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FEATURES AND EFFICIENCY OF INTERPHASE HEAT AND MASS TRANSFER WITH A PULSATION ORGANIZATION OF THE PROCESS

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It is shown that, with a low-frequency organization of transient interphase heat and mass transfer, its intensity is higher than in the case of a stationary organization. Algorithms for computation of the interface and the time of phase contact in jet mixing of mutually insoluble media are given.

The predominant number of physicochemical processes in mobile heterogeneous systems occur by the so-called diffusion kinetics when the limiting link is heat and mass transfer (in what follows, transfer) and the major resistance is concentrated in the vicinity of the interface. Of the components of an interphase transfer equation – the transport coefficient β, the interface S, and the driving force of transfer ΔA – it is the first two components[*]. that are the most difficult to determine. Since the exact solution of hydrodynamical problems is unknown for the majority of physicochemical apparatuses, we relate β and S to the energy expenditure on mixing, the efficiency of energy consumption being very low and not exceeding 10% as a rule. This result comes as no surprise. Although a heterogeneous system can exist only as a kinematically nonequilibrium system and hence there is always a phase "slip," the difference of phase velocities and the velocity gradients in the vicinity of the interface are small, which causes a small fraction of the energy expended on β and on producing S. Indeed, if in a two-phase system a certain energy potential is realized, for example, as the pressure difference Δp, to accelerate the system, with allowance made for the action of the additional mass, the ratio of the dispersed u_2 and dispersion u_1 phase velocities cannot exceed the value

$$\frac{u_2}{u_1} \leq \sqrt{\left(\frac{1.5}{0.5 + \rho_2/\rho_1}\right)}, \tag{1}$$

where ρ_i ($i = 1, 2$) is the density of the ith phase. When $\rho_2 \approx \rho_1$ (liquid emulsions, suspensions), $u_2 \approx u_1$; when $\rho_2 << \rho_1$ (gas–liquid emulsions), $u_2 \leq 1.7u_1$. Naturally, for $\rho_2 >> \rho_2$, the action of the additional masses is insignificant and $u_2/u_1 << 1$, which predetermines the larger phase-velocity difference. This relation of phase densities and velocities is characteristic of gas suspensions, which are not considered here.

The space-time redistribution of mechanical energy, its local concentration, or what is still better, the concentration in the vicinity of the interface is a powerful factor of increasing β and S. It is precisely transient, pulsed processes that exhibit a remarkable property of the energy redistribution in time and space. As an illustration, we can give a gas-pulse device with a variable geometry of the working volume which makes it possible to locally concentrate the energy and to produce superpositive–supernegative pressures [1]. Pulsation motion here is organized as monotonically accelerating motion with a sharp retardation late in each cycle and the subsequent high-amplitude fluctuations of the basic parameters in the localized zone. Systems that are a spatial combination of these devices can perform various technological problems. Another example can be "provoking" the release of gas or vapor bubbles in a heterogeneous system with their subsequent collapse. Since a new phase occurs

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[*] The coefficient β can be the coefficient of transmission or transfer depending on the interpretation of ΔA

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predominantly in the vicinity of structural "defects" of the system and the interface is actually one version of these "defects," it is precisely on the interface that "boiling–condensation" will be realized. Kinetic, energy, and turbulent effects of collapse can be estimated on the basis of the Rayleigh formulas for the simplest case of a gas bubble [2]:

$$\frac{dR}{dt} = \sqrt{\left(\frac{2}{3}\frac{p_\infty}{\rho}\left(\frac{R_0 - R}{R}\right)^3\right)}, \quad R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{p_R - p_\infty}{\rho}, \tag{2}$$

where R is the bubble radius; p is the pressure; t is the time; r is the coordinate; ρ is the liquid density; R_0 is the initial radius, which satisfies the condition $p_R = 0$; p_R is the pressure for $r = R$; p_∞ is the pressure as $r \to \infty$. According to (2), when a bubble collapses $(R \to 0)$: $dR/dt \to \infty$ and $p_R \to \infty$.

Thus, pulsed collapse of the bubbles is accompanied by powerful dynamic effects, which intensify precisely the interphase heat and mass transfer by deforming the interface and increasing convective and turbulent components of the transfer. The calculation of a flow channel with the production and subsequent collapse of vapor bubbles is presented in [3]. It is easy to combine the effects of bubble collapse with the pulsation treatment accompanied by the development of negative pressures.

Pulsation organization of physicochemical processes can prove effective by purely formal indications. If the quantities $x = \{\dot{M}, \beta, S, \Delta A\}$ that enter in the transport equation are represented as the sum of the components $\langle x \rangle$, averaged over the time interval τ, and the deviations from them x':

$$x = \langle x \rangle + x'(t),$$

$$\langle x' \rangle \equiv \frac{1}{\tau}\int_\tau x' dt = 0, \tag{3}$$

then after the procedure of averaging with allowance made for the Reynolds laws, we obtain

$$\langle \dot{M} \rangle = \overset{\text{I}}{\langle \beta \rangle \langle S \rangle \langle \Delta A \rangle} + \overset{\text{II}}{\langle \beta \rangle \langle S' \Delta A' \rangle} + \overset{\text{III}}{\langle S \rangle \langle \beta' \Delta A' \rangle} + \overset{\text{IV}}{\langle \Delta A \rangle \langle \beta' S' \rangle} + \overset{\text{V}}{\langle \beta' S' \Delta A' \rangle}, \tag{4}$$

where $\dot{M}$ is the transfer efficiency and τ involves a sufficiently wide range of pulsation cycles. The expenditure of mechanical energy on the process, for a small change in the interphase tension, is proportional to the surface S and, therefore, taking (3) into account, it will almost be the same both with the pulsation organization and traditional pseudostationary organization. By the latter, we mean both continuous and periodic organizations in the universally accepted interpretation since the basic transfer parameters β and S in these schemes are determined as constant with time and hence $\dot{M}_{\text{st}}$ will be expressed by the first term on the right-hand side of (4):

$$\dot{M}_{\text{st}} = \langle \beta \rangle \langle S \rangle \langle \Delta A \rangle. \tag{5}$$

Thus, the effect of the pulsation organization of the process as compared to the traditional pseudostationary organization is reflected by the sum of terms II-V of expression (4) for the same useful energy consumptions. As has been noted above, in any heterogeneous system, there is a phase "slip." With velocity of motion, the magnitude of the "slip" increases, and consequently both convective and turbulent components of the interphase transfer and deformation of the interface increase synchronously. Since here we deal with low-frequency pulsations (with frequencies $f_{\text{low}} \sim \text{sec}^{-1}$) and the turbulent components of momentum, heat, and material transfer are determined by pulsations with frequencies of energy-containing vortices [4]

$$f_e \sim \sqrt{\left(\frac{\varepsilon}{100\nu}\right)} >> f_{\text{low}}, \tag{6}$$

where ε is the rate of turbulent-energy dissipation (usually $\varepsilon \leq 1$ W/kg), ν is the kinematic viscosity factor which has a value of the order $\nu \sim 10^{-6}$ m^2/sec, these vortices will practically instantaneously react to a variation in low-frequency characteristics and be, in essence, in equilibrium with them. Therefore, we can write the following relationship:

$$\begin{aligned} &\text{for } S' > 0 \quad \beta' > 0, \ \Delta A' < 0; \\ &\text{for } S' < 0 \quad \beta' < 0, \ \Delta A' > 0. \end{aligned} \tag{7}$$

According to (7), central moments of the second order II and III will be negative in the majority of cases, while moment IV will be positive. The central moment of the third order V will change sign, but its contribution can be disregarded since as the order of the moment increases its effect decreases.

Terms II and III can be positive when the variation in A is directionally controlled in the unit. Another method to unconditionally enhance the transfer intensity is increasing the values of A to such a level when $\Delta A' \to 0$. In this case, instead of (4) we obtain

$$\langle \dot{M} \rangle = \langle \Delta A \rangle \left(\langle \beta \rangle \langle S \rangle + \langle \beta' S' \rangle \right), \tag{8}$$

in which, according to (7), the moment $\langle \beta' S' \rangle$ is always positive. The possible overexpenditure of A can easily be avoided by introducing a recycle.

To establish the basic quantities β and S which govern interphase transfer, a clear idea of the structure of the flow in the apparatus or the technological cell is required. Condition (6) enables us to interpret $\beta(t)$ as a function determined from "pseudostationary" dependences which reflect the flow structure at instant t. This approach yields acceptable results [5]. If we restrict ourselves to two-phase liquid systems whose dispersed phase is a liquid, or a gas, or solid particles, insoluble in the dispersion medium, then, in spite of the variety of possible motion patterns, they will be reduced to two basic types: a "blurred" mixing layer (the first type) and the motion of pronounced, in some cases, easily deformable, dispersions (the second type). Under certain conditions, the first type can be transformed into the second type (for example, a turbulent jet of mutually insoluble liquids which is unbounded in the longitudinal direction [6]), while the second type can be transformed into the first type (for example, bubbling of single bubbles which go into a jet at a distance from the nozzle). There are no special problems for establishing the interface S for the second type. As far as constructing here the model to determine the coefficient β is concerned, much depends on the phase slip and interface deformability. If the slip is substantial, we can orient ourselves to the Higby–Dankwerts–Kishinevskii penetration models or to Levich's concepts of a diffuse boundary layer. In the latter case, the expression for a turbulent-diffusion coefficient depends substantially on the interface mobility. For dispersed systems with similar phase densities, the relative phase velocity is insignificant. Since, as a rule, a turbulent regime of motion is realized and the dispersion size is larger than the size of energy-containing vortices, the problem of interphase mass transfer here can be solved within the framework of the Kolmogorov–Obukhov concept of homogeneous isotropic turbulence and the Landau–Levich concept of a viscous sublayer. It is much more difficult to construct a physically substantiated model of interphase transfer for flows of the first type: a mixing layer with a "blurred" pattern of motion.

It has been established [7] and repeatedly substantiated [8] that formation of a mixing layer is the result of a cascade pairwise merging of quite determined vortex formations. Vortices are the "closest" (almost within slip) interaction of particles, and if the times of phase contact are known, the transfer in vortices can be considered within the framework of the Higby–Dankwerts–Kishinevskii concepts.The transfer through the surface between vortex formations can be considered within the framework of the concepts of the boundary-layer theory.

Quantitative relations that determine the interface evolution and the time of phase contact in the mixing layer are as follows. The first coalesence of the vortices occurs at a distance of one characteristic dimension d (the nozzle diameter, the slot width, the size of a lattice, a technological cell, a trace-forming obstacle, etc.) from the beginning of the flow. The subsequent ith coalescences are offset from the beginning of the flow by the following distances [7]:

$$x_i \approx 1.40 x_{i-1} \quad (i = 1, 2, \ldots), \tag{9}$$

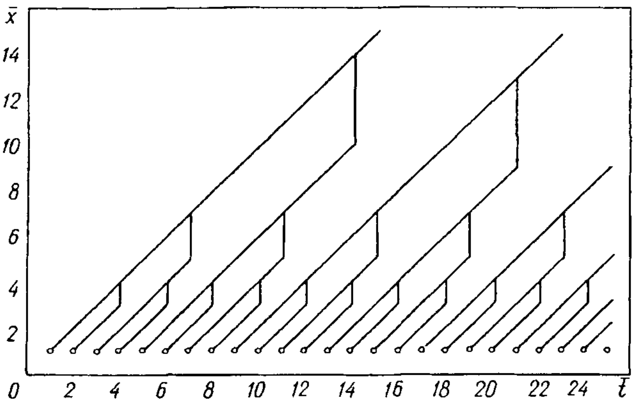

Fig. 1. Space-time diagram of the evolution of vortex formations in a jet mixing layer.

where $x_0 = 0.71d$. The vortex velocity is a magnitude of the order [7]:

$$u_c \approx \frac{u_1 + u_2}{2} \approx \text{const}\,. \tag{10}$$

The vortices coalesce when the leading vortex is sharply retarded for a short time and the vortex that follows it is sharply accelerated for a short time (see Fig. 4 of [7]). The flow pattern in the layer will be a set of pronounced vortex formations that move with a constant velocity and constant distances until $x_i < 1.40x_{i-1}$. After the time interval $\tau = d/u_c$ at distance d from the beginning of the flow, a new merged vortex will appear, which evolves according to (9) and (10). Figure 1 gives a space-time ($\bar{x}$–$\bar{t}$) diagram of trajectories and coalescences of the basic vortex formations, which is calculated by (9) and (10). We took d and τ ($\bar{x} = x/d$, $\bar{t} = t/\tau$) as units of length and time. The largest mixing-layer length cannot exceed $L_{\max} = 15d$ [9], which limited the ordinate of the universal plot. The problem is specified by cutting off the upper portion of the diagram $\bar{x} > \bar{L}$ ($\bar{L} = L/d$). As the plot shows, the recurrence period of the flow pattern (cycle) begins for $\bar{L} = 14$ after $\bar{t}_{\text{cycle}} = 8$, for $\bar{L} = (7-13)$ after $\bar{t}_{\text{cycle}} = 4$, for $\bar{L} = (4-6)$ after $\bar{t}_{\text{cycle}} = 2$, and for $\bar{L} < 4$ after $\bar{t}_{\text{cycle}} = 1$.

The vortex size changes due to the longitudinal, nearly layer-by-layer, involvement in the mixing layer of the ith phase that moves with velocity larger than the vortex velocity ($u_i > u_c$), i, $j = 1$, 2 (the "padded collar" model). The ith phase's band, involved in the vortex, determines the increase in the interface S in the vortex:

$$dS = k_S\, \Pi_i\, (u_i - u_c)\, dt\,, \tag{11}$$

or after substituting $t = x/u_c$,

$$dS = k_S\, \Pi_i \frac{u_i - u_c}{u_c}\, dx\,. \tag{12}$$

Here Π_i is the perimeter of the mixing-layer cross section on the side of the ith phase in which $u_i > u_c$, k_S is the coefficient of the completeness of phase stratification in the vortex, which has a rigorous upper bound $k_S \leq 2$. Integration of (11) and (12) presents no difficulties and, accurate to k_s, determines both the interface in the vortex and the duration of phase contact. The characteristics of the merged vortex are established by simple additive relations when the ($\bar{x}$–$\bar{t}$) diagram is considered. The vortex sizes will be in the neighborhood of the mixing-layer thickness at the site of vortex formation (coalescence) [7]. The variation in the mixing-layer thickness along the length is established according to the investigations of [6, 9]. These also contain data on variation in the ejection coefficient along the layer length, while in [6] there are data on the distribution in the mixing layer of the function-phase indicator β_i – the analog of the local volume concentration α_i whose average value in the mixing layer $\langle\alpha_i\rangle(x)$ will be

$$\langle \alpha_i \rangle \cong \frac{\int_{y_0}^{y_0+\delta} B_i 2^k y^k dy}{(y_0 + \delta)^{1+k} - y_0^{1+k}}, \tag{13}$$

where y is the transverse coordinate, counted off from the axis of the jet device; $y_0(x)$ is the potential-nucleus size; $\delta(x)$ is the mixing-layer thickness; $k = 0$ in the plane case; $k = 1$ in the axisymmetric case. The characteristics of the first merged vortex should be calculated especially "accurately." Thus, we can calculate all the basic structural, hydrodynamic, and time parameters within the framework of the concepts of [7].

Clearly, the construction of a mathematical model by the algorithm presented here is a rather cumbersome procedure, which even in the case of a steady-state process, will lead to a system of equations in partial derivatives. We can propose a simplified model which is based on the traditional continuous and smooth variation in mixing-layer parameters [6, 9] with the addition of relations (11)-(13) that allow for the interface evolution in the mixing layer. Comparison of "discrete" and "continuous" variants in the value of the interface S yields similar results. For example, for a plane mixing layer for $\overline{L} = 10$, according to the $(\overline{x}-\overline{t})$ diagram, at instants $\overline{t}$ which enter in to the cycle and are equal to 15, 16, 17, and 18, we have values of, respectively, 7, 8, 9, and 9 for $\overline{S} = S/S_1$, where S_1 is the interface in the first "vortex" formation. For the "discrete" variant, we should add to S pseudoplane interfaces between the vortices. For the "continuous" variant, according to (12), we have $\overline{S} = 10$.

The data presented here are sufficient to construct physically substantiated relations for determining the interface, time of phase contact, and transport coefficient in mobile liquid–solid particles, liquid–liquid, and liquid–gas systems in apparatuses with external energy supply which operate both in steady-state and low-frequency pulsation regimes. Clearly this is the most complicated type of interaction, i.e., a mixing layer, which is considered in detail in the light of recent achievements in the hydrodynamics field. Here, it is appropriate to note that, when low-frequency pulsations are superimposed on the jet mixing layer, the region of frequency values that lead to the intensification of turbulent mixing must be limited from above and below [8]. When these recommendations are extended to the case, considered the relation

$$f_{\text{low}} = a \frac{|u_1 - u_2|}{d}, \tag{14}$$

should be fulfilled, where the coefficient a can vary within $a = 0.2-1.2$. If we place emphasis on the pulsation organization of a chemical-technological process with directional use of the manifestations of unsteadiness and inertia, we should note the advantages of this organization, which lead to:

(1) renewal of the interface and its turbulization, which makes the transport coefficient higher;

(2) prevention of the "tunnel" effect occurring in apparatuses;

(3) space and time redistribution and concentration of energy;

(4) specific transformation of energy (thermal-to-mechanical energy transformation, kinetic-to-potential energy transformation, and vice versa);

(5) improvement of efficiency not only due to the increase in the basic components of transfer but also due to the formal pulsation organization of the process.

If we are to share the thesis of a rational arrangement of the Universe and its subsystems, then, in light of the aforesaid, the exclusive preference of the pulsation organization of mass-transfer processes, for example, blood circulation, in living organisms becomes clear.

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