THEORY OF DESCRIBING PROCESSES WITH PHASE TRANSFORMATIONS IN SPOUTED BED APPARATUS

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The article presents the averaged equations of mass, momentum, and energy transfer for the zones of the ring and the core of spouted beds. An analytical relation for determining the diameter of the bed diameter is given.

Spouting is an efficient method of bringing the particles of the processed material in contact with gases or liquids, and it is ever more widely used in practice. A topical problem is therefore the selection of the hydrodynamic regimes ensuring intense mass and heat exchange, and the investigation of the mass transfer processes occurring in spouted bed apparatus.

Although many authors [1-4] investigated the processes in spouted beds, so far we lack the theoretical foundations for describing the processes with phase transformations in apparatus of this type, based on strict relations of the thermomechanics of multiphase media. The result is a large number of empirical relationships of special nature which are badly reproducible on equipment of different size, and in particular, we have no strict analysis of the interaction of the streams in the zones of the core and the ring, taking the changes of their configuration into account.

The present article describes the mass, momentum, and energy transfer in the zones of the core and the ring with a view of the entrainment of gas from the core to the spout ring, the polydispersity of the disperse phase, and phase transitions on the basis of the mechanics of heterogeneous media. An analysis of the entropy of the system yielded a relation for determining the profile of the core under conditions of stable spouting.

A spouted bed apparatus may be divided into two zones: the zone of the core characterized by the ascending stream of the fluidized agent and particles, high speeds of the gas and the particles, great porosity, and the zone of the ring where the disperse phase in countercurrent to the fluidizing agent descends, being characterized by lower speed of the gas and smaller porosity than in the core.

We examine the steady-state case of operation of the apparatus taking into account the radial transfer of gas from the core to the ring, but we do not take into account radial particle transfer or effects connected with a change of the interphase surface such as crumbling, coalescence, aggregation, etc.

In each zone we examine a multispeed, multitemperature medium taking into account the assumptions adopted in [5, 6]. The first phase is the carrier phase, i.e., a gas ascending with speed v_1 and having the temperature T_1, the m-th phase are particles or drops whose mass lies within the limits $(m - dm, m + dm)$, moving at the speed v_2 and having the temperature T_2. We use the system of equations of thermohydrodynamics for describing processes with phase transformations (taking the polydispersity of inclusions into account) at a local point of the apparatus obtained in [5, 6], and we write the differential equation of the conservation of mass of the carrier phase in the zone of the spout core in projections onto the axis of the apparatus:

$$\iint\limits_{F_c} \frac{\partial}{\partial x} \rho_{1c} v_{1cx} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial y} \rho_{1c} v_{1cy} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial z} \rho_{1c} v_{1cz} dF_c = \iint\limits_{F_c} \int\limits_0^M f\eta \, dm \, dF_c. \quad (1)$$

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By using the Green formula [7], we change the second and third terms on the left-hand side of Eq. (1) to the form

$$\iint\limits_{F_c} \frac{\partial}{\partial z} \rho_{1c} v_{cz} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial y} \rho_{1c} v_{1cy} dF_c = \oint\limits_{L_c} \rho_{1c} v_{1cz} dy - \rho_{1c} v_{1cy} dz = -2 \oint\limits_{L_c} \rho_{1c} v_{1cy} dz \sim 4\rho_{1c} \hat{v}_{1cy} d_c.$$

Integration over the closed contour enabled us to eliminate the projection of the speed onto the z axis (here we take as the positive direction the direction opposite to the entrainment of the gas from the core). Then the equation of continuity of the carrier phase in the spout core (1) may be represented as follows:

$$\frac{d}{dx}(\rho_{1c} \hat{v}_{1cx} F_c) = \int\limits_0^M f_c \eta dm F_c - 4\rho_{1c} \hat{v}_{1cy} d_c, \tag{2}$$

where the last term on the right-hand side of Eq. (2) takes into account the entrainment of gas from the core to the ring.

We write the differential equations of the conservation of momentum for the carrier phase in projections onto the axis of the apparatus:

$$\iint\limits_{F_c} \frac{\partial}{\partial x} \rho_{1c} v_{1cx} v_{1cx} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial y} \rho_{1c} v_{1cx} v_{1cy} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial z} \rho_{1c} v_{1cx} v_{1cz} dF_c = -\iint\limits_{F_c} \alpha_{1c} \frac{\partial P}{\partial x} dF_c - \tag{3}$$

$$- \iint\limits_{F_c} \int\limits_0^M m f_c f_{12xc} dm dF_c - \iint\limits_{F_c} \rho_{1c} F_{1cx} dF_c + \iint\limits_{F_c} \int\limits_0^M f_c \eta v_{2cx} dm dF_c - f_{c\,\text{к}},$$

$$\iint\limits_{F_c} \frac{\partial}{\partial x} \rho_{1c} v_{1cx} v_{1cy} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial y} \rho_{1c} v_{1cy} v_{1cy} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial z} \rho_{1c} v_{1cy} v_{1cz} dF_c = -\iint\limits_{F_c} \alpha_{1c} \frac{\partial P}{\partial y} dF_c. \tag{4}$$

Using the Green formula [7], we transform the second and third terms on the left-hand side of Eqs. (3) and (4) into

$$\iint\limits_{F_c} \frac{\partial}{\partial z} \rho_{1c} v_{1cx} v_{1cz} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial y} \rho_{1c} v_{1cx} v_{1cy} dF_c \sim 4\rho_c \hat{v}_{1cx} \hat{v}_{1cy} d_c, \tag{5}$$

$$\iint\limits_{F_c} \frac{\partial}{\partial z} \rho_{1c} v_{1cy} v_{1cz} dF_c + \iint\limits_{F_c} \frac{\partial}{\partial y} \rho_{1c} v_{1cy} v_{1cy} dF_c \sim 4\rho_{1c} \hat{v}_{1cy}^2 d_c. \tag{6}$$

Taking into account expressions (5), (6), and the relation

$$\iint\limits_{F_c} \alpha_{1c} \frac{\partial P}{\partial y} dF_c \sim \alpha_1 4 \int\limits_0^{\frac{d_c}{2}} \int^{\sqrt{\frac{d_c^2}{4} - z^2}} \frac{\partial P}{\partial y} dy dz \sim 2 d_c \alpha_{1c} (P_c - P_c), \tag{7}$$

we transform the equations of motion of the carrier phase (3) and (4):

$$\rho_{1c} \hat{v}_{1cx} F_c \frac{d}{dx} \hat{v}_{1cx} = -\alpha_{1c} \frac{dP_c}{dx} F_c - \int\limits_0^M f_c m f_{12x} dm F_c - \rho_{1c} F_{1cx} F_c + \int\limits_0^M f_c \eta (\hat{v}_{2cx} - \hat{v}_{1cx}) dm F_c - f_{c\,\text{к}}, \tag{8}$$

$$\rho_{1c} \hat{v}_{1cx} F_c \frac{d}{dx} \hat{v}_{1cy} = 2 d_c \alpha_{1c} (P_c - P_c) - \int\limits_0^M f_c \eta \hat{v}_{1cy} dm F_c. \tag{9}$$

Equation (8) characterizes the change of the mean speed of the carrier phase in the core of the stream in the projection onto the axis of the apparatus. It follows from Eq. (9) that the change of speed of gas entrainment from the core to the ring along the axis of the apparatus proceeds on account of a change of pressure gradient in the section ($P_c \neq P_K$) over the height of the apparatus. We average similarly the other equations of the system obtained in [5] for the zones of the core and of the ring, and we write the mathematical model of the processes with phase transformations in spouted bed apparatus.

Model of Processes with Phase Transformations in Spouted Bed Apparatus

Zone of the Core. The equations of conservation of mass and of the balance of the number of particles are:

$$\frac{d}{dx}(\rho_{1c}\hat{v}_{1cx}F_c) = \int_0^M f_c \eta \, dm F_c - 4\rho_{1c}\hat{v}_{1cy}d_c, \tag{10}$$

$$\frac{d}{dx}(c_c\hat{v}_{1cx}F_c) = \int_0^M f_c \eta \, dm F_c - 4c_c v_{1cy} d_c, \tag{11}$$

$$\frac{\partial}{\partial x}(f_c\hat{v}_{2cx}F_c) - F_c\frac{\partial}{\partial m}(f_c\eta) = 0. \tag{12}$$

Equations (10) and (11) characterize the change of mass of the carrier phase and of a separate component in the spout core over the height of the apparatus with a view to the entrainment of gas into the ring zone and to the phase transformation. Equation (12) expresses the change of the number of particles in the spout core over the height of the apparatus; we neglect radial particle transfer.

The equations of motion of the carrier phase and of the m-th phase are:

$$\rho_{1c}\hat{v}_{1cx}F_c\frac{d}{dx}\hat{v}_{1cx} = -\alpha_{1c}\frac{dP_c}{dx} + \int_0^M f_c\eta(\hat{v}_{2cx} - \hat{v}_{1cx})\,dmF_c - f_{cK} - \int_0^M f_c m f_{12cx}\,dmF_c - \rho_{1c}F_{1cx}F_c, \tag{13}$$

$$\rho_{1c}\hat{v}_{1cx}F_c\frac{d}{dx}\hat{v}_{1cy} = 2d_c\alpha_{1c}(P_c - P_c) - \int_0^M f_c\eta v_{1cy}\,dmF_c, \tag{14}$$

$$\hat{v}_{2cx}f_c m\frac{\partial v_{2cx}}{\partial x} - f_c m\eta\frac{\partial \hat{v}_{2cx}}{\partial m} = -f_c r\frac{\partial P_c}{\partial x} + f_c m f_{12cx} - f_c m F_{2cx}. \tag{15}$$

Equations (13) and (14) characterize the change of the projections of the speed vector of the carrier phase over the height of the apparatus taking into account the mass transfer from the zone of the core to the ring zone, phase transformations, interaction between the streams of carrier phase in the zone of the core and of the ring, and interaction between the carrier phase and inclusions. Equation (15) expresses the change of speed of the m-th phase taking into account the phase transformation, the polydispersity of the disperse phase, and interaction with the carrier phase.

The equations of change of energy of the carrier and m-th phases are:

$$\rho_{1c}C_{P1c}\hat{v}_{1cx}F_c\frac{dT_{1c}}{dx} = -\Delta h\int_0^M f_c\eta\,dmF_c - \int_0^M 4\pi a^2\beta_Q f_c(T_{1c} - T_{2c})\,dmF_c +$$

$$+ \int_0^M f_c m f_{12cx}(\hat{v}_{2cx} - \hat{v}_{1cx})dm + f_{cK}(\hat{v}_{1cx} - \hat{v}_{1cx}) - F_c\int_0^M f_c\eta\frac{(\hat{v}_{2cx} - \hat{v}_{1cx})^2}{2}\,dm, \tag{16}$$

$$f_C m \hat{v}_{2Cx} C_{P2C} \frac{dT_{2C}}{dx} = 4\pi a^2 \beta_Q f_C (T_{1C} - T_{2C}). \tag{17}$$

Equation (16) characterizes the change of temperature of the carrier phase in the spout core over the height of the apparatus, taking into account the phase transformation (it is accepted that the heat of phase transformation is liberated or consumed by the phase with higher thermal conductivity), the heat exchange between the carrier phase and the inclusions, energy dissipation on account of interaction of the carrier phase with the m-th phase, interaction between the streams of carrier phase in the zone of the core and of the ring on account of nonequilibrium exchange of momentum in phase transformations. Equation (17) characterizes the change of temperature of the m-th phase over the height of the apparatus due to heat exchange with the carrier phase.

The equation of state of the carrier phase in the spout core is:

$$P_C = \rho_{1C}^0 R T_{1C}. \tag{18}$$

Zone of the Ring. The equations of conservation of mass and of the balance of the number of particles are:

$$\frac{d}{dx}(\rho_{1Cx} \hat{v}_{1Cx} F_C) = \int_0^M f_C \eta \, dm F_C + 4\rho_{1C} \hat{v}_{1Cy} d_C, \tag{19}$$

$$\frac{d}{dx}(c_K \hat{v}_{1Kx} F_K) = \int_0^M f_K \eta \, dm F_K + 4 c_C \hat{v}_{1Cy} d_C, \tag{20}$$

$$\frac{\partial}{\partial x}(f_K v_{2Kx} F_K) - F_K' \frac{\partial}{\partial m} f_K \eta = 0. \tag{21}$$

The equations of motion of the carrier and the m-th phases are:

$$\rho_{1K} v_{1Kx} F_K \frac{d}{dx} \hat{v}_{1Kx} = -\alpha_{1K} \frac{dP_K}{dx} F_K - \int_0^M f_K m f_{12Kx} dm F_K - \rho_{1K} F_{1Kx} F_K - \int_0^M f_K \eta (\hat{v}_{2Kx} - \hat{v}_{1Kx}) dm F_K + f_{CK} - f_{CT}, \tag{22}$$

$$v_{2Kx} m f_K \frac{\partial \hat{v}_{2Kx}}{\partial x} - m f_K \eta \frac{\partial \hat{v}_{2Kx}}{\partial m} = -f_K r \frac{dP_K}{dx} + f_K m f_{12Kx} F_{2Kx}. \tag{23}$$

The equations of change of energy of the carrier and the m-th phases are:

$$\rho_{1K} C_{P1K} \hat{v}_{1Kx} F_K \frac{dT_{1K}}{dx} = -\Delta h \int_0^M f_K \eta \, dm F_K - \int_0^M 4\pi a^2 f_K \beta_Q (T_{1K} - T_{2K}) dm F_K + \int_0^M f_K m f_{12Kx} (\hat{v}_{2Kx} - \hat{v}_{1Kx}) dm F_K -$$

$$- \int_0^M f_K \eta \frac{(\hat{v}_{2Kx} - \hat{v}_{1Kx})^2}{2} dm F_K - f_{CK} (\hat{v}_{1Cx} - \hat{v}_{1Kx}) + f_{CT} \hat{v}_{1Kx}, \tag{24}$$

$$f_K m \hat{v}_{2Kx} C_{P2K} \frac{dT_{2K}}{dx} = 4\pi a^2 \beta_Q f_K (T_{1K} - T_{2K}). \tag{25}$$

The equation of state of the carrier phase in the zone of the ring is:

$$P_K = \rho_{1K}^0 R T_{1K}. \tag{26}$$

Boundary conditions: lower

zone of the core zone of the ring

$$\rho_{1C}v_{1Cx}F_C|_{x=x_0}+\rho_{1K}v_{1Kx}F_K|_{x=x_0}=G_{10}, \tag{27}$$

$$v_{1Cy}=0,\ \rho_{1C}|_{x=x_0}=\rho_{10}, \qquad \alpha_{2K}=0{,}4,\ c|_{x=x_0}=0,$$
$$c|_{x=x_0}=c_0,\ T_{1C}|_{x=x_0}=T_{10}, \qquad T_{1K}|_{x=x_0}=T_{10},\ T_{2K}|_{x=x_0}=T_{20}, \tag{28}$$
$$T_{2C}|_{x=x_0}=T_{20},$$

upper

$$f_K|\hat{v}_{2Kx}|F_K|_{x=H}+G_{20}=f_C|\hat{v}_{2Cx}|F_C|_{x=H}, \tag{29}$$

fitting condition

$$f_K|\hat{v}_{2Kx}|F_K|_{x=x_0}+G_{20}=f_C|v_{2C}|F_C|_{x=x_0}, \tag{30}$$

condition for determining the spouting height (the mean masses of the inclusions at the uppermost point of the spout in the core and the ring are equal)

$$\left.\frac{\int\limits_0^M mf_C dm}{\int\limits_0^M f_C dm}\right|_{x=H}=\left.\frac{\int\limits_0^M mf_K dm}{\int\limits_0^M f_K dm}\right|_{x=H}. \tag{31}$$

Relations (27)-(31) fully determine the specification of the boundary conditions for the system (10)-(26). Here we took as the positive direction the upward direction along the axis of the apparatus, where $F_{1CX}=F_{1KX}=g$, $F_{2CX}=F_{2KX}=g$. The expressions for f_{12}, f_{cK}, f_{cT}, representing the interactions between the components of the mixture, are written analogously [8]:

$$f_{12}=\frac{3}{4}\frac{\rho_1^0}{\rho_2^0}\frac{c_{12}}{dc}\frac{(\hat{v}_{1x}-\hat{v}_{2x})^3}{|\hat{v}_{1x}-\hat{v}_{2x}|},\ c_{12}=c_{12}(\mathrm{Re}_{12},\ \alpha_1);$$
$$f_{CK}=c_{CK}\pi d_C\rho_1^0(\hat{v}_{1Cx}-\hat{v}_{1Cx})^2,\ c_{CK}=c_{CK}\left(\frac{dc}{d_K},\ \mathrm{Re}_{1C},\ \mathrm{Re}_{1K}\right); \tag{32}$$
$$f_{CT}=c_{CT}\pi F_K\rho_1^0\hat{v}_{1Kx}^2/d_K;\ c_{CT}=c_{CT}(\mathrm{Re}_{1K}).$$

For the complete closing of the system of hydromechanical equations describing processes with phase transformations in the spouted bed we have to know the shape and dimensions of the spout core. The relation for the diameter of the spout core we obtain from an analysis of the entropy of the system in the steady state.

We adopt the hypothesis of local equilibrium within the limits of each phase, then the Gibbs relations apply:

$$\rho_1\frac{d_1s_1}{dt}=\frac{\rho_1}{T_1}\frac{d_1u_1}{dt}+\rho_1\frac{P}{T_1}\frac{d_1}{dt}\frac{1}{\rho_1^0}-\frac{\mu_1}{T_1}\rho_1\frac{d_1c_1}{dt}; \tag{33}$$

$$fm\frac{d_2s_2}{dt}=\frac{fm}{T_2}\frac{d_2u_2}{dt}+fm\frac{P}{T_2}\frac{d_2}{dt}\frac{1}{\rho_2^0}. \tag{34}$$

Using the Gibbs relations (33), (34), the equations of change of energy (16), (17), and the equations of conservation of mass (10), (11), we write the expression for the origin of entropy of the zone of the core relative to any cross section of the spout core:

$$\frac{D\hat{S}^{(l)}}{Dt}=\int\limits_{F_C}\rho\frac{DS^{(l)}}{Dt}dF_C=\left[\frac{f_{CK}}{T_1}(\hat{v}_{1Cx}-\hat{v}_{1Kx})+\right.$$

$$+\frac{1}{T_1}F_c\int_0^M f_c m f_{12cx}(\hat{v}_{1cx}-\hat{v}_{2cx})\,dm+F_c\int_0^M 4\pi a^2 f_c\beta_Q\,(T_1-T_2)\times\left(\frac{1}{T_2}-\frac{1}{T_1}\right)dm+F_c\int_0^M f_c\eta X_{12}^M dm\Bigg]\geqslant 0. \quad (35)$$

Each term in expression (35) is the product of the thermodynamic forces and the thermodynamic streams. In the stable steady state all moving forces are constant. We write relation (35) in the form

$$\frac{D\hat{S}^{(l)}}{Dt}=J_{cK}^F X^F+F_c\int_0^M J_{12}^F X_{12}^F dm+F_c\int_0^M J_{12}^T X_{12}^T dm+F_c\int_0^M J_{12}^M X_{12}^M dm,$$

where $X_{cK}^F=(\hat{v}_{1cx}-\hat{v}_{1Kx})/T_1$ is the moving force of interaction between the zones of the spout core and the ring, determined by the difference of speed of the carrier phase in the zones of the core and the ring; $X_{12}^F=(\hat{v}_{1cx}-\hat{v}_{2cx})/T_1$ is the moving force of interaction between the carrier force and the inclusions, determined by the difference of the speeds of the carrier phase and of the inclusions in the spout core; $X_{12}^T=\left(\frac{1}{T_2}-\frac{1}{T_1}\right)$ is the moving force of heat exchange between the carrier phase and the inclusions, determined by the temperature difference between the phases; X_{12}^M is the moving force of mass exchange between the carrier phase and the inclusions, determined by the difference between the chemical potentials in the carrier phase and in the inclusions [9]; $J_{cK}^F=f_{cK}$ is the flux of the mechanical interaction force between the zones of the core and the ring, determined by relation (32); $J_{12}^F=f_{12}$ is the flux of the mechanical interaction force between the carrier phase and the inclusions, determined by relation (32); $J_{12}^T=4\pi a^2\beta_Q\,(T_1-T_2)$ is the flux of the thermodynamic force of heat exchange; $J_{12}^M=f\eta dm$ is the flux of the thermodynamic force of mass exchange.

The dependences $J_{ij}^n=f(X_{ij}^n)$ [n = F, F, T, M; i = c, 1, 1, 1; f = K, 2, 2, 2] are unknown in the general form. However, taking into account that when the system as a whole is in equilibrium, there are no fluxes and the moving forces are equal to zero, we expand the functions into Taylor series with respect to the state of equilibrium:

$$J_{ij}^n=f(X_{ij}^n)=f_{ij}^n(0)+X_{ij}^n f_{ij}^{n'}(0)+\frac{(X_{ij}^n)^2}{2!}f_{ij}^{n''}+\cdots$$
$$[n=F,\ F,\ T,\ M;\ i=c,\ 1,\ 1,\ 1;\ j=K,\ 2,\ 2,\ 2]. \quad (36)$$

When there are small deviations of the system from equilibrium, the linear kinetic relations between the thermodynamic fluxes and forces are correct:

$$J_{ij}^n=\beta_{ij}^n X_{ij}^n,$$
$$[n=F,\ F,\ T,\ M;\ i=c,\ 1,\ 1,\ 1;\ j=K,\ 2,\ 2,\ 2]. \quad (37)$$

It is easy to see that formula (32) for determining f_{cK} is a special case of relation (36).

Assume that the system is subject to perturbation along the force X_{cK}^F (e.g., random fluctuations changing the profile of the spout core), while all the other variables X_{ij}^n ($n\neq$ F, T, M; $i\neq$ c; $j\neq$ K) remain unchanged. Then, taking relation (36) into account, the change of origin of entropy by this variable will have the form

$$\frac{\partial}{\partial X_{cK}^F}(f_{cK}X_{cK}^F)=f_{cK}+X_{cK}^F\frac{\partial}{\partial X_{cK}^F}f_{cK}.$$

The following relation corresponds to the minimum change of origin of entropy:

$$\min\left[f_{cK}+X_{cK}^F\frac{\partial}{\partial X_{cK}^F}f_{cK}\right]. \quad (38)$$

The force of the resistance between the zones of the spout core and ring may be represented in the form

$$f_{\text{cK}} = \frac{A}{\text{Re}_{12}} (X_{\text{cK}}^F)^2 \tag{39}$$

— laminar regime or

$$f_{\text{cK}} = \beta_{\text{cK}}^F X_{\text{c.K}}^F,\ \beta_{\text{cK}}^F \neq \beta_{\text{cK}}^F (X_{\text{cK}}^F); \quad f_{\text{cK}} = \beta_{\text{cK}}^F (X_{\text{cK}}^F)^2 \tag{40}$$

— self-similar regime

$$\beta_{\text{cK}}^F \neq \beta_{\text{cK}}^F (X_{\text{cK}}^F).$$

Then the following relation (in deriving it we took into account the dependences (39) and (40)) corresponds to the minimum of origin of entropy for the two cases of regimes (laminar and self-similar):

$$\min [f_{\text{cK}}]. \tag{41}$$

Consequently, when the moving force of interaction between the zones of the spout core and ring deviates from the steady state, the endeavor of the entropy to inhibit its departure from the previous state is most strongly fulfilled when the relations (38), (41) are fulfilled: the spout core assumes the shape that puts up the least resistance to the gas stream. If the shape of the core is stable, then in every section along the axis of the core of the spouted bed either condition (38) or condition (41), depending on the flow regime, has to be fulfilled. From relations (38), (41) we determine the diameter of the spout core at every point over the height of the apparatus. The papers [10, 11] confirm experimentally the correctness of relations (38) and (41). The conditions (38) and (41) together with relations (27)-(31) and the specification of the kinetics of phase transformations close the system of equations (10)-(26).

Thus we obtained a generalized system of hydromechanical equations which may serve as the basis of the full mathematical description of multiphase, multicomponent mixtures with processes of heat and mass transfer in spouted bed apparatus.

NOTATION

$f(m)dm$, number of particles per unit volume whose mass lies within the limits $[m - dm, m + dm]$; m, mass of the inclusions; M, mass of the largest inclusions; ρ, ρ_1, mean density of the mixture and of the carrier phase, respectively; ρ_1^0, ρ_2^0, true density of the carrier phase and of the inclusion, respectively; v_1, v_2, speed of the carrier phase and of the m-th phase, respectively; η, observed rate of change of mass of the inclusion (in our case decrease of mass) per unit volume; t, time; x, y, z, coordinate system; x, direction of the axis of the apparatus; F, cross-sectional area; L, length of the closed curve bordering the core section; d, diameter; c, concentration of a component (kg/m^3); P, pressure; $f_{12}(m)$, force of interaction between the carrier phase and an inclusion with mass m; F_i, mass force acting on the i-th phase; α_i, volume content of i-th phase; f_{cK}, force of interaction between the zones of the core and the ring of the spouted bed; f_{cT}, force of interaction between the carrier phase and the apparatus wall; Re, Reynolds number; r, a, volume and radius of the inclusion, respectively; T_i, temperature of the i-th phase; R, universal gas constant; Δh, heat of phase transformation; β_Q, heat transfer coefficient from carrier phase to inclusion; C_{p_i}, heat capacity of the i-th phase; G, mass rate of the gas; H, spouting height; g, acceleration of gravity; c_{12}, resistance coefficient in interaction between carrier phase and inclusion; c_{cK}, coefficient of friction in interaction between the carrier phases in the zone of the core and of the ring; c_{cT}, resistance coefficient in interaction between the carrier phase in the zone of the ring and the apparatus wall; μ_1, chemical potential of a component in the carrier phase; S, s_1, s_2, specific entropies of the mixture, the carrier, and the m-th phases, respectively; X, moving force; J, thermodynamic flux; β, kinetic coefficient; A, constant. Subscripts: 1) relates to the carrier phase; 2) relates to the disperse phase; c, core; K, ring; 0, initial state; cT, wall; x, y, z, projections onto the 0x, 0y, and 0z axes, respectively; $\wedge$, mean value over the cross section.

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HYDRODYNAMICS OF MIXING OF LIQUID—SOLID SYSTEMS

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We present a model of the process of distribution of solid particles over the volume of a mixer. We analyze the kinetics of suspension, and show there is agreement between experimental and calculated data.

In carrying out reactions it is necessary to know the solution of the problem of mixing of solid particles in a liquid. A major part of the investigation of this problem seemed to be the determination of the operating conditions of a mixer to ensure suspension of the solid particles. These conditions were described by the minimum rotational speed n_0 of the mixer [1-4], of the specific power $\varepsilon_v = N/V_a$ [5, 6]. The effect of the size of the devices was studied in detail in [1-3] and in [7]. However, the kinetics of the formation of a suspension, and the effect of mixing on the homogeneity of the particle distribution in the active volume of a reactor were hardly studied, although these phenomena are important in carrying out chemical transformations such as condensation polymerization.

In the present article we study the hydrodynamics of mixing of liquid—solid systems on the basis of the circulation cell model proposed earlier [8]. According to this model the active volume of the reactor is divided into cells by intersecting horizontal and vertical planes. The displacement of a liquid particle and its macromixing are described by a system of material balance equations formulated for each cell, taking account of flow conditions. The flow rates through the cell faces are determined from the calculated velocities w_φ, w_r, w_z of the medium at the plane faces of the cells by using an analytic model of the spatial hydrodynamics of mixers [9].

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