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EVOLUTION OF THE INHOMOGENEOUS STATE OF A FLUIDIZED BED

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The article examines the change of the characteristics of the dilute and dense phases over the height of a fluidized bed, caused by the regular gas exchange between them and by the process of bubble coalescence.

The intensity of exchange processes in apparatus with a fluidized bed is largely determined by the local hydrodynamic state in the given section of the bed; the local values of the hydrodynamic parameters may substantially differ from the respective mean values for the bed as a whole. It is therefore indispensable to have hydrodynamic models of fluidization which would make it possible to describe the dependence of such parameters at different points of the bed on the physical characteristics of the particles and of the gas as well as on the type of apparatus and the regime parameters of the process.

The existing approximate models are of an empirical nature and do not meet this requirement. Within the framework of the two-phase theory of fluidization [1], the bed is regarded as a spatially homogeneous system. The "bubble" models of fluidization, which came into use in connection with the modeling of the longitudinal agitation in the bed [2, 3], are also based on the ideas of the two-phase theory, and differences in the state of the bed at different levels above the distributor grid are viewed as the consequences of bubble coalescence of the dilute phase; the properties of the dense phase are then taken to be homogeneous.

The principal relationship $u=u_*+\varphi u_b$ of the two-phase theory was already criticized by Turner [4], and deviations from it were experimentally confirmed by Pyle and Harrison [5] and in subsequent works. Attempts to modify this theory by taking into account the relative gas stream though the bubbles while maintaining the principal assumption $u_d=u_*$ (so that $u = u_*(1+m\varphi)+\varphi u_b$, where m is a parameter), begun by Grace and Clift [6], were unsuccessful, as was demonstrated by Davidson and Harrison [7]. Investigations in which the inadequacy of the two-phase theory was explained by pointing out that in reality $u_d > u_*$ [8, 9] permitted a number of empirical conclusions but they did not lead to the establishment of dependences of a sufficiently general nature.

The main circumstance determining the difference between the filtration rate in the dense phase and the speed of minimum fluidization is the difference between the "initial" in-

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homogeneous state directly above the grid and the state satisfying the requirements of the two-phase theory. If the bubbles form as a result of the collapse of the elementary gas streams flowing from nozzles or perforated holes, about 40-50% of the gas is ejected from the flares to the dense phase [10, 11]. An analogous conclusion follows from [5, 8, 9] and other works. With uniform distribution of the gas through the porous grid, the porosity of the dense phase in the initial inhomogeneous state also exceeds the value characterizing the immovable bed [12].

The principal factor, which, together with bubble coalescence, causes a change of the characteristics of the inhomogeneous bed with height, is the specifid dynamic instability of the bubbles: large bubbles grow on account of the inflow of gas from the dense phase into them [13, 14], small bubbles become smaller and may even completely disappear [15]. A theory of this phenomenon, neglecting the tangential stresses in the disperse phase, was suggested by Buyevich [16]. Of interest is the devising of a mathematical model describing the effect of such gas exchange between the disperse and the dense phases on the evolution of the state of the bed, and also its investigation for the purpose of answering the question whether a limit steady state exists, and if it exists, how quickly it is attained. The solution of this problem is also the subject of the present work.

Models of Bubbles and of the Dense Phase. Assuming that the hydraulic resistance is linear with respect to the filtration speed of the gas in the dense phase, we have [12]

$$u_d = \frac{1}{k_1}\,\frac{\varepsilon_d^3}{1-\varepsilon_d}\,\frac{\varkappa g(2a)^2}{\nu},\quad \varkappa = \frac{d_1}{d_0} \gg 1. \tag{1}$$

According to the formulas of Karman–Cozeni and Ergan, k_1 = 180 or 150; the value u_* is obtained from (1) for $\varepsilon_d = \varepsilon_*$.

For the steady-state ascending velocity of a bubble with the radius R of the head we use the formula that is also correct for $\varkappa \gg 1$:

$$u_b = k_2(2gR)^{1/2}(1+\alpha\varphi). \tag{2}$$

According to the Davis–Taylor theory, k_2 = 0.711; the factor $1 + \alpha\varphi$ was introduced in order to take into account the influence of the collective effects on the velocity u_b [12].

Assuming that the shape of the growing bubble is retained, we see that R can depend only on h, its value of R_0 for h = 0, the acceleration g, and on the value of $u_d - u_*$ which unambiguously characterizes the state of the dense phase when $\varkappa \gg 1$. According to the theory of dimensionalities, $R \sim h\Phi(x, y)$, where $x = (u_d - u_*)^2/gh$, $y = R_0/h$. At a distance $R_0 \ll h$ from the grid, we also have $y \approx 0$. When $u_d = u_*$, the bubbles do not grow, therefore $\Phi(x, 0) = x^m$, and from [16], we have m = 1/3. Thus,

$$R = k_3(u_d - u_*)^{2/3}g^{-1/3}h^{2/3}. \tag{3}$$

Tamarin et al. [13] empirically obtained that m = 1/3, Rowe [14] gives m = 3/4. It we disregard that in [13] $u - u_*$ is used incorrectly instead of $u_d - u_*$ for correlating the experimental data (obviously, $u \to u_d$ when $\varphi \to 0$), we can obtain from the result of [13] that k = 0.93. Here we examine the coefficients k_1, k_2, and k_3 in the general form as magnitudes needing further refinement.

Taking it that the volume of a bubble is $V = (4\pi/3)R^3(1-f)$, where f is part of the sphere with radius R occupied by the wake zone, we obtain from (3)

$$\frac{dV}{dh} = \frac{c}{(1-f)^{1/2}}\,\frac{u_d - u_*}{g^{1/2}}V^{1/2},\quad c = 2\left(\frac{4\pi}{3}\right)^{1/2}k_3^{3/2}. \tag{4}$$

If the particles in the wake zones of the bubbles were on the average immovable, the condition of retaining the gas volume would lead to the equation

$$u = (1+2\varphi)u_d + \varphi u_b. \tag{5}$$

(This version is sometimes being disputed [3]; a strict derivation of (5) is contained in [12].) In reality the particles in wake zones move upward together with the bubbles, and this leads to the appearance of a downward stream of particles in the dense phase. If the mean speed of such a stream is equal to u_s, then the gas speed in the gaps between the particles of the dense phase is $u_d/\varepsilon_d - u_s$, and the ascending velocity of the bubbles in the laboratory system of coordinates is $u_b - u_s$, i.e., instead of (5) we have to write

$$u = (1 + 2\varphi)(u_d - \varepsilon_d u_s) + \varphi(u_b - u_s). \quad (6)$$

The full volumetric upward flow of particles, due to their ascent with the bubbles, is equal to $(1-\varepsilon_d)(u_b-u_s)\varphi f(1-f)^{-1}$ (it was taken that the porosity of the wake zones approximately coincides with ε_d, and we took into account the difference between the volumetric concentrations φ of the dilute phase and $\varphi(1-f)^{-1}$ of the spheres with radius R which include both the bubbles and their wake zones). The downward volumetric flow of particles in the dense phase is obviously equal to $(1-\varepsilon_d)u_s[1-\varphi(1-f)^{-1}]$. If we equate these flows, we obtain

$$u_s = \frac{f\varphi}{(1-f)(1-\varphi)} u_b. \quad (7)$$

Hence it can be seen that when $u_b \gg u_d$, the gas motion in the dense phase may be "reversed" when its absolute velocity is directed downward. In beds containing a sufficient amount of large bubbles, this phenomenon was observed experimentally [3].

We will evaluate the coefficient α in (2), and for that we use, like in [12], the empirical relationship [17]:

$$u_b = u - u_d + u_{b0}, \quad (8)$$

where u_{b0} is the ascending velocity of a single bubble, approximately correct for $u_d \ll u_b$. Taking formulas (6) and (7) into account, we obtain from (8) that

$$\alpha = \frac{G}{1-\varphi G}, \quad G = \frac{1-f-\varphi-\varepsilon_d f(1+2\varphi)}{(1-f)(1-\varphi)}, \quad (9)$$

which replaces the equality $\alpha = 1$ corresponding to $f \to 0$ that was used in [12]. We want to emphasize that the considerations leading to formula (9) are heuristic, and the formula should therefore be accepted with some reservations. As long as a strict theory of constrained bubble motion in a fluidized bed has not been worked out, the use of (2) with the coefficients α from (9) does not yield any basic advantages over the use of relationship (8) which was viewed as an experimental fact.

Evolution of the Phases of the Bed with Bubble Coalescence Disregarded. Directly above the distributor grid the initial state forms which is characterized by the concentration n_0 and volume V_0 of the bubbles ($\varphi_0 = n_0 V_0$) and the initial porosity of the dense phase ε_{d0} which are henceforth treated as specified. When elementary gas filament bands flow into the bed, these magnitudes can be evaluated on the basis of the results of [10, 11], in outflow through a porous grid they can be evaluated with the aid of the theory in [12]. The dependence of φ, V, and ε_d on the height h in the bed has to be found.

At first we disregard the bubble coalescence, when $n = n_0 = \text{const}$. Then the equation $\varphi = nV$ can be easily obtained from (4):

$$\frac{d\varphi}{dh} = \frac{cu_*}{(1-f)^{1/2}} \left(\frac{n_0}{g}\right)^{1/2} \left(\frac{u_d}{u_*} - 1\right) \varphi^{1/2}. \quad (10)$$

To make this equation fully determinate, the ratio u_d/u_* has to be expressed via the physical and regime parameters of the bed. First of all we obtain from (1) that

$$\frac{u_d}{u_*} = \left(\frac{\varepsilon_d}{\varepsilon_*}\right)^3 \frac{1-\varepsilon_*}{1-\varepsilon_d}, \quad (11)$$

and from (6)-(9) after a number of transformations we have

$$\frac{u_d}{u_*} = \frac{1+\varphi(-2+F)}{1+\varphi F} \frac{u}{u_*} - \frac{\varphi(2-F)}{1+\varphi F} \frac{u_{b0}}{u_*}, \quad (12)$$

where we introduce the function

$$F = 1 + \frac{f}{1-f} \frac{\varepsilon_d(1+2\varphi)+\varphi}{1-\varphi}, \quad (13)$$

which becomes equal to unity when $f = 0$. If we equate (11) and (12), we obtain the algebraic correlation between ε_d and φ; this same correlation has to exist between ε_{d0} and φ_0.

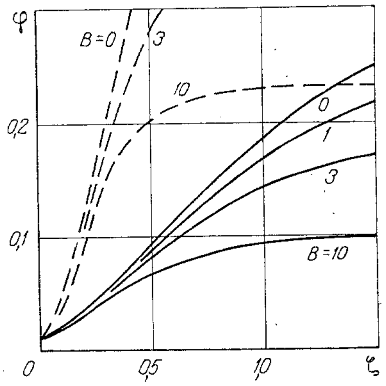

Fig. 1

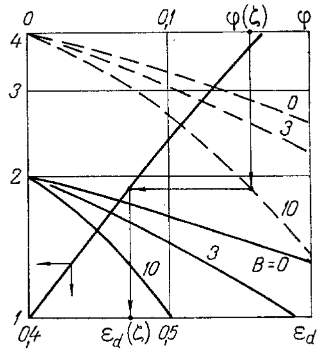

Fig. 2

Fig. 1. Dependence of the volumetric concentration of the dilute phase on the dimensionless height in the bed without coalescence for N = 2, 4 (solid and dashed curves, respectively) and different B (numbers next to the curves).

Fig. 2. Illustration to the determination of the porosity of the dense phase. The solid and dashed curves correspond to N = 2 and 4, respectively, the numbers next to the curves give the values of the parameter B. The arrows indicate the sequence of determining ε_d from the specified φ; it is accepted that $\varepsilon_* = 0.40$.

We transform (12), taking it that $R = 0.62(1-f)^{-1/3}V^{1/3}$, and also formulas (1) for $\varepsilon_d = \varepsilon_*$ and (2) for $\alpha = 0$. After determining the fluidization number $u/u_* = N$, we obtain for u_{b0}/u_*

$$u_{b0}/u_* = B\varphi^{1/6}, \tag{14}$$

where the following parameters are introduced:

$$B = \frac{1-\varepsilon_*}{\varepsilon_*^3}\,\frac{1.11\,k_1k_2(1-f)^{-1/6}}{[\varkappa \mathrm{Ar}]^{1/2}\,[8a^3n_0]^{1/6}}, \quad \mathrm{Ar} = \varkappa\,\frac{g(2a)^3}{\nu^2}. \tag{15}$$

If we introduce the dimensionless vertical coordinate $\zeta = h/H$, where

$$H = \frac{1}{cu_*}\left[(1-f)\,\frac{g}{n_0}\right]^{1/2} = \frac{k_1}{c}\,\frac{1-\varepsilon_*}{\varepsilon_*^3}\,\frac{2a(1-f)^{1/2}}{[\varkappa \mathrm{Ar}]^{1/2}\,[8a^3n_0]^{1/6}}, \tag{16}$$

we obtain from (10), (12), and (14) the equation (the magnitude ε_d is considered an implicit function of φ)

$$\frac{d\varphi}{d\zeta} = \left[\frac{1+\varphi(-2+F)}{1+\varphi F}\,N - B\,\frac{\varphi^{7/6}(2-F)}{1+\varphi F} - 1\right]\varphi^{1/2}. \tag{17}$$

In the special but very important case, when the downward motion of the particles of the dense phase with speed u_s may be neglected (e.g., for $f \approx 0$ or $\varphi \approx 0$), Eq. (17) is simplified:

$$\frac{d\varphi}{d\zeta} = \left[\frac{1-\varphi}{1+\varphi}\,N - B\,\frac{\varphi^{7/6}}{1+\varphi} - 1\right]\varphi^{1/2}. \tag{18}$$

In this case, the nature of the change of φ and ε_d over the height of the bed is determined practically by the value of only two parameters: the complexes $\varkappa \mathrm{Ar}$ and $8a^3n_0$ on which B and H depend, and by the principal regime parameter, the fluidization number N. The integral curves of Eq. (18) for different N and B are presented in Fig. 1. If $\varphi \ll 1$, $B \leqslant 1$, we have approximately

$$\varphi \approx [\varphi_0^{1/2} + (N-1)\,\zeta/2]^2. \tag{19}$$

The values of porosity ε_d are determined from the equation

$$\frac{1-\varphi}{1+\varphi}N-\frac{\varphi^{7/6}}{1+\varphi}B=\left(\frac{\varepsilon_d}{\varepsilon_*}\right)^3\frac{1-\varepsilon_*}{1-\varepsilon_d}, \tag{20}$$

which follows from the formulas given previously. At the same time Fig. 2 shows the dependences of the right-hand side of this equation on ε_d for $\varepsilon_* = 0.40$ and of the left-hand side on φ for different N and B; these curves make it possible with the aid of the curves in Fig. 1 to plot the dependences of ε_d on ζ for different N and B. When $\zeta \to \infty$, the boundary state becomes established, and the volumetric concentration φ_∞ of the dilute phase in it satisfies Eq. (20) with the right-hand side equal to unity. The values of φ_∞ are determined by the points of intersection of the curves in Fig. 2 with the axis of abscissas. The porosity of the dense phase in the boundary state is obviously equal to ε_*.

The found dependences make it possible to calculate the values characterizing the hydrodynamics and agitation at different levels of the bed. Examples are the break-through frequency of bubbles at the given point of the bed or the part of the time during which this point is situated within the dilute phase, which are important for calculating external heat exchange (see, e.g., [18]), and also characteristics of the small-scale pseudoturbulent motion of particles and gas, e.g., the coefficients of pseudoturbulent diffusion of particles whose dependence on ε_d was examined in [19].

It is also easy to carry out numerical calculations for the case when the initial particle motion cannot be neglected. In this case we have to use, instead of Eq. (18), Eq. (17) which depends on the additional parameter f that is part of the determination of the magnitude F figuring in (17).

Effect of Coalescence. In real fluidized beds, a very important process is the coalescence of bubbles forming a larger bubble. Coalescence entails (even on condition that the full volume of the dilute phase is retained) a reduction of the area of the interface between the dilute and the dense phases, and consequently it reduces the rate of increase of the volumetric concentration of the dilute phase on account of the inflow of gas into it when compared with an analogous system without coalescence.

First we will examine a single act of coalescence, the merging of two separately taken bubbles. Formally we may take it that at some level the bubbles with size $R^{(1)}$ with the full concentration $\varphi^{(1)}$ coalesce in pairs forming half the number of bubbles of size $R^{(2)}$ with the concentration $\varphi^{(2)}$. The process of coalescence lasts only a fraction of a second, and it is natural to assume that within such a short time the state of the dense phase does not change, i.e,, the magnitudes ε_d and u_d retain their values. Then we obtain from Eq. (12) that

$$\frac{[1-\varphi^{(i)}(2-F^{(i)})]N-\varphi^{(i)}(2-F^{(i)})(u_{b0}^{(i)}/u_*)}{1+\varphi^{(i)}F^{(i)}}=\text{const}, \tag{21}$$

where the functions $F^{(i)}$ are determined by the relationships analogous to (13), and the expressions for $u_{b0}^{(i)}/u_*$ follow from (14). Obviously, we must take it that $n_0^{(1)} = 2n_0^{(2)}$, i.e., where $B^{(1)} = e^{1/6}B^{(2)}$, where B is determined in (15). If we disregard the existence of wake zones (i.e., with $f \approx 0$, as was also assumed in deriving (18)), we obtain from (21) that

$$\frac{N(1-\varphi^{(i)})-B^{(i)}\varphi^{(i)7/6}}{1+\varphi^{(i)}}=\text{const}. \tag{22}$$

The coefficient of retention of the volume upon coalescence $\gamma=\varphi^{(2)}/\varphi^{(1)}$ increases monotonically from its limit value $\gamma = 2^{-1/7}$ for $N \ll B$ to unity in the opposite limit case. It is therefore permissible to neglect the small gas losses upon coalescence and to take it that $\gamma \approx 1$. The change of φ upon coalescence was experimentally investigated in [20].

The mechanisms of coalescence, ultimately determining the frequency distribution of these processes throughout the bulk of the bed, are very variegated, and their analysis is beyond the scope of this article. Here we will point out only two boundary situations which have to be investigated by different methods. When the bubbles form randomly in the zone adjacent to the grid and consequently their spatial distribution is also random, the principal mechanism is the capture of smaller bubbles in the wake zone of a larger rising bubble and its subsequent absorption. Such a mechanism is considered most characteristic, and it is de-

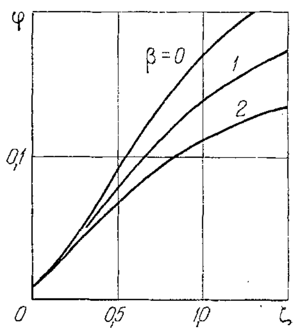

Fig. 3

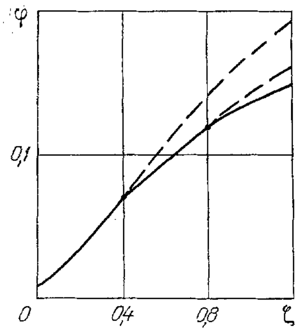

Fig. 4

Fig. 3. Dependence of φ on ζ in random coalescence for N = 2, B = 1 and different β (numbers next to the curves).

Fig. 4. Dependence of φ on ζ with ordered coalescence for N = 2, B = 1. To the two successive levels of coalescence correspond values of ζ equal to 0.40 and 0.80. The dashed curves show the evolution of φ as it would be if there were no coalescence at separate levels.

scribed in [2, 3, 17]. It has to be put into effect when the gas is introduced through the prorous grid and the formation of bubbles is spontaneous [12], or through nozzles or perforated holes if there is incoherent separation of the initial bubbles from the adjacent elementary filament bands. To devise a theory of coalescence we need in this case a complex statistical analysis of the spatial distribution of the bubbles and of the acts of coalescence taking into account their kinematic and dynamic properties. At present it is apparently convenient to use the empirical formula [2]

$$n = n_0 \exp(-\beta' h) = n_0 \exp(-\beta\zeta), \quad \beta = H\beta', \tag{23}$$

where usually $\beta' \sim 100\ \text{cm}^{-1}$. In the general case, n represents a discontinuous function: to each act of coalescence corresponds its jump in the value of n, and between successive acts, n does not change. Therefore, (23) has to be regarded as some continuous approximation of the true function of the numerical concentration of the bubbles.

The magnitude V is also discontinuous for each bubble, and in the intervals between the acts of coalescence its change is governed by Eq. (4). Therefore for the magnitudes φ = nV we may write $d\varphi/dh = \Phi_1 + \Phi_2$, where Φ_1 is determined by the jumps, and Φ_2 by the continuous growth of the bubbles on account of the inflow of gas during the intervals between the jumps. When γ = 1, which we assume on the basis of what was said above, we have $\Phi_1 = 0$ and $\Phi_2 = n dV/dh$ and dV/dh and n are described by formulas (4) and (23). In this case therefore, instead of (18), we obtain the equation

$$\frac{d\varphi}{d\zeta} = \left[\frac{1-\varphi}{1+\varphi} N - B\frac{\varphi^{7/6}}{1+\varphi}\exp\left(\frac{\beta\zeta}{6}\right) - 1\right]\exp\left(-\frac{\beta\zeta}{2}\right)\varphi^{1/2}, \tag{24}$$

where β and ζ are, as before, determined in (15) and (16). Thus, when random coalescence is taken into account, another parameter, viz., β, affecting evolution, appears. The integral curves of Eq. (24) for different β are shown in Fig. 3. It can be seen that coalescence greatly retards the increase of φ with increasing height and attainment of the limit state.

The second limit situation is encountered with coherent bubble formation above adjacent nozzles or holes. In this case there are horizontal layers of parallelly rising bubbles "with equal rights," and pairwise coalescence at some level occurs as a result of the "lateral" merger of adjacent bubbles after these bubbles have grown to such an extent that the regions of closed circulation surrounding them merge [21]. As a result, a new ordered horizontal layer of bubbles forms in which the bubbles simultaneously coalesce at a new and higher level, etc. Sometimes such layers form initially upon disintegration of the horizontal cavities which form above the distributor on account of the merger of the elementary gas filament bands [22]. Various random factors may infringe such an ordered pattern because somewhere high above the grid a random regime arises.

In this situation, the equation governing the evolution of the dilute phase in the interval between the (i–1)-st and the i-th coalescence levels has the form (again we use the simplifications leading to (18) and (24))

$$\frac{d\varphi}{d\zeta} = \left[\frac{1-\varphi}{1+\varphi} N - B\frac{2^{(i-1)/6}\varphi^{7/6}}{1+\varphi} - 1\right] \frac{\varphi^{1/2}}{2^{(i-1)/2}}. \quad (25)$$

An ideal of the nature of the evolution can be obtained from Fig. 4 which shows the curves $\varphi(\zeta)$ at the first three such intervals. It was arbitrarily accepted that to the first two levels of coalescence correspond the values $\zeta_{1,2}$ = 0.40 and 0.80. The curves in Fig. 4 confirm the previously made conclusion that coalescence retards the rate of evolution.

In conclusion, we will show that in real, horizontally bounded beds, coalescence leads to a loss of bubbles in the regions near the walls, as was observed in [23], and to the transformation of the initial profile of gas speed, first into a profile with several maxima, and then into a profile with a single maximum near the axis of the apparatus [24]. This is directly related to the shedding of light on the mechanisms determining the scale effect, and it therefore deserves independent examination.

NOTATION

a, particle radius; B, parameter defined in [15]; c, numerical coefficient in (4); d_0, density of the continuous phase; d_1, density of the disperse phase; F, G, functions defined in (9) and (13), respectively; f, part of the volume of the sphere with radius R occupied by the wake zone of the bubble; g, acceleration of gravity; H, scale of length from (16); h, height in the bed; k_i, coefficients in (1)-(3); N, fluidization number; n, numerical concentration of the bubbles; R, radius of the bubble head; u_b, speed of ascent of a cluster of bubbles; u_{b0}, speed of ascent of a single bubble; u_d, rate of filtration in the dense phase; u_s, speed of descent of particles of the dense phase, u, total fluidization flow in the bed; V, volume of the bubble; α, coefficient introduced in (2); β, β', constants of the coalescence rate introduced in (23); γ, coefficient of conservation of volume with coalescence; ε_d, porosity of the dense phase; ζ, dimensionless height; $\varkappa$, d_1/d_0; ν, kinematic viscosity of the fluidizing medium; φ, volumetric concentration of the dilute phase; Ar, Archimedes number. Subscripts: 0, initial state at the grid; *, state of minimum fluidization.

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A SYSTEM OF HEAT—MASS-TRANSFER EQUATIONS FOR VAPOR FILTRATION IN DISPERSED MEDIA

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A system of heat—mass-transfer equations describing filtration of a vapor in dispersed media is presented. The cases of "local thermal equilibrium" and temperature difference between the filtering agent and medium particles are considered.

Interest in the study of vapor filtration in dispersed media has increased recently. This is primarily due to the promise of vapor—fuel methods for increasing petroleum and gas output.

To describe the filtration process, a number of studies have proposed use of the system of equations presented in [1], which is not a totally justifiable approach. That system was obtained on the basis of the following assumptions: the change in mass content of the medium was expressed by the formula

$$dU_i = \frac{\varepsilon\sigma_i M_0}{R}\left(dP - \frac{1}{T^2}\,dT\right) + \frac{\varepsilon P M_0}{RT}\,d\sigma_i; \tag{1}$$

the saturation of the medium by the i-th component was assumed to change insignificantly, i.e., $d\sigma_i \approx 0$; the filtering vapor was regarded as an ideal gas. Thus, according to [2], the filtration equation was linearized, i.e.,

$$\frac{\partial P}{\partial \tau} = A\,\mathrm{div}\,(\mathrm{grad}\,P), \tag{2}$$

where

$$A = \left(\frac{k_p}{c_p\rho_b} - \frac{\varepsilon a_m}{c_p}\,\delta_p\right). \tag{3}$$

The total flux of the liquid component was defined as

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