi\omega''\left(t - \frac{m+\chi}{\omega}\right) + \pi\right] \quad \text{for} \quad \frac{m+\chi}{\omega} \le t < \frac{m+1}{\omega}, \tag{1}$$

where $\chi = \omega''/(\omega' + \omega'')$, $0 < \chi < 1$; $\omega' = \omega/2\chi$, $\omega'' = \omega/2(1 - \chi)$. The parameter χ accounts for the relationship between the duration of the first and second parts of the period. This representation of gas velocity allows one to assign harmonic and anharmonic, as well as pulsed (sinusoidal, rectangular) forms of gas oscillations.

We will consider the case where the interaction of particles with each other can be neglected by virtue of the fact that their volumetric concentration is not very high. Within the framework of interpenetrating continua, the volumetric concentration of a solid phase will be represented as a "frozen" one.

Subject to the assumptions made, the equations of nonstationary motion of phases can be presented in the form [8]

$$\varepsilon_1 \rho_1 \frac{dv_1}{dt} = -\nabla p - nf + \varepsilon_1 \rho_1 g + nj_{21}(v_{1R} - v_1), \tag{2}$$

$$\varepsilon_2 \rho_2 \frac{dv_2}{dt} = nf + \varepsilon_2 \rho_2 g + nj_{12}(v_{2R} - v_2). \tag{3}$$

The velocities v_{1R} and v_{2R} determine the average momentum of the mass coming into the carrying phase as a result of phase transitions. In the majority of practical cases, the change in the momentum of the mass of phase conversion upon transition through the interphase boundary can be neglected: $|j_{12}(v_{2R} - v_{1R})| << f$.

Further it is assumed that $v_{1R} = v_{2R} - v_2$. The force f acting on a particle in a disperse mixture is defined as the force acting on a certain test particle. When the equations of motion are considered in a noninertial frame moving with the gas velocity v_1, the test particle has a velocity $v_{21} = v_2 - v_1$. An analysis of the acting forces results in isolation of the following components: f_A, f_μ, f_m, and f_B. Then we may write

$$f = f_A + f_m + f_\mu + f_B = f_A + \hat{f}, \quad \hat{f} = f_m + f_\mu + f_B, \quad f_A = \frac{4\pi R^3}{3}\rho_1\left(\frac{dv_1}{dt} - g\right). \tag{4}$$

On substituting (4) into (2) and (3), we obtain the following equations of the momenta of phases:

$$\rho_1 \frac{dv_1}{dt} = -\nabla p - n\hat{f} + \rho_1 g + nj_{21}(v_1 - v_1), \tag{5}$$

$$\varepsilon_2 \rho_2 \frac{dv_2}{dt} = -\varepsilon_2 \nabla p + \varepsilon_1 n\hat{f} + \varepsilon_2 \rho_2 g + \varepsilon_2 nj_{21}(v_2 - v_1), \tag{6}$$

$$\varepsilon_1 + \varepsilon_2 = 1. \tag{7}$$

Bringing out the pressure gradient from Eq. (5) and substituting it into (6), we obtain

$$\varepsilon_2\,\rho_2\frac{dv_2}{dt}=\varepsilon_2\,\rho_1\frac{dv_1}{dt}+n\hat{f}+\varepsilon_2\,(\rho_2-\rho_1)\,g\,. \tag{8}$$

The number of particles per unit volume is

$$n=\frac{3\varepsilon_2}{4\pi R^3}\,. \tag{9}$$

The forces of hydrodynamical drag and of virtual masses for the disperse mixture will be represented respectively as

$$nf_\mu=\frac{3}{8}\frac{\varepsilon_2}{R}\zeta\rho_1\left|v_1-v_2\right|(v_1-v_2)\,, \tag{10}$$

$$nf_\mathrm{m}=\frac{2}{3}n\pi R^3\rho_1\frac{\partial}{\partial t}(v_1-v_2)=\frac{1}{2}\varepsilon_2\,\rho_1\frac{\partial}{\partial t}(v_1-v_2)\,. \tag{11}$$

The force attributable to the nonstationarity of the viscous boundary layer around the particles (the "hereditary" Basset force) will be defined by the expression [14]

$$nf_\mathrm{B}=\frac{9\varepsilon_2}{2\pi R}\sqrt{\pi\rho_1\mu_1}\int_0^t\frac{\partial}{\partial\tau}(v_1-v_2)\frac{d\tau}{\sqrt{t-\tau}}\,. \tag{12}$$

Calculation of the integral for the Basset force in the above expression complicates the solution of the problem. It can be found by using the theorem of the mean. Following [6, 13], we find

$$nf_\mathrm{B}=\frac{9\varepsilon_2\sqrt{2\pi\rho_1\,\mu_1\omega}}{2\pi R}\left[v_1-v_1\,(0)-v_2+v_2\,(0)\right]. \tag{13}$$

Then, substituting expressions (10), (11), and (13) into (8), we obtain

$$\frac{dv_2}{dt}=-\frac{2\,(\rho_2-\rho_1)}{2\rho_2+\rho_1}g+\frac{3\rho_1}{2\rho_2+\rho_1}\frac{dv_1}{dt}+\frac{3}{4}\frac{\zeta}{R}\frac{\rho_1}{2\rho_2+\rho_1}\left|v_1-v_2\right|(v_1-v_2)+$$

$$+\frac{9}{\pi R}\frac{\sqrt{2\pi\rho_1\,\mu_1\omega}}{2\rho_2+\rho_1}\left[v_1-v_1\,(0)-v_2+v_2\,(0)\right], \tag{14}$$

$$\frac{dx}{dt}=v_2\,. \tag{15}$$

Here, the hydrodynamic drag factor was determined with allowance for the constrained motion from the following dependence [8]:

$$\zeta=\psi^2\,\tilde{\zeta}\,(\mathrm{Re}^*)\,, \tag{16}$$

where

$$\mathrm{Re}^*=\psi\,\mathrm{Re}\,;\quad\tilde{\zeta}\,(\mathrm{Re}^*)=\frac{24}{\mathrm{Re}^*}+\frac{4}{\sqrt{\mathrm{Re}^*}}+0.4\,;\quad\psi=\frac{\varepsilon_1}{1-1.16\varepsilon_2^{2/3}}\,.$$

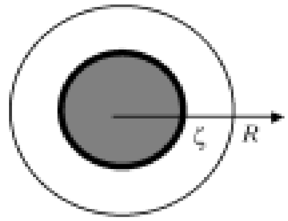


Fig. 1. Toward a statement of the problem of heat and mass transfer in a porous particle.

Low-frequency oscillations of the gas are considered when the amplitude of the displacement of the medium is larger than the diameter of the solid particles and the process of flow around them can be considered quasi-stationary, i.e., the field of the gas velocities at each moment of time obeys the laws of a stationary flow. This condition is usually met in installations operating at low frequencies [6].

The process of heat and mass transfer in capillary-porous bodies is often accompanied by deepening of the evaporation zone. This occurs if steam removal is so intense that the capillary mechanism of transfer fails to supply liquid to the pores dried. A mathematical description of such a process is based on the Stefan-type problem. It should be noted that generally evaporation takes place not only on a moving front but also in a certain zone. This phenomenon is attributable, in particular, to different forms of bonding between moisture and material.

A great number of investigations have been devoted to modeling and studying the processes of heat and mass exchange with the mobile zone (boundary) of phase transition [15–21]. In [15], a system of equations of interrelated heat and mass transfer was obtained. For the process considered, general equations are written for the dry and moist zones, and the phase-change number is represented in the form of a discontinuous function and its dependence on the process parameters is not taken into account. This approach presents difficulties for implementation. In the simplest models, e.g., [16–20], the influence of steam filtration in the dry zone is neglected or the temperature at the evaporation boundary is assumed constant.

In the present work, an approximate method of calculating the processes of heat and mass transfer in capillary-porous particles is considered on the assumption of the evaporation-zone deepening (Fig. 1). In a heated gas flow, a heat flux acts on the surface of a capillary-porous particle. It is assumed that heat is supplied to the evaporation boundary by heat conduction from the dry layer of the material, and it is spent on moisture vaporization. An excess steam pressure develops inside the capillary-porous body, which causes the steam to filtrate from the evaporation boundary to the surface. As a result, the rate of drying is determined by the heat and filtration resistances. The transfer gradients in the moist zone of the body are neglected. The temperature and pressure at the evaporation boundary are interrelated as the saturated steam parameters by the Clapeyron–Clausius equation. In the dry zone, the body temperature depends linearly on the coordinate. Subject to the assumptions adopted, the equation for the rate of the evaporation-boundary deepening under the boundary condition of the 3rd kind on the surface $q = \alpha(T_\infty - T_R)$ can be written as

$$\left[c_{\mathrm{dr}}\,\rho_{\mathrm{dr}}\,\frac{T_R - T_\xi}{2} + (c_{\mathrm{dr}}\,\rho_{\mathrm{dr}} + c_{\mathrm{w}}u)\,(T_\xi - T_{20}) + ur\right]\xi^2\,\frac{d\xi}{dt} = -R^2\left[\frac{1}{\alpha} + \frac{R^2}{\lambda}\left(\frac{1}{\xi} - \frac{1}{R}\right)\right]^{-1}(T_\infty - T_\xi)\,. \tag{17}$$

From taking into account the fact that heat from the material surface is transferred into the interior by heat conduction, it follows that

$$R\alpha\,(T_\infty - T_R) = \frac{\lambda\xi}{R - \xi}\,(T_R - T_\xi)\,, \tag{18}$$

whence

$$T_R = \frac{1}{\dfrac{\lambda\xi}{R - \xi} + R\alpha}\left(\frac{\lambda\xi}{R - \xi}\,T_\xi + R\alpha T_\infty\right). \tag{19}$$

After substituting (19) into (17) and performing simple algebra, we obtain

$$\frac{d\xi}{dt} = -\frac{R^2 (T_\infty - T_\xi)}{\xi^2 \left[\frac{1}{\alpha} + \frac{R^2}{\lambda}\left(\frac{1}{\xi} - \frac{1}{R}\right)\right]\left[\frac{a}{2}\,\frac{R\alpha (R-\xi)}{\lambda\xi + R\alpha (R-\xi)} (T_\infty - T_\xi) + b (T_\xi - T_{20}) + ur\right]}, \tag{20}$$

where $a = c_{dr}\rho_{dr}$ and $b = d_{dr}\rho_{dr} + c_w u$.

The change in the moisture content of the particles is related to the displacement evaporation zone by the relation

$$\frac{dU}{dt} = \frac{3\xi^2 u}{R^3 \rho_{dr}} \frac{d\xi}{dt}, \tag{21}$$

whereas the moisture content is connected with the coordinate of the evaporation front by the relation

$$U = \frac{\xi^3 u}{R^3 \rho_{dr}} . \tag{22}$$

Upon integration of Eq. (21), we may determine the time of extension of the evaporation zone into the body, i.e., the time of drying. Under the boundary condition of the first kind, i.e., at $T_R = T_\infty = \text{const}$, the time of the evaporation boundary displacement is defined by the expression

$$t = \frac{\frac{a}{2} (T_R - T_\xi) + b (T_\xi - T_{20}) + ru}{6\lambda (T_R - T_\xi)} \left[R^2 - \frac{\xi^2}{R} (3R - 2\xi)\right]. \tag{23}$$

The steam flow in the dry zone from the evaporation boundary to the surface can be represented as

$$q_{st} = \frac{4\pi\rho_{st}K_{st}}{\mu_{st}} \frac{R\xi}{\xi - R} (p_R - p_\xi) . \tag{24}$$

Then

$$\frac{d\xi}{dt} = \frac{\rho_{st}K_{st}}{u\mu_{st}} \frac{R}{\xi (\xi - R)} (p_R - p_\xi) . \tag{25}$$

For the flow of steam on the body surface we may write

$$\frac{\rho_{st}K_{st}}{\mu_{st}} \frac{R}{R (\xi - R)} (p_R - p_\xi) = \beta (p_R - p_\infty) , \tag{26}$$

whence

$$p_R = \frac{D\xi p_\xi - \beta R (\xi - R)\, p_\infty}{D\xi - \beta R (\xi - R)} , \tag{27}$$

where $D = \rho_{st}K_{st}/\mu_{st}$. At $\xi = R$ we have $p_R = p_\xi$. On substituting (27) into (25), we obtain

$$\frac{d\xi}{dt} = -\frac{\beta D R^2}{u\xi [D\xi - \beta R (\xi - R)]} (p_\xi - p_\infty) . \tag{28}$$

The dependence of the steam pressure on temperature at the evaporation boundary is determined by the Clayperon–Clausius equation:

$$\frac{1}{p_\xi}\frac{dp_\xi}{dT_\xi}=\frac{r(T_\xi)}{\tilde{R}T_\xi^2}, \tag{29}$$

whence, provided that $r(T_\xi)$ = const, it follows that

$$p_\xi=\tilde{p}\exp\left(-\frac{\tilde{T}}{T_\xi}\right), \tag{30}$$

where $\tilde{p}$ = 6.4072·10^{10} Pa and $\tilde{T}$ = 4996 K. Thus, we have three equations, (20), (28), and (30), with three unknowns, p_ξ, T_ξ, and ξ. From this system of equations, we can determine the temperature T_ξ at the evaporation boundary as a function of its coordinate ξ. To do this, we equate the right-hand sides of Eqs. (20) and (28) and, after substituting (30) and rearranging, we write

$$T_\xi=-\tilde{T}\ln^{-1}\left\{\frac{R^2(T_\infty-T_\xi)}{AC\tilde{p}\,[B(T_\infty-T_\xi)+b(T_\xi-T_{20})+ru]}+\frac{p_\infty}{\tilde{p}}\right\}, \tag{31}$$

here

$$A=\xi^2\left[\frac{1}{\alpha}+\frac{R^2}{\lambda}\left(\frac{1}{\xi}-\frac{1}{R}\right)\right];\quad B=\frac{a}{2}\frac{R\alpha(R-\xi)}{\lambda\xi+R\alpha(R-\xi)};\quad C=\frac{\beta DR^2}{\xi^2u\left[D-\beta R^2\left(\frac{1}{R}-\frac{1}{\xi}\right)\right]}.$$

The transcendental equation (31), on being represented as $T_\xi = \varphi(T_\xi)$, will be solved by the method of successive approximations. The sufficient conditions of the iterative convergence to the equation root are as follows: in a certain vicinity of the root the function $\varphi(T_\xi)$ is continuous, and it satisfies the "compression" condition $|\varphi'(T_\xi)| < 1$. Its derivative is found to be

$$\varphi'(T_\xi)=-\frac{T_\xi^2R^2\tilde{p}}{\tilde{p}\tilde{T}R^2(T_\infty-T_\xi)+\tilde{T}p_\infty X}\left[1+\frac{AC\tilde{p}\,(b-B)(T_\infty-T_\xi)}{X}\right], \tag{32}$$

where $X = AC\tilde{p}\,[B\,(T_\infty - T_\xi) + b\,(T_\xi - T_{20}) + ur]$. It can be shown that in the investigated region of parameters the condition $|\varphi'(T_\xi)| < 1$ is fulfilled. The average temperature of the particle is

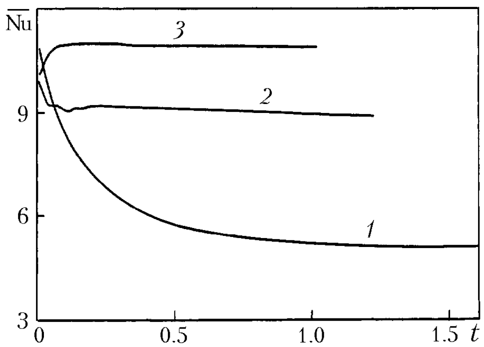
$$\overline{T}_2=\frac{aT_R(R^3-\xi^3)+bT_\xi\xi^3}{a(R^3-\xi^3)+b\xi^3}. \tag{33}$$

The particle density is

$$\rho_2(t)=\rho_{\mathrm{dr}}+\frac{\xi^3}{R^3}u. \tag{34}$$

As has already been noted, in this case the process of heat transfer can be considered quasi-stationary, and the Nusselt number can be determined from the dependence $\mathrm{Nu} = 2 + 0.55\mathrm{Re}^{0.5}\mathrm{Pr}^{0.33}$. The time-averaged Nusselt number was found from the expression

$$\overline{\mathrm{Nu}}=\frac{1}{\Delta t}\int_{\Delta t}\mathrm{Nu}\,dt. \tag{35}$$



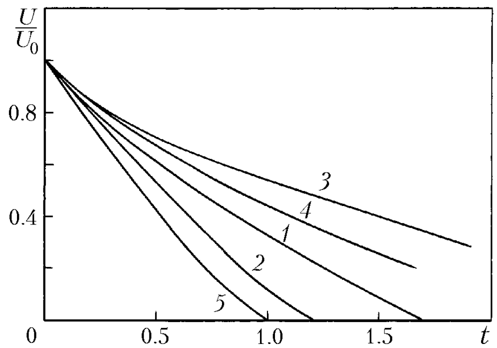


Fig. 2. Average Nusselt number vs. time ($\bar{v}_1$ = 20 m/sec): 1) $v_1^a = v_1^{a\prime} = v_1^{a\prime\prime}$ = 0; 2) v_1^a = 20 m/sec, sinusoidal form of gas oscillations; 3) rectangular form (ω = 100 Hz, χ = 0.5, $d = 6\cdot10^{-4}$ m, ρ_{dr} = 900 kg/m^3, u = 450 kg/m^2; c_{dr} = 1200 J/(kg·K), λ = 0.6 W/(m·K), $D = 5\cdot10^{-8}$ sec, T_1 = 523 K).

Fig. 3. Moisture content of particles vs. time: 1, 3) v_1^a = 0; 2, 4) 20 m/sec [1, 2) $D = 5\cdot10^{-8}$; 3, 4) $5\cdot10^{-12}$ sec]; 5) rectangular form of gas oscillations at the parameters corresponding to curve 1. Remaining parameters are the same as in Fig. 2.

The initial conditions at t = 0 are: x = 0, $v_2 = dx/dt$ = 0, $T_2 = T_{20}$, $T_1 = T_{10}$, $v_1 = v_1(0)$, v_2 = 0, $U = U_0$, and $\xi = R$.

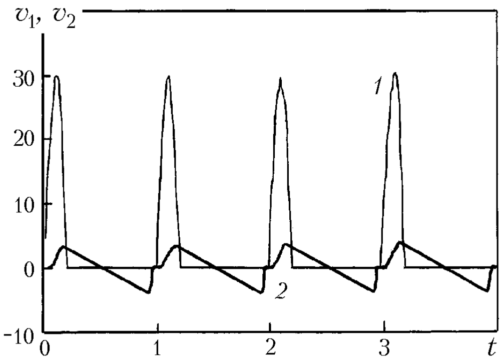
We have obtained the numerical solution of differential equations (14), (15), and (20) at the constant parameters T_{20} = 293 K; ε_1 = 0.99; c_w = 4190 J/(kg·K); $r = 2.25\cdot10^6$ J/kg, and p_∞ = 20 kPa.

Let us investigate the nonstationary wave motion of porous particles in an oscillating gas flow with allowance for the internal heat and mass transfer accompanied by deepening of the evaporation zone. In [6], an estimation was made for the contribution of the forces acting on particles in a pulsed gas flow. The gas velocity is a function of time (1) that specifies its periodic (harmonic and anharmonic) oscillations. In a harmonically oscillating gas flow, when the velocity changes according to the sinusoidal dependence, the particles undergo a wavy motion. The modulus of the relative velocity of the phases increases as against the velocity of particles in a stationary flow in which the difference between the velocities of the phases is appreciable only over the acceleration path of the particles. A similar behavior of particles is also observed in the case of periodic gas oscillations of rectangular form. Here, the relative velocity of phases increases as compared to the case of sinusoidal gas oscillations. As a result, the periodic gas oscillations of rectangular form with a larger velocity amplitude lead to enhancement of heat and mass transfer on removal of a free and loosely bound moisture, i.e., in solving an exterior problem. This is clearly demonstrated by the time dependences of the averaged Nusselt number (Fig. 2) and of the moisture content of particles under the indicated gas oscillation conditions (Fig. 3). Therefore, to attain a high heat- and mass-transfer intensity, in particular, in the processes of drying and thermoprocessing of finely divided particles, it is most worthwhile to apply gas flow interrupters of slit and valve types that ensure a rectangular form of gas oscillations. The efficiency of such interrupters in liquefaction of disperse materials is noted in [22].

With an increase in the intradiffusion resistance, the influence of hydrodynamic drag factors on mass transfer decreases, which is to be taken into account in selecting an energy-efficient regime of drying.

Further, we will consider the pulsed effect of a gas on porous particles and its influence on the heat and mass transfer which is accompanied by evaporation-zone deepening. Such an effect represents a sinusoidal form of gas-velocity fluctuations in the first part of the period and virtually an absence of gas flow rate in its second part at a gas-velocity close to zero. Pulsed modes of thermoprocessing can be very efficient when processing is arranged in a suspended (fluidized) bed of finely divided materials, as well as dispersed thermolabile products and materials with an appreciable intradiffusion resistance.

From the time dependences of the velocities of phases depicted in Fig. 4, it follows that the pulsed effect of the gas flow makes the particles ascend, but when gas supply is stopped, the particles are settled, and thus the cycles are repeated. With a decrease in the frequency of the gas pulses, the time of immobile state of the particles, i.e., the rest time, increases.



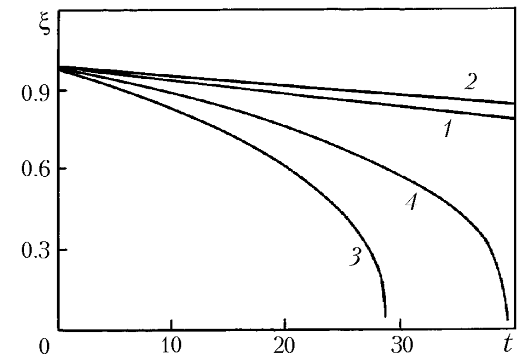
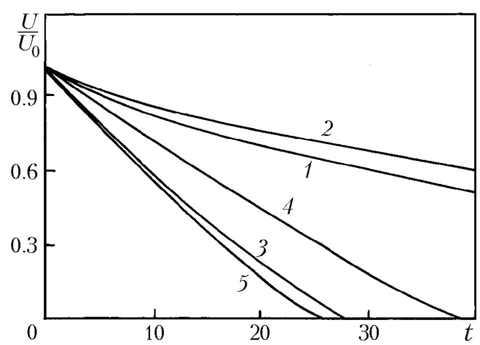


Fig. 4. Velocity of the gas (1) and particles (2) vs. time at χ = 0.2, ω = 1 Hz, $v_1^{a\prime}$ = 30 m/sec, $v_1^{a\prime\prime}$ = 0; $\bar{v}_1$ = 0.01 m/sec, $d = 3 \cdot 10^{-3}$ m, $D = 5 \cdot 10^{-8}$ sec, T_1 = 523 K, ρ_{dr} = 1200 kg/m^3, and u = 450 kg/m^3.

Fig. 5. Change in time of the evaporation-boundary coordinate at $D = 5 \cdot 10^{-13}$ sec: 1) χ = 0.2, ω = 1; 2) 0.1 and 0.5 Hz; at $D = 5 \cdot 10^{-8}$ sec: 3) ξ = 0.2, ω = 1; 4) 0.1 and 0.5 Hz. Remaining parameters are the same as in Fig. 4.



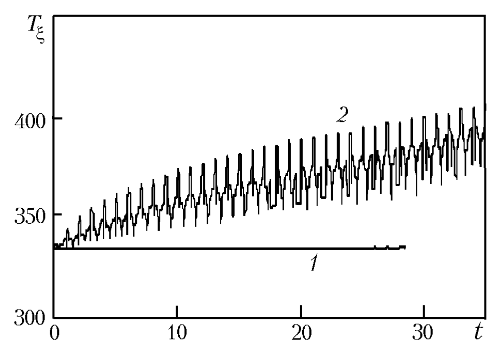


Fig. 6. Kinetics of the drying of particles in pulsed gas action. Curves 1–4 correspond to the parameters of the curves of Fig. 5; 5) rectangular form of gas oscillations at the parameters corresponding to curve 4.

Fig. 7. Temperature at the evaporation boundary vs. time: 1) $D = 5 \cdot 10^{-11}$ sec; 2) $5 \cdot 10^{-13}$; χ = 0.2; ω = 1 Hz.

From the time dependences of the evaporation-zone deepening (Fig. 5) and of the moisture content of particles (Fig. 6), it is seen that with an increase in the internal resistance to steam motion, the influence of the frequency of pulses on the mass-transfer intensity is decreased. Acceleration of the evaporation-boundary deepening is conditioned by the spherical shape of the particles. Therefore, for materials with a rather high internal resistance to mass transfer, the mode with a low frequency of gas pulses may turn out to be energetically favorable. In the given case, as is seen from Fig. 6, the rectangular form of gas oscillations ensures a higher mass-transfer intensity. However, it should be kept in mind that such a mode leads to higher ascending of particles, after which they begin to descend. In particular, such a mode can be implemented in a bed of material on periodic successive suspension of individual zones of the bed with a specified frequency of gas supply.

At high values of the permeability of porous particles, the temperature at the evaporation boundary, on its deepening, remains virtually constant and equal to the temperature of adiabatic saturation (wet bulb temperature). In the case of low permeability of particles, as the evaporation zone extends into the interior, the temperature on its evaporation boundary is increased considerably, and it is of oscillating character (Fig. 7). The thermophysical parameters of a porous medium and the mode of heat transfer exert a substantial influence on temperature on the receding evaporation surface and on the velocity of the latter. Therefore, it is not always correct to assume the temperature at the evaporation boundary to be constant and equal to the temperature of adiabatic saturation, which is to be taken into account in solving such kind of heat- and mass-transfer problems.

The results presented can be useful in calculating and designing heat- and mass-transfer apparatuses with pulsed gas input.

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NOTATION

c, heat capacity, J/(kg·K); d, diameter of particles, m; f, force per particle, N; f_A, f_μ, f_m, and f_B, buoyancy (Archimedean) force, force attributable to the viscosity of the carrying phase, virtual masses due to inertial effects, and the Basset force due to the nonstationarity of the viscous boundary layer around particles, N; g, free fall acceleration, m/sec^2; $j_{12} = -j_{21}$, evaporation intensity, kg/sec; K_{st}, factor of stream permeability in the dry zone of the particle, m^2; m, number of the period, m = 0, 1, 2, ...; n, number density of particles, m^{-3}; Nu, Nusselt number; p, gas pressure, Pa; Pr, Prandtl number; r, specific heat of vaporization, J/kg; R, radius of particles, m; $\tilde{R}$, gas constant, J/(kg·K); Re, Reynolds number; t, time, sec; T, temperature, K; u and U, moisture content of the body, kg/m^3, kg/kg; v, velocity, m/sec; x, vertical coordinate, m; α and β, heat- and mass-transfer coefficients, W/(m^2·K) and kg/(m^2·sec·Pa); ζ, coefficient of hydrodynamic drag; ε_1, porosity; ε_2, volumetric concentration of particles; λ, thermal conductivity of material in the dry zone, W/(m·K); μ and ν, dynamic and kinematic viscosities, Pa·sec and m^2/sec; ξ, running coordinate of the evaporation boundary, m; ρ, density, kg/m^3; τ, time ($0 \le \tau \le t$), sec; ω, frequency, Hz. Subscripts: 1 and 2, gas and solid particles, respectively; a, amplitude; w, moisture (water); m, virtual mass; st, steam; dr, dry material; R, on the particle surface; ξ, evaporation boundary; 0, initial value; overbar, average value; $'$, $''$, the first and second parts of the period; ∞, environment.

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