ROMAN KLIMOV
Dnieprovsk State Technical University,
Ukraine e-mail: rklimov@yandex.ua

ANATOLIY PAVLENKO
Kielce University of Technology
e-mail: apavlenko@tu.kielce.pl

DISPERSED PHASE BREAKUP AT EMULSION BOILING

Abstract

In this paper we consider the breakup processes of the emulsion dispersed phase. The possibility of large droplets splitting by small ones under boiling water phase due to a sharp release of pressure is shown, we also take into account the force impact of one drop on the another, based on the instability criteria of Bond and Weber. It is indicated the applicability of the model to determine the processes of displacement, deformation or breakup of inclusions of dispersed phase.

Keywords: heat transfer coefficient, turbulence level, dispersed phase

1. Introduction

The processes of breakup and deformation of the dispersed phase is considered by many researchers [1-7], but these data require further study, which will determine the most profitable in economic and environmental terms parameters for their implementation.

The classical theory of drops deformation and destruction depending on the turbulence level belongs to [3]. He considered this process as a result of realization of a large number of random events and on the basis of the probability theory he obtained the logarithmic drops distribution basing on the drops size. In general, the problem of breakup of liquid dispersions in a continuous medium is divided into two [3-5]: liquid droplets breakup in the emulsions and gas streams. When considering these processes the drop stability to the effecting forces is important, as these forces tend to destroy it. In most cases presented in references calculations are based on Bond and Weber criteria [1-4, 9], i.e. they consider only the Rayleigh-Taylor and Kelvin-Helmholtz instability, which are more specific for emulsification or destabilization of dispersed media. The droplets breakup and deformation processes while moving in a liquid are described in [3-5]. However, the existing models do not consider the breakup process of the secondary fluid with taking into account the formation of vapor layer at the boundary between the two phases as well as the force interaction regarding several simultaneously boiling particles of dispersed phase [8, 10, 11]. The vapor cavity formation is assumed to be homogeneous and only the maximum dynamic effects are considered, while the destruction of the dispersed phase can occur at any time due to the fact that the hydrodynamic environment even in the vicinity of two growing bubbles is undefined and if a particle of the dispersed phase is at some distance from these bubbles (or between them at a certain distance), then the effect of the particle breakup will be on reaching the maximum force that will exceed a critical value, calculated by Weber or Bond criteria, but it won't necessarily be equal to maximum which can act in this system. The process becomes even more complicated and requires further study if we consider the breakup process of dispersed phase which begins to boil by itself.

2. Statement of a problem

In accordance with Weber and Bond criteria [1-4, 9], the main factors determining the fragmentation of the dispersed phase are respectively: speed (relative speed) w and acceleration g influencing a given particle. The speed at any point of volume in the vicinity of the growing or imploded steam room can be determined by the ratio

$$w(r) = \frac{w_R R^2}{r^2} \tag{1}$$

where: w_R – radial velocity motion of interface between oil-steam, m/s; R – radius of the particle, m; r – radius vector, m.

The acceleration distribution in the vicinity of the bubble is determined by ratio

$$g(r,\tau)=\frac{dw(r,\tau)}{d\tau}=\frac{\partial w(r,\tau)}{\partial\tau}+w(r,\tau)\frac{\partial w(r,\tau)}{\partial r} \quad (2)$$

Considering equation (1)

$$\frac{\partial w}{\partial\tau}=\frac{dw_R}{d\tau}\frac{R^2}{r^2}+2\frac{w_R^2R}{r^2} \qquad \frac{\partial w}{\partial r}=-\frac{2w_RR^2}{r^3} \quad (3)$$

Insert (3) in (2) and we get

$$g(r,\tau)=\frac{1}{r^2}\left[\frac{dw_R}{d\tau}R^2+2w_R^2R-\frac{2w_R^2R^4}{r^3}\right] \quad (4)$$

Then, taking into account the Rayleigh-Plesset equation [4] we can get

$$g(r,\tau)=\left(p_R-p_\infty+0.5w_R^2\rho_i-\frac{2\rho_i\,w_R^2R^3}{r^3}\right)\frac{R}{\rho_i\,r^2} \quad (5)$$

where p_R – pressure of interface between oil-steam, Pa; p_∞ – infinity pressure, Pa; ρ_i – oil density, kg/m³.

The results of calculations according to the equation (5) are shown in Figure 1.

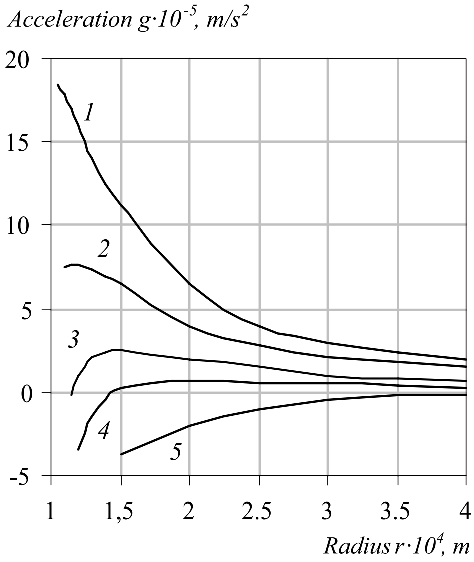

Fig. 1. Acceleration distribution in the vicinity of the steam layer while its growth for R_{10} = 100 μm, t_0 = 180°C, p_∞ =10^5 Pa at different time points: 1 – 10^{-6} s; 2 – $1.5\cdot10^{-6}$ s; 3 – $2.5\cdot10^{-6}$ s; 4 – $3.5\cdot10^{-6}$ s; 5 – 10^{-5} s

As can be seen from this figure at certain time points the acceleration ambiguously depends on the distance *r*: it can have a negative value on top-section of oil-steam in the heated emulsion, it increases with the increase of *r*, having reached the maximum, it decreases; and even at a distance which in four times greater than the droplet radius the acceleration exceeds the acceleration of gravity by many times. So we can conclude that the dispersed phase droplet, located at a distance several times greater than the radius of the particle, begins to boil and undergoes the influence of acceleration, causing a destabilizing effect of the droplet and at specific parameters (*R, σ, g*) the droplet may be destroyed.

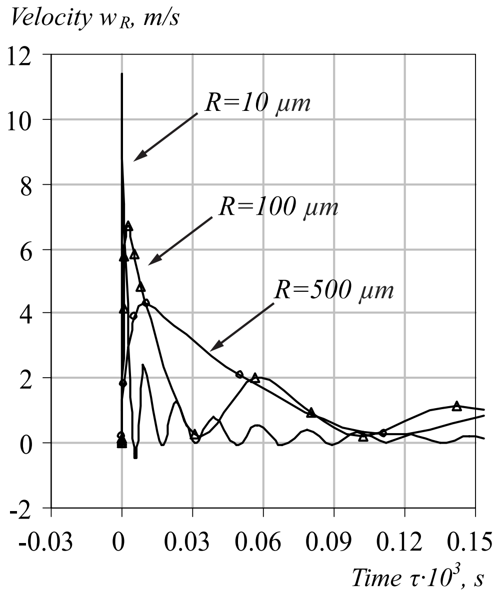

Fig. 2. The dependence of velocity motion change of interface between oil-steam in time for different initial radius of droplets

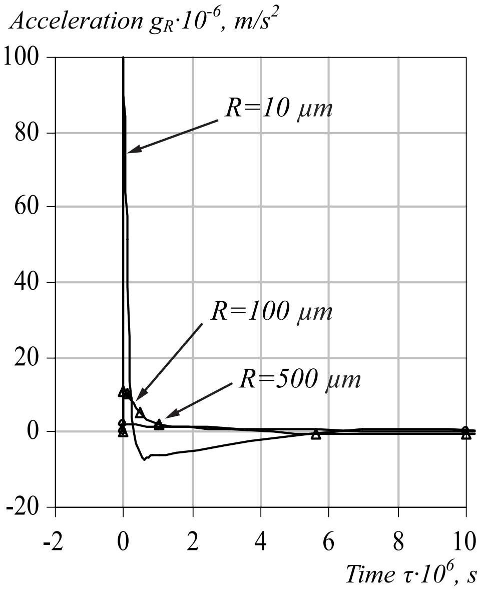

Fig. 3. Dependence of motion acceleration change of interface between oil-steam in time for different initial radius of the droplets

Figure 2-3 presents combined graphs of velocity change of interface movements between the oil-steam and its acceleration at the initial temperature system

$t_0 = 180°\text{C}$ for different initial droplet radius according to the model [6], taking into account the vapor phase growth in the volume of oil. These graphs show that the smaller the initial-radius of the droplets is the more intense is the rising vapor phase, i.e. the higher is the speed and acceleration of interface.

When droplets are of different radius, we can observe joint-maxim (minimum) speed (acceleration) as well as the significant difference between the data of speed (acceleration). Then, taking into consideration that the speed for different initial radii has different amplitude and frequency changes at the time, we can assume that at some time point it may appear the Kelvin-Helmholtz instability, and for accelerate – the Rayleigh-Taylor instability respectively.

Let us consider a system consisting of two different size of boiling droplets as a result of pressure relief at a distance h from each other (Fig. 4).

Define force interaction, which can lead to the instability state. From the consideration of Bond and Weber criteria [1, 2] with Rayleigh-Plesset equation it follows that the critical forces, leading to Rayleigh-Taylor and Kelvin-Helmholtz decomposability state are respectively equal

$$F_{Bo}^{cr} = 40\pi\sigma R_i \qquad F_{We}^{cr} = 30\pi\sigma R_i \tag{6}$$

where: σ – surface tension, N/m; i – particle number ($i = 1, 2$).

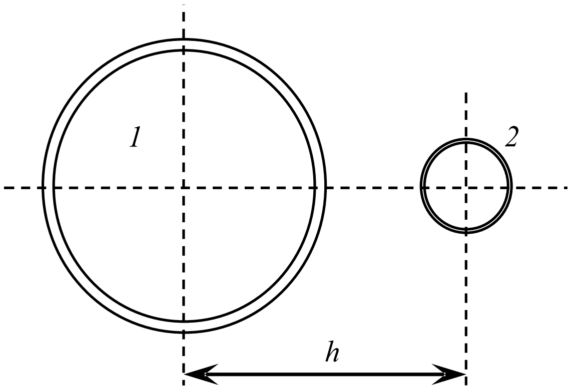

Fig. 4. Breakup droplets model

Deformation and fragmentation of vapor layer and a water droplet in the water-oil emulsion may be due to different directions of the acceleration vector or of the velocity vector. Assume that the deformation, breakup or moving will occur only in the case when the acceleration vector has positive direction and notwithstanding it the velocity vector is also positive. We assume that the droplet №1 (Fig. 4) is at zero point, and a droplet №2 is at a distance h from the center of the first droplet, i.e. $x_1 = 0$, $x_2 = h$.

Acceleration, trying to destroy the droplet interface №1, is equal

$$g_{p_1} = \begin{cases} \sum_{i=1}^{2} g_i; & k_1 \geq 0, k_2 \geq 0, \\ -\sum_{i=1}^{2} g_i; & k_1 \leq 0, k_2 \leq 0, \\ g_2; & k_1 < 0, k_2 > 0, \\ -g_2; & k_1 > 0, k_2 < 0, \end{cases} \tag{7}$$

where

$$g_i = k_i \frac{R_i (x_i - R_1)}{\rho_i \, d_i^3} \qquad d_i = |x_i - R_1|$$

$$k_i = p_{R_i} - p_\infty + 0.5 w_{R_i}^2 \rho_i - \frac{2\rho_i \, w_{R_i}^2 R_i^3}{d_i^3}$$

Then the force caused by acceleration or flow deceleration is

$$F_{Bo_1} = 4\pi\rho_i g_{p_1} R_1^3 \tag{8}$$

Similarly, we can get the equation for the velocity

$$w_{p_1} = \begin{cases} \sum_{i=1}^{2} w_i; & w_{R_1} \geq 0, w_{R_2} \geq 0, \\ -\sum_{i=1}^{2} w_i; & w_{R_1} \leq 0, w_{R_2} \leq 0, \\ w_2; & w_{R_1} < 0, w_{R_2} > 0, \\ -w_2; & w_{R_1} > 0, w_{R_2} < 0, \end{cases} \tag{9}$$

where

$$w_i = w_{R_i} R_i^2 \frac{(x_i - R_1)}{d_i^3}$$

Then the force of dynamic velocity pressure

$$F_{We_1} = 6\pi\rho_i R_1^2 \left| w_{p_1} \right| w_{p_1} \tag{10}$$

It is known that the capillary force F_σ regardless the droplets shape deformation is always directed so as to regain a spherical shape, i.e. so that the surface energy of Gibbs was minimal. Therefore, if a drop in the direction of its movement is deformed into an oblate ellipsoid, capillary force counteracts the external force. If it is deformed in elongated ellipsoid, the capillary force coincides with the direction of the external force. It follows that during the deformation the shape of elongated ellipsoid is unstable, while the shape of an oblate ellipsoid can be quasistable.

There may be a minimum of the capillary force. Let us assume that the minimum is determined by the Laplace force and corresponding the force is

$$F_{\sigma_1} = 8\pi\sigma R_1 \qquad (11)$$

Thus, when external force exceeds the force F_σ the volume deformation will take place, when the forces are balanced – we observe the balance, and under $F_\sigma > F_{Bo', We}$ – the volume will repulse without deformation.

The difference between $F_{Bo', We}$ and F_σ is

$$\Delta F_{Bo} = F_{Bo} - F_\sigma \qquad \Delta F_{We} = F_{We} - F_\sigma \qquad (12)$$

Considering the example with force, caused by acceleration or deceleration of the flow, it is possible to obtain following conditions: $F_{Bo} \geq 0\, F_{Bo}^{cr}$ – for breakup; $\Delta F_{Bo} > 0$ – for deformation; $\Delta F_{Bo} = 0$ – for balance; and $\Delta F_{Bo} < 0$ – for movement.

The system of equations (7)-(11) for particles № 2, located at a distance h from the first particle is the following

$$g_{p_2} = \begin{cases} -\sum_{i=1}^{2} g_i; & k_1 \geq 0, k_2 \geq 0, \\ \sum_{i=1}^{2} g_i; & k_1 \leq 0, k_2 \leq 0, \\ g_1; & k_1 < 0, k_2 > 0, \\ -g_1; & k_1 > 0, k_2 < 0, \end{cases} \qquad (13)$$

$$w_{p_2} = \begin{cases} -\sum_{i=1}^{2} w_i; & w_{R_1} \geq 0, w_{R_2} \geq 0, \\ \sum_{i=1}^{2} w_i; & w_{R_1} \leq 0, w_{R_2} \leq 0, \\ w_1; & w_{R_1} < 0, w_{R_2} > 0, \\ -w_1; & w_{R_1} > 0, w_{R_2} < 0, \end{cases}$$

where

$$g_i = k_i \frac{R_i (x_i - j)}{\rho_i d_i^3} \qquad w_i = w_{R_i} R_i^2 \frac{(x_i - j)}{d_i^3}$$

$$d_i = |x_i - j| \qquad j = h - R_2$$

$$F_{Bo_2} = 4\pi\rho_i g_{p_2} R_2^3$$

$$F_{We_2} = 6\pi\rho_i R_2^2 \left|w_{p_2}\right| w_{p_2} \qquad (14)$$

$$F_{\sigma_2} = 8\pi\sigma R_2$$

3. The calculation results

For example let us consider two droplet of emulsion with R_{10} = 100 μm, and R_{20} = 10 μm, which are at different distances h from each other, at an initial temperature of 180°C (130°C) and the corresponding saturation pressure. At some time point the pressure is reduced to atmospheric pressure, thereby causing an intensive growth of the vapor phase at the interfaces of the oil-water boundary and the further growth of oil-steam boundary. We investigate how forces are changed causing displacement, deformation or breakup of the steam volume at the time at different distances between the droplets on the surface of the big and small drops. The calculation results are presented in Fig. 5-10.

The given data show that the greatest effect in the destruction of the droplets is caused by the instability like the Rayleigh-Taylor instability. In all of the shown cases instability plays a decisive role, while the instability, like the Kelvin-Helmholtz instability, is also observed (Fig. 9), but only after its dynamic effect will lead to the destruction of a large drop (from a comparison of Fig. 7) and as a consequence the destruction of small droplets will not happen. When distances aren't big (Fig.7-8) the destruction of the steam volume of a large drop will occur almost immediately after the pressure relieve. As the distance enlarges (Fig. 5-6), the time till destruction is also increasing, which should be expected, passing in the limit to infinity, if we do not consider the force interaction between the drops as they approach and contact surfaces. When the distance between the droplets is equal to 250 μm (Fig. 5), i.e. 2.5 times higher than the initial radius of the large drop, breakup will occur on the second peak of force fluctuating F_{Bo}, while at lower distances this is the first peak. When $\Delta F_{Bo,We} > 0$, $\Delta F_{Bo,We}$ we can observe that at this moment the volume displacement or deformation is possible. It is interesting that at the distance of 150 μm (Fig. 7, 9) small droplet is deformed before it crushes the larger one, while the larger drop will not even be deformed until this point. This can be explained by the fact that the processes of acceleration-deceleration of the interface of small droplets is much faster and the force deformation peak (Fig. 9) is due to a sharp slowdown of its interface, while the interface between the oil-vapor of a large drop still accelerates. It is also necessary to take into account the fact that a large flat surface (larger drop radius) creates larger influence area.

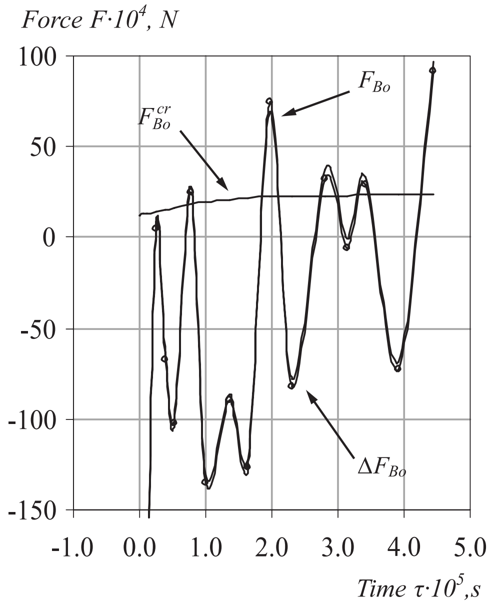

Fig. 5. Forces changes, influencing the droplet №1 (Fig. 4), at the time at R_{10} = 100 μm, R_{20} = 10 μm, t_0 = 180°C, p_∞ = 10^5Pa, h = 250 μm

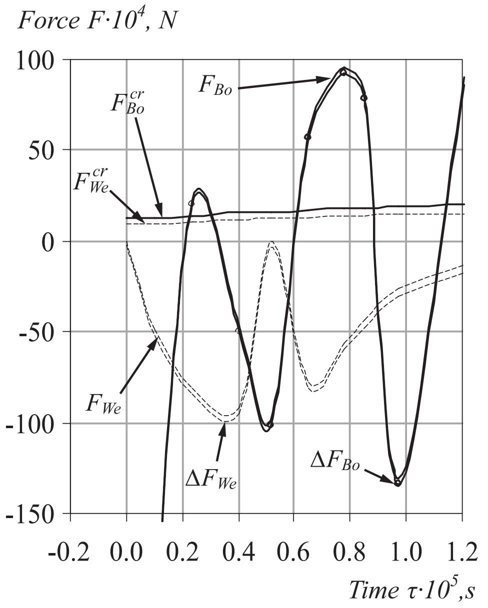

Fig. 6. Conditions are the same as in Figure 5, except h = 200 μm

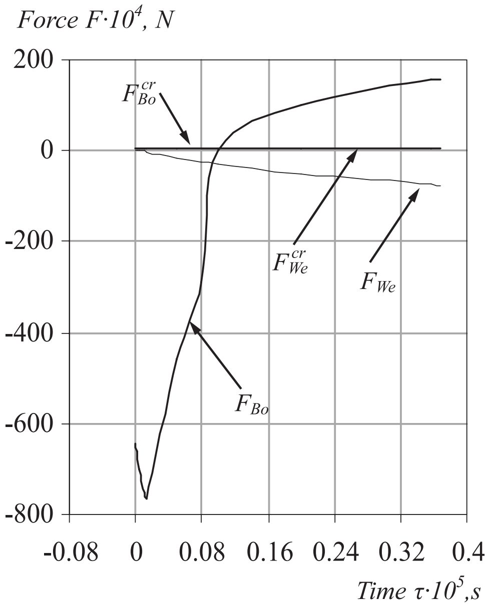

Fig. 7. Conditions are the same as in Figure 5, except h = 150 μm

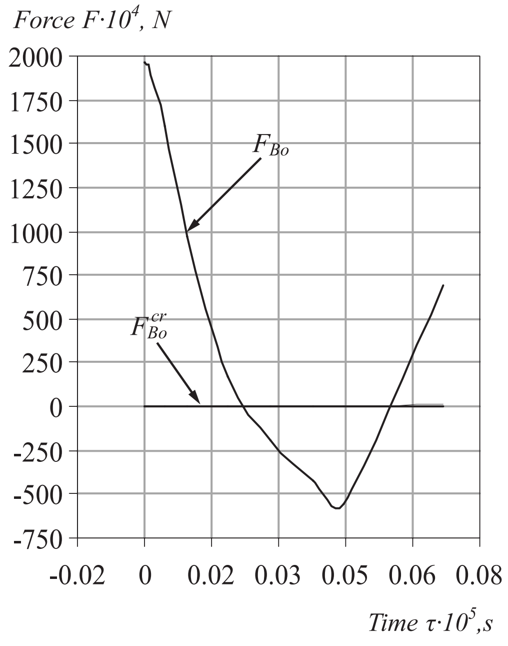

Fig. 8. Conditions are the same as in Figure 5, except h = 120 μm

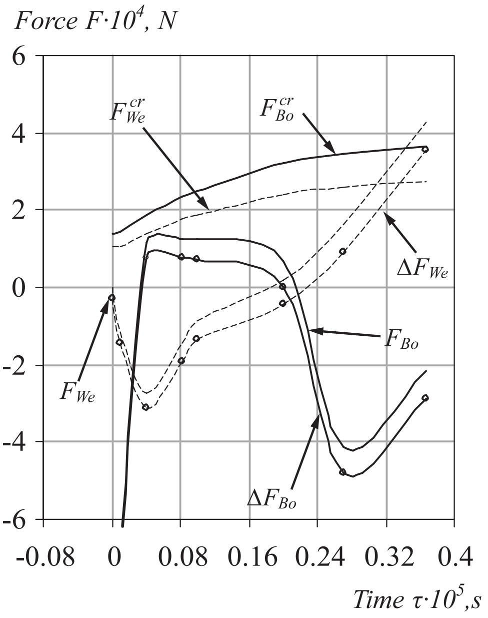

Fig. 9. Forces changes, influencing the droplet №2 (Fig. 4), at the time at $R_{10} = 100$ μm, $R_{20} = 10$ μm, $t_0 = 180$°C, $p_\infty = 10^5$Pa, $h = 150$ μm

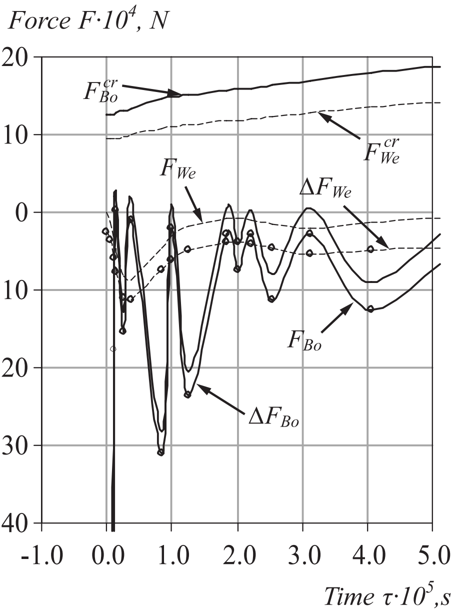

Fig. 10. Forces changes, influencing the droplet №1 (Fig. 4), at the time at $R_{10} = 100$ μm, $R_{20} = 10$ μm, $t_0 = 130$°C, $p_\infty = 10^5$ Pa, $h = 150$ μm

As it is shown in Fig. 10 by reducing the initial temperature up to 130°C, even at a distance of 150 μm, in general breakup or deformation effects are not observed. The calculation is found that the initial temperature reduction from 180°C to 130°C at the saturation pressure relief to atmospheric value, the data droplet radius result in a reduction of the maximum distance under which the breakup is still possible in ≈ 3 times.

4. Conclusions

Presented in [9] photos of industrial emulsion-technology media show the typical size and the distance between the dispersed particles. From these pictures it follows that the large and small droplets of emulsions are practically always closely located. Taking into consideration the specific relative droplet size and the distance between them it can be concluded that at the temperatures of 180°C and 130°C splitting will definitely occur. Of course, for this type of emulsions it is necessary to consider the effects occurring in the inverse emulsion inside the direct emulsion, as well as the question of steam layer formation time remains important. The droplets displacing also remains unclear, because it leads to the mutual movement of a water drop and steam, whereby the steam layer can be broken. Of course, the greatest dynamic force for estimated drops can be at their maximum approach. At larger distances it is possible to observe the steam disruption, at smaller distances and high initial temperatures it is possible to observe water drops breakup. Drops boiling at different surfaces do not occur at the same time; even more intensive processes of breakup of the emulsion dispersed phase can be predicted.

In the whole, this model allows to consider the breakup process of large droplets of the dispersed phase with the neighboring of small droplets under different initial temperatures and the distances between them. The further improved model can carry out the calculations of droplets moving and merging.

References

[1] Pavlenko A.M., Basok B.I., *Heat Conduction of a Multi-Layer Disperse Particle of Emulsion*. Heat Transfer Research, 2005, Vol.36, Nos.1&27 pp. 55-61

[2] Dolinskij A.A., Ivanickij G.K., *The Theoretical substantiation of the principle of discrete-impulse input energy*. The model of the dynamics of a single vapor bubble. Prom. teplotehnika. 1995. v.17, №5. pp. 3-28.

[3] Шурчкова Ю.А., Малишевский Т.В. *Анализ механизмов дробления капель при адиабатном вскипании и смешении дисперсных систем.* // Пром. теплотехника. 2000. Т.22. №1. С. 17-23.

[4] Иваницкий Г.К. *Разрушение капель эмульсии в адиабатно вскипающих потоках* // Пром. теплотехника. 1999. Т.21. №4-5, С.10-15.

[5] Olenets M.O., Piotrowski J.Z., Stroy A.F., *Mathematical description of heat transfer and air movement processes in convectional elements of a*

building's passive solar heating systems, Energy Procedia, Vol. 57, 2014, pp. 2070-2079.

[6] Pavlenko A.M., Basok B.I., (2005). *Regularities of boiling-up of emulsified liquids*. Heat Transfer Research, volume 36, Issue 5, pp. 419-424.

[7] Иваницкий Г.К. *Моделирование процессов деформирования и дробления капель при движении в жидкости*. // Пром. теплотехника. 1997. Т.19. №1. С. 9-16.

[8] Pavlenko A.M., Koshlak A.V., *The processes of heat and mass exchange in the vortex devices*/ Metallurgial and Mining Industry, №3, 2014. pp. 55-60

[9] Долинский А.А., Павленко А.М., Басок Б.И. *Теплофизические процессы в эмульсиях*. Киев, Наукова думка, 2005. С. 265.

[10] Павленко А.М., Климов Р.А. *Динамика фазовых переходов в эмульсиях* // Системні технології. 2006. №4 (45). С. 40-45.

[11] Nigmatulin R.I., Habeev N.S., *The dynamics and heat and mass transfer of gas-vapor bubbles with the liquid*. Nekotorye voprosy mehaniki sploshnoj sredy. M.: Institute of Mechanics, Moscow State University, 1978. pp. 229-243.