Destruction of the Structure of Boiling Emulsions

Anatoliy Pavlenko[1][*], Viktor Melnyk[2]
[1]Kielce University of Technology, Poland
[2]Ivano-Frankivsk National Technical University of Oil and Gas, Ukraine
*[*]corresponding author's e-mail: apavlenko@tu.kielce.pl*

1. Statement of the problem

Existing methods for calculating the processes of emulsification and homogenization of fluids are based on the dynamics of a single particle, which either boils with a sudden change in external parameters (Dolinsky et al. 2001, Dąbek et al. 2016, Dąbek et al. 2018), or is subjected to the action of dynamic impact during the acceleration (deceleration) of flow, as well as is subjected to mechanical effects (Dolinsky & Ivanitsky 1995, Ivanitsky 1997). The examination of the dynamic interaction of two particles while boiling of light boiling component of the emulsion is given in (Pavlenko & Koshlak 2017). Therefore, the study and development of the theoretical grounds of multitude drops breakup of discretely distributed phase is important for the determination of the optimal dispersion modes which results in a significant reduction in energy costs both during the grinding and crushing process, as well as reduction of the financial costs with repeated use of the same lubricating fluids, previously prepared before each cycle of use.

2. Identification of previously unsettled parts of the general problem

We research the droplets breakup of the dispersed phase, which is surrounded by other droplets during their boiling. As an object of our study we take an emulsion, shown in (Pavlenko 2018) and schematically presented in Fig. 1.

The diagram (Figure 1) shows a fragment of the structure of the fuel emulsion. It can be of any configuration. The main parameters that affect the homogenization process are the size of the dispersed phase droplets and the distance between the droplets. These parameters can determine the level of energy impact on the emulsion in order to reduce the size of the dispersed phase.
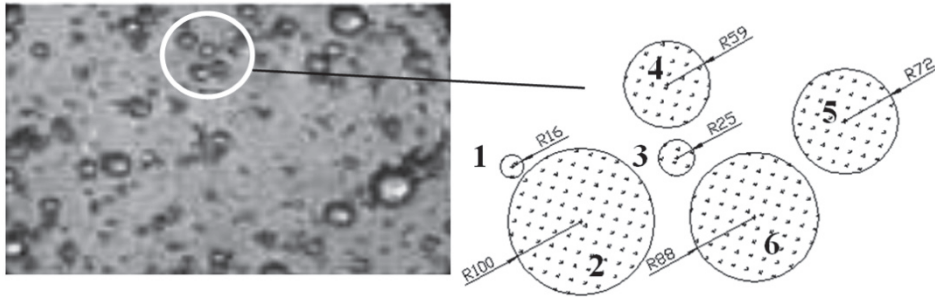
Fig. 1. To the calculated model of droplet breakup of the dispersed phase of the emulsion (characteristic dimensions in microns)

As can be seen from this figure, there are "small" drops between the "large" water drops, the small ones can serve as the sources of increased dynamic forces while boiling and thereby initiate the process of larger droplets breakup, because of the significant difference in accelerations and/or growth rates between them (Pavlenko 2018, Koshlak & Pavlenko 2019, Pavlenko & Koshlak 2019). The main types of instability are the Kelvin-Helmholtz instability caused by the speed difference, and the Rayleigh-Taylor instability, which is caused by the acceleration difference (Pavlenko 2018). Considering a drop of emulsion, it can be concluded that the main role in the processes of its breakup will be played by the forces acting on the normal component to the drop surface, i.e. forces directed either toward the drop center or from it. Acceleration and speed, as the exponents of forces acting on the drop surface from several sources are determined by equation:

$$g_{nr}(x_0, y_0) = \sum_{i=1}^{N-1} g_i(x_0, y_0) \cdot k_{nr_i} \qquad (1)$$

$$w_{nr}(x_0, y_0) = \sum_{i=1}^{N-1} w_i(x_0, y_0) \cdot k_{nr_i} , \qquad (1a)$$

where: x_0, y_0 – the point coordinates on the drop surface; g – acceleration at the desired point, acting from some source, m/s^2; w – speed, acting at a given point from the source, m/s; k_{nr} – correction for the normal component; N – total number of boiling drops of the dispersed phase.

The acceleration and speed acting on the drop surface are determined by equations (Pavlenko 2020):

$$g_i(d_i) = \left[p_{Ri} - p_\infty + 0.5 w_{Ri}^2 \rho_{oil} \left(1 - \frac{4R_i^3}{d_i^3} \right) \right] \frac{R_i}{\rho_{oil} d_i^2} ; \qquad (2)$$

$$w_i(d_i) = \frac{w_{Ri} R_i^2}{d_i^2} , \qquad (2a)$$

where: $d_i(x_0, y_0)$ – the radius vector from the center of i-drop to the surface of the considered particle; where w_R – motion speed of the interface oil-vapor, m/s; p_∞ – the pressure in the oil volume at an infinitely large distance from the particle, Pa; R_i – the radius of the i-drop particle ($i = 1, 2, ..., n$), m; ρ_{oil} – oil density, kg/m³.

It is important to consider the forces acting on opposite sides of inclusion. Taking a variable angle β, we can determine the coordinates of the unknown opposite points of the particle surface:

$$x_{s1} = x_n + \Delta x ; \ y_{s1} = y_n + \Delta y ; \qquad (3)$$

$$x_{s2} = x_n - \Delta x ; \ y_{s2} = y_n - \Delta y ; \qquad (3a)$$

$$\Delta x = R_n \sin \beta ; \ \Delta y = R_n \cos \beta ; \ 0 \le \beta < 180° , \qquad (3b)$$

where: x_0, y_0 – the coordinates of a given particle; x_{s1}, y_{s1} – coordinates of the surface of one side of the drop; x_{s2}, y_{s2} – coordinates of the opposite side.

Then the correction k_{nr} is determined by the equation

$$k_{nr_i} = \frac{(x_i - x_{s1,s2}) \sin \beta + (y_i - y_{s1,s2}) \cos \beta}{d_i(x_{s1,s2}, y_{s1,s2})} . \qquad (4)$$

Using the equations (1)-(4), it is possible to determine the acceleration profile on the surface of the selected droplet. The results of calculations using the equations (1)-(4) for particle 2 (Figure 1) are shown in Fig. 2.
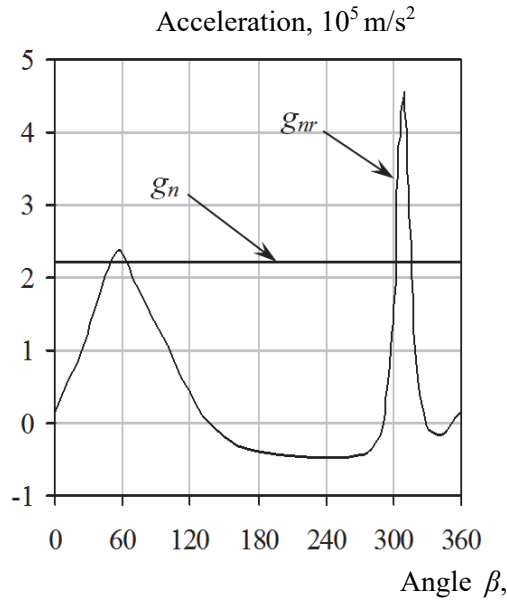
Fig. 2. Acceleration diagram acting on the drop surface No. 2 (Figure 1) from the neighboring boiling particles (g_{nr}) and counteracting acceleration of the particle itself (g_n)

It was assumed for the calculation that the considered system consisting of 6 particles at the initial time is under pressure, which corresponds to the saturation pressure of the thermolabile (water) phase of the emulsion at a temperature of $t_0 = 105°C$. At some timepoint, the pressure drops sharply to atmospheric pressure, as a result of which the water is superheated relative to the saturation temperature at atmospheric pressure, which leads to the appearance and intensive growth of the vapor phase. For the calculation, it was assumed the initial existence of a vapor interlayer (1 μm) on all selected particles at initial temperature and saturation pressure. The results of the calculations are given for the initial moment of pressure release.

Fig. 2 shows a clearly noticeable dependence between the angles of the droplet location relative to the selected one and the magnitude of the acceleration acting from them. There are at once two maxima of acceleration – angle $\beta \approx 57°$ and $\beta \approx 310°$, which corresponds to the angles of the nearest neighboring drops (No. 1 and No. 3, respectively, from Fig. 1). It is clear that the determining effect will have the force caused by the maximum acceleration, i.e. the maximum that is at an angle $\beta \approx 310°$. But in this case, we should also take into account the force that acts on the opposite side of the inclusion. Let us consider the principal

differences in determining the forces acting on the non-boiling and boiling inclu-
sion of the dispersed phase of the emulsion.

Finding, for example, the acceleration and the force caused by it on one
and the opposite drop side, we will assume that if two opposing forces are directed
toward the center of the selected drop, then the total force acting on the drop is
equal to the sum of these two forces. If both forces are directed from the center
of the drop, then the total force is also equal to the sum of two vector forces. In
case when both forces act in different directions in relation to the center of the
drop, i.e. are in one-direction in space, we will consider the driving force the one
that has a greater value of the two acting. Thus, the inclusion of a dispersed phase
that does not boil (i.e. does not create any counteraction to the forces acting on
it), the determining effect leading to possible breakup will be the maximum of
two forces that act on opposite sides, under the conditions described above.

In the case where the drop of emulsion begins to boil, it has its own
strength, which will counteract the external impact from other sources. Then the
driving force can be the one that acts on one side of the inclusion and exceeds the
counter-force. This is the main difference in consideration of the forces acting on
the boiling drop unlike the non-boiling drop. This means that it is necessary to
take into account the two given maxima and determine the main one from them.
It is possible the coincidence of these forces maxima.

Taking into consideration the fact accepted in (Pavlenko 2018) that the
force action of a drop cannot break this drop, it is possible to write down the equa-
tions that will determine the accelerations and speeds acting on the inclusion of the
dispersed phase and leading to its breakup. Assuming that the resulting acceleration
or speed are positive, then they are the cause of instability, and if they are negative,
then there is no destabilizing effect, and we can write

$$g_{p1} = \begin{cases} g_{s1} - g_n; g_n \geq 0, g_{s1} \geq 0, \\ -g_{s1}; g_n > 0, g_{s1} < 0, \\ g_{s1}; g_n < 0, g_{s1} > 0, \\ g_n - g_{s1}; g_n \leq 0, g_{s1} \leq 0, \end{cases} \tag{5}$$

where: g_{p1} – resulting acceleration, acting on one side of the inclusion, m/s^2;
g_n – acceleration of the oil-steam interface of the considered inclusion, m/s^2.

For the opposite side we can write an equation similar to (5), but, instead
of g_{p1} and g_{s1}, substituting respectively g_{p2} and g_{p2}.

Then, the total acceleration acting on the drop is determined by the equation:

$$\Delta g = g_{p1} + g_{p2},$$

(6)

with necessary conditions, taking the coefficient $Z = \dfrac{g_{s1}}{g_{s2}}$

$$g_{p1} = \begin{cases} 0; Z < 0, |g_{s1}| - |g_{s2}| < 0; \\ 0; Z > 0 : \begin{cases} \begin{pmatrix} g_n > 0, g_{s1} > 0, g_{s2} > 0, \\ g_{s1} - g_n < 0, g_{s2} - g_n > 0; \end{pmatrix} \\ \begin{pmatrix} g_n < 0, g_{s1} < 0, g_{s2} < 0, \\ g_{s1} - g_n > 0, g_{s2} - g_n < 0; \end{pmatrix} \end{cases} \end{cases}$$

$$g_{p2} = \begin{cases} 0; Z < 0, |g_{s1}| - |g_{s2}| > 0; \\ 0; Z > 0 : \begin{cases} \begin{pmatrix} g_n > 0, g_{s1} > 0, g_{s2} > 0, \\ g_{s1} - g_n > 0, g_{s2} - g_n < 0; \end{pmatrix} \\ \begin{pmatrix} g_n < 0, g_{s1} < 0, g_{s2} < 0, \\ g_{s1} - g_n < 0, g_{s2} - g_n > 0. \end{pmatrix} \end{cases} \end{cases}$$

(7)

If the maxima of the forces (accelerations, speeds) do not coincide, acting on the opposite sides of inclusion and on one side, we consider the driving force the one that is of greater value

$$g_d = \begin{cases} \Delta g_1, \Delta g_1 > \Delta g_2; \\ \Delta g_2, \Delta g_1 < \Delta g_2, \end{cases}$$

(8)

where: Δg_1, Δg_2 - the total acceleration acting on the drop, calculated on the maxima acting respectively on opposite sides and on the one side.

Similarly, we can obtain equations for the speed. In this case, in equations (5)-(8) it is necessary to change the acceleration «g» for speed «w», and equation (6) will be the following:

$$\Delta w = k \sqrt{|w_p|},$$

(9)

where: $k = \begin{cases} +1, w_p \geq 0; \\ -1, w_p > 0, \end{cases}$ $w_p = w_{p1}|w_{p1}| + w_{p2}|w_{p2}|$.

Investigations have been carried out on how the forces, acting on the droplet, change as time passes, and also how the angle of maximum force impact changes. The forces caused by acceleration play a decisive role (in comparison with the forces of dynamic pressure), we calculate them by the equations. For these conditions, forces acting on different sides of the surface of the considered particle

$$F_{g1} = 4\pi R_n^3 \rho_{oil} g_{s1},$$ (10)

$$F_{g2} = 4\pi R_n^3 \rho_{oil} g_{s2}.$$ (11)

The force of counteraction from the oil-vapor interface of the drop itself

$$F_g = 4\pi R_n^3 \rho_{oil} g_n.$$ (12)

The total force acting on the drop

$$F_{Bo} = 4\pi R_n^3 \rho_{oil} g_d.$$ (13)

Critical force causing instability according to Bond

$$F_{Bo}^{cr} = 40\pi\sigma R_n,$$ (14)

where σ is the surface tension at the oil-vapor interface, N/m.

The force that determines the deformation or displacement of a drop

$$\Delta F_{Bo} = F_{Bo} - 8\pi\sigma R_n.$$ (15)

The calculation is carried out either before the fulfillment of the condition

$$F_{Bo} \geq F_{Bo}^{cr},$$ (16)

or before the mutual drops contact, determined by the condition

$$\Delta R_{i,j} \leq 0,$$ (17)

where: $\Delta R_{i,j} = d_{i,j} - (R_{n_i} + R_{n_j})$, $d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$; $i = 1,2...N$; $j = i+1, i+2...N$; i, j – the number of drops with the corresponding coordinates $x_i, y_i; x_j, y_j$.

3. Statement of assignment and methods of its solving

The results of calculations using equations (1)-(17) with the equations of the model (Pavlenko 2018) are presented in Fig. 3-4. The calculation was carried out for $t_0 = 105°C$.

Force $F \cdot 10^5$, N

Angle β, g
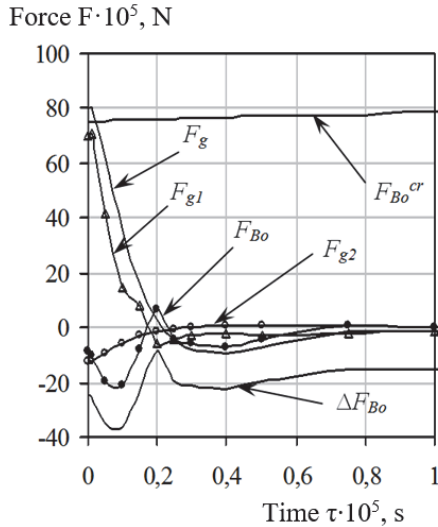
Fig. 3. The changes of forces acting on the drop No 4 over some time period (Fig. 1)
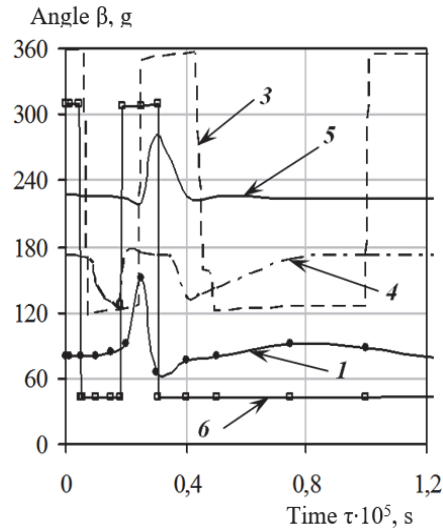
Fig. 4. The changes of the force angle of the maximum force for particles 1, 3-6 (Fig. 1) over some period of time

Fig. 3 shows that the critical force F_{Bo}^{cr} increases with time, which is associated with an increase in the radius of the selected droplet, and the values of forces acting on the drop tend to zero through time. Therefore, we can conclude that if we do not take into account the further interaction of the droplets when they contact, then at $t_0 = 105°C$ if at the initial moments of pressure drop the systems of large drops breakup does not occur, then before the moment of contact they won't breakup. Change curves F_{g1}, F_{g2} show the maximum force that affects at a given time moment. These curves determine the predominance of these forces over the force of opposition F_g, or their insignificance over this force. They also do not determine the force acting at the same angle β, as they greatly depend on the given angle, which is shown in Fig. 4.

If we consider them together, this allows us to determine the force F_{B0}, which, in turn, plays a major role in this process. It can be seen that for the drop No. 4 (Figure 3) with a positive force value F_{B0} is possible only its displacement, which is indicated by a negative sign ΔF_{B0}.

We can also observe a sudden alteration of the force angle of the maximum force mostly for the drops No 3 and 6 (Fig. 4). At the same time particle No 2 was almost fractured at the initial time and, as a consequence, the graph of the force angle change of the maximum force in Fig. 4 for it is not given. As an example we consider the drop No 6. As can be seen from Fig. 4 with the change of the force angle of the maximum force, the dominant effect changes either of the fifth drop ($\beta \approx 40°$) or the third together with the fourth ($\beta \approx 300°$). The first peak of the angle change β at $\tau \approx 0.05 \cdot 10^{-5}$ s can be explained by a sharp decrease in the acceleration of the drop boundary No. 3 and the further predominant action from particle No. 5, after which at $\tau \approx 1.8 \cdot 10^{-6}$ s the third particle has the greatest force.

At the same time, despite the sharp change in the angle β of maximum force action for particles No 3 and 6, for No 5 this angle changes quite smoothly, most of the time is equal to $\approx 230°$, i.e. near the action of the maximum force from the drop No 6.

It can be concluded that the angle β can sharply change only in those droplets that are surrounded by others, while for the droplets located quite far from the center the force angle of the maximum force will change by a small value. This can be explained by the fact that for droplets that are inside the emulsion, a maximum force can change quite rapidly both in value and in direction, due to the close position of neighboring droplets, which change their dominant impact on this particle. At the same time, the droplets in the outer layers have neighbors at a small part of their circle, which predetermines the small change value in the force angle of the maximum force.

Fig. 5 shows the changes of the angle of action of the maximum force acting on one side of the inclusion $F_{\Delta g2}$ and on the opposite sides $F_{\Delta g1}$.

It can be seen that there is no clear dependence between the force angles of these forces, they can both coincide and be very much different. Therefore, it is necessary to consider the possible maximum of the force and the angle of its action.

The calculations have been carried out for temperatures $t_0 = 180°C$ and $t_0 = 130°C$, they showed that at the instant of instantaneous pressure drop, practically all large drops will be crushed, whereas at $t_0 = 105°C$ only the largest drop will be crushed, because of the maximum approximation to its smallest particle.
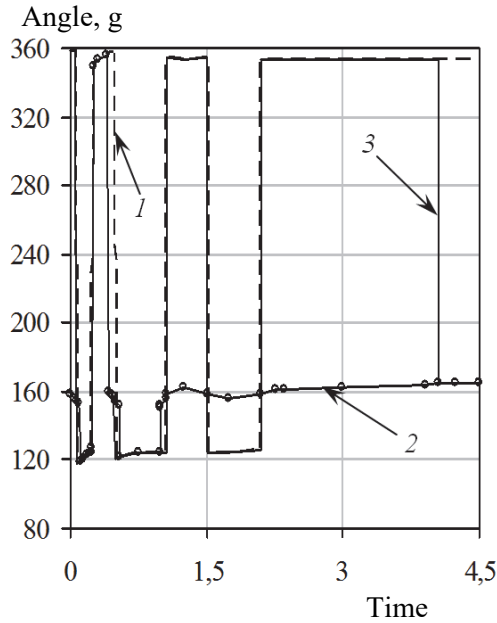
Fig. 5. The changes of the force angle of the maximum force for particle No 3 (Fig. 1), acting on one side (1) and on opposite sides of the inclusion (2), as well as the angle of action of the driving force (3) over some time period

4. Conclusion

A model for the fragmentation of large inclusions of the emulsion dispersed phase under the dynamic influence from boiling neighboring particles is considered. With the help of calculation we found out the force angles of the maximum forces, it can also be seen that the process of boiling inclusions breakup starts at different maximum forces (different angles β) in comparison with non-boiling particles. This indicates the need to find at least two maximal forces that can coincide with the angle of their action on the drop, or differ significantly in this force angle. Of course, it is necessary to take into account both the deformation of the inclusions surface and their displacement, as well as the boiling irregularity of droplets of various sizes. A large role is also played by surface active agents which allow to break up the particle with much less applied effort from other boiling inclusions. The behavior of two or more drops as they approach each other as well as the influence of neighboring drops on the growth of the selected one is still an open question. Taking these phenomena into account

will allow even more detailed and accurate consideration of the processes of growth and the dispersed phase inclusions breakup.

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Abstract

In this paper we consider the processes of dynamic interaction between the boiling particles of the dispersed phase of the emulsion leading to the large droplet breakup.

It is indicated the differences in the consideration of forces that determine the crushing of non-boiling and boiling drops. It is determined the possibility of using the model to define the processes of displacement, deformation or fragmentation of the inclusion of the dispersed phase under the influence of a set of neighboring particles.

The proposed method allows us to determine the main energy parameters of the homogenization process by boiling the emulsion.

Keywords:
crushing, desorption, force, speed, acceleration, pressure, dispersed phase

Niszczenie struktury wrzących emulsji

Streszczenie

W tym artykule rozważamy procesy dynamicznej interakcji między wrzącymi cząsteczkami zdyspergowanej fazy emulsji, prowadzące do rozpadu dużych kropel.

Wskazano na różnice w uwzględnianiu sił, które determinują kruszenie kropli niewrzących i wrzących. Określono możliwość wykorzystania modelu do zdefiniowania procesów przemieszczenia, deformacji lub fragmentacji włączenia fazy rozproszonej pod wpływem zestawu sąsiednich cząstek.

Proponowana metoda pozwala określić główne parametry energetyczne procesu homogenizacji podczas ogrzewania i wrzenia emulsji.

Słowa kluczowe:
kruszenie, desorpcja, siła, prędkość, przyspieszenie, ciśnienie, faza rozproszona.