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PROCESSES AND EQUIPMENT OF CHEMICAL INDUSTRY

Fragmentation of Low-Boiling Disperse Phase in Turbulent Flow of Cooling Emulsion

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Abstract—A qualitative analysis of a character of joint heat transfer and drop fragmentation of an overheated disperse phase at a movement of a cooling emulsion in a turbulent regime was carried out. We considered a general model of a drop fragmentation into the emulsion volume by turbulent pulsations of the flow in view of the presence of an excess heat energy in it. Conditions when an effect of the overheating the disperse phase exerts a maximum resistant size of a drop relative to the fragmentation were determined.

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An intensity of the heat transfer upon the boiling in uniform liquids depends on a character of metastable states, which inhibit a start stage of the first type phase transfer, on thermal parameters of a heat carrier, on a hydrodynamic regime and on physicochemical properties of a flow [1]. In the course of the boiling the emulsion with low-boiling disperse phase the heat exchange conditions are essentially complicated since there is high-boiling and of cause more viscous disperse medium between a heating surface and the drops. This promotes a transfer of the boiling forward a volume of the disperse phase that significantly increases the heat surface by an interphase surface which performs this function. Moreover a decrease of the heat-transfer coefficient α_{boil} is inhibited due to a premature formation of a vapor phase.

Also it is known that an enlargement of sufficiently small and a destruction of abundantly large drops of the disperse phase occur in the emulsion due to energy of dynamic and viscous forces of the flow. At a junction of small drops their size on the turbulent flow can grow to some critical value that is determines by a surface tension force. Sufficiently coarse drops of the disperse phase subjected to the turbulent pulsation and viscous shear tension capable of deformation to a drop breaking in two and rather in several parts [2].

Experimental and theoretical investigations show that the emulsion with the low-boiling phase can significantly enhance the heat transfer in comparison with any uniform liquid that belongs to the emulsion. For example, the emulsion of organosilicon liquids with water disperse phase is widely used for cooling the cutting devices of a metal thermal treatment On the basis of experimental data was found significant overheating of the emulsion and then was studied an effect of a delay of the boiling onset ΔT. It was demonstrated that a heat removal is intensified by the drop boiling of the disperse phase with boiling temperature essentially lower than one of a uniform medium [3].

Abnormal metastable state of the cooling emulsion is explained by complex transfer character inherent to many thermodynamic systems [4]. Possible approaches to a solution of the like problems are also considered in [5] when in the case of a vapor explosion an understanding multipronged and multistage process as a set of possible mechanisms of fundamental physical phenomena and their interrelation becomes basic.

Simulation of composition and structure of cross transfers by a set of elementary physical phenomena. The heat transfer by the cooling emulsions is determined by physicochemical characteristics as well as their temperature dependences. Under conditions of the turbulent flow an essential contribution also relates to process specific for liquid systems: coalescence, and fragmentation of the disperse phase drops. For example, some effects found as a result of experimental investigations of the disperse phase boiling in the liquid volume can be elucidated by the drop coalescence [6]. Also an influence of the fragmentation on the structure of the heat transfer into non-uniform liquid with participation of the low-boiling disperse phase is not the least.

In particular, if the pressure of the liquid vapor reaches the value of outside pressure in the uniform medium, the formation of bubbles of the vapor phase can occur along with the evaporation from interphase surface inside the drops [7]. This promotes an increase in the size of the vapor-liquid drops and creates prerequisites for their destruction, and periodic removal of the vapor phase along with a continuous surface boiling. The heat transfer structure is supplemented with the physical phenomena whose mechanisms are predetermined hydrodynamically by the characteristics of the turbulent flow of the uniform medium.

The noted features of the cooling emulsions result in a complicated behavior caused by exchange of energy and of substance under non-equilibrium conditions [4], and also in the formation of the cross transfers where a gradient of one physical value leads to the transfer of another. Mutual influence of the flow of impulse and heat in the heterogeneous systems essentially hinders the isolation of their individual, specific feature because of the variety of actual conditions. Furthermore, ambiguity and statistical nature of the mechanisms of each of the interrelated processes complicates not only their theoretical description but also sufficiently substantiated structural image of phenomenological relationships.

For the same reasons the possibilities of experimental research techniques are limited. An analysis of the vapor explosion performed in [5] demonstrates that the overwhelming majority of available reliable experimental data is useful only for molding of ideas as a whole, without isolation of quick-flowing subprocesses and thin fragmentation. Their characteristic time usually equals from one to tens of microseconds. The technical complexities of the realization of the focused high-speed shooting, which would ensure single-valued interpretation of the observed effects, are not overcome completely.

Although both empirical data and theoretical models of redistribution of substance and energy in the turbulent liquid flow cannot be written down in the common format, nevertheless only they can exhibit entire variety and specific features of the complex processes of the transfer. The substantiation of the composition of elementary physical phenomena with the help of dimensionless similarity criteria corresponding to them makes it possible to base the structure of their interrelations in the complex disperse systems of the heat carriers by agreement with a priori transfer characteristics [8].

Preliminary information relative to physical nature of any phenomenon usually appeared as the phenomenological models which postulate general balance relationships for mechanic and thermodynamic characteristics. The obtained analytical expression then is reduced to the dimensionless form, and model looks as a ratio between basic dimensionless combinations of the independent variables, i.e. the criteria of similarity $\Pi_1, \Pi_2,..., \Pi_n$:

$$\Pi_1 = f(\Pi_2, \Pi_3,..., \Pi_n). \quad (1)$$

If a priory ideas are sufficiently complete they are manifested by general form of the expected interrelation between them.

Elementary physical phenomena are denoted by the simplest relationships with one criterion which are of universal nature:

$$f(\Pi_1) = \text{const}. \quad (2)$$

If the real process can be represented only by this phenomenon then in this case practically unchangeable value of constant C_1 corresponds to the experimental research data presented by (2) after statistical evaluation of parameters of model function $f(\Pi_1)$. This result is qualitative assessment of the correspondence of the initial model picture to the real character of the physical phenomenon. From a formal point of view the adequacy of initial model testifies on the consistency of the physical mechanism accepted.

But if the value of the constant of C_1 is varied, then we cannot consider as revealed all statistically significant independent factors, the mechanisms of the physical phenomena presented by them. The modification of the initial interrelation of the similarity criteria (2) is carried out also in accordance with the a priori physical conception of the possible influence of other factors. Here the independent variable of the initial model, with which is connected the influence of additional mechanism, is substituted by the effective value, which includes the similarity criterion connected with it.

We can modify a variable of the initial model, for example x, with the help of the exponential expression: $x_e = x\Pi_2^{\alpha}$, where Π_2 is an additional criterion present ingan interconnected mechanism of the transfer. The constant value is selected by such means that the extended model

$$f[\Pi(x\Pi_2{}^{\alpha})_1] = \text{const} \qquad (3)$$

simulated empirical correlation of this variable x.

The following step is the representation of experimental data in generalized variables Π_1 and Π_2 and estimation of the constants of hypothetical regularity with the help of the accepted statistical procedure (3). Thus is reached the necessary complete conception of the physical nature of the studied phenomenon that enables the modification of the model. The relationships obtained in the averaged form are manifested as the summary estimations of the real contribution of each elementary physical phenomenon reflected by the results of an experimental study of a complex process.

The efficiency of each of the possible mechanisms of elementary physical phenomena, and also their mutual influence are in direct dependence on the boundary and initial conditions. As a result the agreement of the characteristic scales of the totality of elementary physical phenomena in the space and the time is achieved on the basis of experimental data. The procedure examined makes it possible to form the complex structures of the transfer that possesses the predetermined properties: power and resource saving [8].

The fragmentation character of the overheated drop of the dispersed phase. The important special feature of the overheated drop fragmentation under the action of the turbulent pulsations of the speeds of the uniform medium is the presence in them of excess thermal energy [9]. It is obvious that this factor decreases stability and as a result the probability of retaining the integrity of the drops of dispersed phase, which a capillary energy provides. However, an increase in the frequency of the drop fragmentation is not the only consequence of their overheating. Another possible consequence is the formation of bubbles of vapor phase caused by the local resonance pulsations of pressure inside the drops that is generated by the turbulent pulsations of the uniform medium.

It should be noted that in the absence of the turbulence the contribution of the fluctuation mechanism of the formation of vapor nuclei in the volume of the quiescent liquid is insignificant in comparison with the usual phenomenon of vaporization near to the solid surface. In this case its role plays the interphase surface with the high-boiling liquid, thereby the summary surface area of dispersed phase with the drops of sufficiently small size can repeatedly exceed the area of the solid surface. Moreover such well studied factors of the formation of the nuclei of vapor phase become predominant as the presence of the air bubbles, solid particles and other macroscopic heterogeneities of the external surface of drops [10].

Energy of the turbulent pulsations of the uniform medium speed under certain conditions causes in the volume of the drops of dispersed phase the formation of the forced pulsations of pressure with a certain frequency spectrum. The agreement of the natural vibration frequency of drop with one of the frequencies, which possess a sufficient energy of pulsations, leads to their resonant amplification. If the local concentration of external energy of the turbulent flow is sufficient for the overcoming the surface energy of drops then occurs their destruction [2, 11]. Under the isothermal conditions the destruction of drops in the turbulent flow of liquid that is not mixed with them despite complexity and stochastic nature of process, explains Kolmogorov's theory about the predominant influence of local turbulence structure on the stability of drops.

In the inertial range of an area of the universal statistic equilibrium expression for the maximum steady size of the drops d_{max} is used as a rule in the form of a ratio of the energy of their surface tension and the energy of the turbulent pulsations:

$$\rho_c \nu'^2 (d_{max}/\sigma) = \text{const}, \qquad (4)$$

where σ is interphase tension, ρ_c, density of the uniform medium, ν'^2, averaged speed of the turbulent pulsations

The generalization of the fragmentation to the nonisothermic conditions of the fragmentation of the low-boiling dispersed phase within the region of the basic model of Kolmogorov consists in the addition of energy of the internal turbulent pulsations of pressure by thermal energy of overheated drops. It is obvious that the factor of overheated drops must promote reduction in the significance of interphase tension which is their stabilizing factor. The physical sense of this phenomenon can consist in a possible increase in the volume with the formation inside the drops of the bubbles of vapor phase. Energy of the pulsations of pressure, insufficient for the direct destruction of drops, can form the local regions of the reduced "negative" pressures, which facilitate reduction in the critical dimension of the viable bubbles of vapor [12].

The identity of the states of overheating to a tension (cavitation) of liquids, that facilitates growth of the experimentally studied in this paper frequency of the nuclei forming, allows formalization of their summary result as the temperature factor. As a result in relationship (4) the real diameter of the drops d_{max} is substituted by the effective size d_{eff} corrected by the value of the volume fraction of the bubbles of the vapor:

$$d_{eff} = d_{max}(E_T/E_{turb})^a, \quad (5)$$

where $E_T = \rho_d C_p \Delta T$ is specific thermal overheating energy, $E_{turb} = \rho_c v'^2$, specific dynamic energy of the turbublent pulsations.

This initial relationship (4) can written as

$$\frac{\rho_c v'^2}{\sigma} d_{max} \left(\frac{C_p \rho_d \Delta T}{\rho_c v'^2}\right)^{\alpha} = \text{const}. \quad (6)$$

Here in the form of exponential function from the ratio of energy of overheating, which stimulates the formation of vapor phase, to the energy of turbulent pulsations is indirectly presented the diameter of vapor-liquid drop. When $\alpha = 0$ in the absence of the energy of overheating expression (3) is reduced to the model relationship of Kolmogorov (4). Another limiting case when $\alpha = 1$ corresponds to the destruction of the overheated drops of the dispersed phase as a result of vapor explosion in the volume of the quiescent emulsion.

The value of the exponent α is found by the agreement of final dependence with the a priori conventional conception about the important characteristics of the fragmentation [2, 11]. Thus, as an example let us examine interrelation for the conditions of the uniform turbulent flow established by Kolmogorov and confirmed by numerous experimental works:

$$d_{max} \approx v'^{-1.2}. \quad (7)$$

Hence, in expression (6) summary power $2(1 - \alpha)$ of pulsations must compose the known value:

$$2(1 - \alpha) = 1.2.$$

Required value for the particular conditions of the homogeneous turbulence of $\alpha = 0.4$.

Taking into account this condition expression (6) is the mechanism of the joint hydro-thermodynamic decomposition of the dispersed phase of the emulsion:

$$\frac{\rho_c v'^2}{\sigma} d_{max} \left(\frac{C_p \rho_d \Delta T}{\rho_c v'^2}\right)^{0.4} = \text{const}. \quad (8)$$

With the flow of emulsions along the pipeline in the uniform turbulent flow the value of the averaged square of a difference in the pulsations of the speed is determined only by energy consumption for the unit of the mass per unit time ε:

$$\varepsilon = \frac{\lambda u_0^3}{2D}, \quad v'^2 \approx (\varepsilon d_{max})^{2/3}, \quad (9)$$

where λ is coefficient of hydraulic resistance, u_0, average relative to the flow speed of the emulsion into the pipe line of diameter D.

After additional trasformations the maximum size of the drops, which preserve integrity at the collisions at the turbulent pulsations, in accordance with the model of the resonance hydrodynamic destruction of drop at $\alpha = 0$ can be written as

$$d_{max}^{res} = C_1 \frac{D^{0.5}}{u_0^{1.1} \rho_c^{0.5}} \sigma^{0.6} \mu_c^{-0.1}. \quad (10)$$

Taking into account the thermal energy of overheating the combined regime of the hydro-thermodynamic destruction of drop when $\alpha = 0.4$ looks as

$$d_{max}^{therm} = C_2 \frac{D^{0.36}}{u^{0.79} \rho_c^{0.36} C_p^{0.29}} \sigma^{0.71} \mu_c^{-0.07} \Delta T^{-0.29} \rho_d^{-0.29}, \quad (11)$$

where C_1 and C_2 are constants found from experiment; μ_c, dynamic viscosity of the uniform medium.

In Fig. 1 are represented the model calculations of the dependence of the maximum diameter of drops in the emulsion water–organosilicon liquid PES-5 on the temperature overheating for two regimes of the fragmentation at the pressure $P = 10^5$ Pa. Temperature dependence for μ_c is taken into account with the aid of

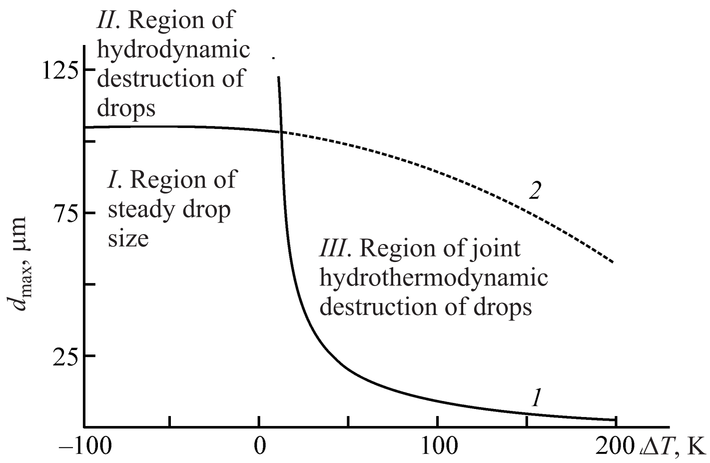

Fig. 1. Dependence of the maximum diameter d_{max} (μm) on temperature overheating ΔT (*1*) at $\alpha = 0.4$ (hydrothermodynamic destruction of a drop), and (*2*) at $\alpha = 0$ (the resonance hydrodynamic destruction of a drop). Pressure $P = 10^5$ Pa, emulsion water–organosilicon liquid PES-5.

the Andrade relationship [13], for σ and ρ_d, with the aid of the approximation of tabulated data [14] in the linear and cubic form, respectively. The model constants C_1 and C_2 are selected on the basis of the experimental data of work [3].

Features of the curves, represented in Fig. 1, make it possible to obtain the following qualitative results. Curve *1*, which corresponds to the hydrothermodynamic regime of destruction, is well correlated with the results of experimental data [3], moreover by an increase in the temperature overheating the maximum diameter of drops decreases. The region *I* limits the sizes of the drops which are steady relative to the fragmentation. Curve *2* corresponds to the hydrodynamic regime of the fragmentation under the isothermal conditions. The region *II*, that is higher than this curve and to the left of curve *1,* limits the hydrodynamic destruction of drops by turbulent pulsations. Finally, the region *III* is the region of joint hydrothermodynamic destruction of drops by turbulent pulsations and excess thermal energy of overheating.

Structure of the interrelations of the mechanisms of elementary physical phenomena upon the heat transfer by the low-boiling drops of dispersed phase. The elementary hydrodynamic mechanism of the fragmentation of the drops of dispersed phase in the turbulent flow of emulsion is determined with the aid of the balance of the counterdirected forces (or energies) of the turbulent pulsations of speed and of surface tension:

$$\rho_c v'^2 \approx \sigma/d. \quad (12)$$

As a result the maximum steady size of the drops d_{max} is formed, which through Weber number is written as

$$\mathrm{We_d} = \frac{\rho_c v'^2 d}{\sigma} = \mathrm{const}. \quad (13)$$

For the elementary thermodynamic mechanism of the destruction of the drops of dispersed phase (thermal explosion [15]) determining is the balance of the thermal energy of the overheating drops and surface tension:

$$C_p \rho_d \Delta T \approx \sigma/d. \quad (14)$$

The condition of destruscrion of the overheated drop in the volume of the quiescent liquid in the form of dimensionless thermal criterion can be presented as

$$\mathrm{Te_d} = \frac{C_p \rho_d d\, \Delta T}{\sigma} = \mathrm{const}. \quad (15)$$

When one of the elementary mechanisms predominates, constants in the right term of equations (13) and (15) keep value at the given initial and boundary conditions. An interaction of these two possible elementary physical phenomena is manifested in the change in the constant of equation (13) that is assumed as initial in accordance with a change in the values of the criterion, which characterizes another, interconnected with it physical phenomenon.

On the basis of these ideas equation (8) that expresses the hydrothermodynamic mechanism of the fragmentation of the drops was obtained as a result of the combined action of two elementary physical phenomena.

Its physical content becomes obvious after reducing it to the dimensionless form with the help of the following transformation:

$$\frac{\rho_c^{0.6}\nu'^{\,1.2}}{\sigma^{0.6}}\, d_{\max}^{0.6}\left(\frac{C_p\rho_d\Delta T d_{\max}}{\sigma}\right)^{0.4}$$

$$\mathrm{We}_d^{0.6}\mathrm{Te}_d^{0.4} = \mathrm{const}. \qquad (16)$$

Accounting for this interrelation equation (13) exhibiting the initial conception for the isothermal conditions is written in more general form revealing the physical sense and the character of the interaction of the elementary transfer of pulse and heat.

Taking into account this interrelation criterial relationship (13), which reflects initial ideas for the isothermal conditions, is written in the more common format of that revealing the physical sense and the nature of interaction of the elementary transport phenomena of pulse and heat.

$$\mathrm{We}_d = \frac{\mathrm{const}}{\mathrm{Te}_d^{2/3}}, \qquad (17)$$

This is the most probable structure of the interrelations of elementary phenomena in the uniform turbulent flow of emulsion with the low-boiling dispersed phase. On the basis of those accepted above assumptions the degree of dimensionless thermal criterion is determined by the constant α of exponential function (5) and depends only on the structure of the turbulent flow of uniform medium. In Fig. 2 are depicted the generalized dependences for the hydrodynamic and hydrothermal destruction of the drops in the form of the dimensionless criteria We_d and Te_d according to equations (13) and (16). The constant in Eq. (13) is accepted equal to 10 for clarity.

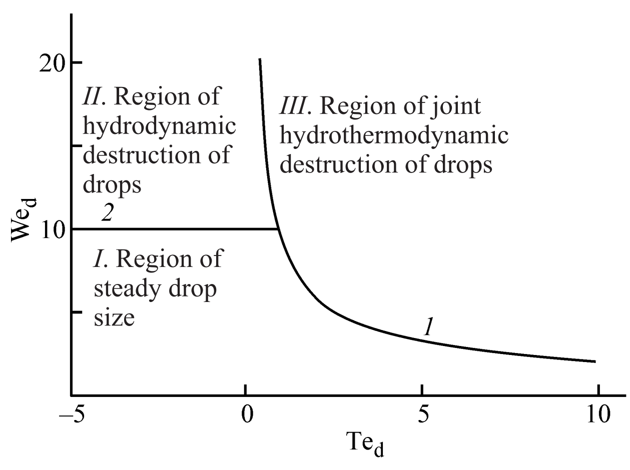

Fig. 2. Dependence of the number We_d on number Te_d for (*1*) hydrothermidynamic, and (*2*) hydrodynamic destruction of the drops.

The noted factors essentially simplify formulation and solution of the new nontraditional problems connected with the innovation and energy-saving industrial technologies [9, 16]. In particular, this relates to the formation of the rational structure of the pulse and heat transfer for the most effective use of the cooling liquids.

CONCLUSION

(1) By the qualitative analysis of the fragmentation the dimensionless thermal criterion, which characterizes the influence of overheating on the fragmentation of the drops of dispersed phase in the turbulent flow of the high-boiling liquid was obtained. This criterion characterizes also the heat transfer to the dispersed phase in the turbulent flow of the emulsion of the cooling liquids.

(2) The model of the fragmentation of the overheated drops of the disperse phase in the turbulent flow of the cooling emulsion was developed taking into account temperature that significantly expands the range of the elementary physical phenomena which determine the feature of boiling and the efficiency of heat transfer.

(3) The presence of the vaporization prerequisites connected with the destruction of coarse dispersed drops, makes it possible to use the suggested model of overheated emulsion (16) with the development of new heat-power engineering systems and plants.

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