INVESTIGATION OF THE KINETIC MODEL FOR THE PROCESS OF LIQUID DROPS FORMATION IN THE FORM OF CAPSULE

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Abstract

Capsulation as a technological principle can provoke an activation of innovative activity in food branch and become a cause of elaboration and introduction of new scientifically grounded technologies of raw material processing, creation of new commodity forms, comfortable in consumption, increase of production volumes and effectiveness of food production use, elaboration and application of the modern principally new technologies, technological processes, methods and equipment that in common can essentially influence the state and development of food technologies.

The model of capsulation of liquids of different origin by extrusion method was elaborated taking into account the regularities of gravitation and using the methods of system analysis. Kinetics of capsule structure creation, regularities of getting round forms with different diameter were determined. The gotten regularities are the base of scientific-technological principles of getting oil-fat production, capsulated with thermo- and acid-stable properties.

It was theoretically proved, that the main factor that limits the process of drop formation and separation is a stage of formation of embryo and drop itself. The time of embryo and drop formation is much more (in 20 times approximately) than the time of bridge rupture. The presence of coat of capsulated liquids essentially influences the sizes of bridge and drop and the time of processes of drop formation and separation. At that, the increase of relative coefficient of surface tension in 3 times increases a drop radius in 1,6 time and full time of drop formation and separation in 2,5 times. The received equations can be used for experimental verification of the offered model of liquid drop formation and separation.

Keywords: liquid capsulation, kinetics of formation, capsule coat, calcium alginate, drop separation, drop bridge, drop embryo.

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1. Introduction

The problem of elaboration of new food and pharmaceutical forms using physical methods of formation is rather topical, because the appearance of new physical form of technological product is a driving force of technologies, processes and equipment development. Capsules as a final commodity form of capsulation including microcapsulation as a process of new form creation is connected with the branch of production and construction of drug delivery system – DDS) [1–3], production and delivery system of biologically active substances [4, 5] and structured food products [6] (sauces [7], dessert sweet dishes [8] and so on). The common aspect for this direction is a fact that output production represents the formed technological systems with new properties, of mainly round form, can be received due to the use of film-like materials.

Most capsulation technologies are based on realization of principle of thermodynamic incompatibility of the components of coat-creator and incapsulant. The polar solutions of polymers, able under certain conditions to controlled film-creation that is capsule coat formation are used for capsulation of hydrophobic substances, including oil-fat raw material. This principle is a base of realization of capsulation processes and is grounded on surface phenomena, appeared on the border of separation of unmixed liquid phases [5–9]. From the colloid point of view, just the limited ability to mixing of the system "oil-fat raw material – water" provides creation of the distinct border of phase separation that prevents the spreading of film-creating material on drops surface [9–11].

At using ionotropic polysaccharides as coat-creator, the need for coaxial extrusion of liquid appears. It takes place according to the principle "tube in tube", where the solution of coat-creator (external tube) and hydrophobic substance (internal tube) are supplied in forming medium through air as formed quasistable capsules. At entering in the receiving medium, the chemical potentials are realized and the texture of capsule gains commodity state.

The general character of the process of drops creation and separation under gravity force is well studied experimentally and looks practically equally for all liquids (**Fig. 1**) [12]. At the beginning the conic embryo of drop forms, then the spherical drop itself begins to form as a result of liquid outflow from the embryo under effect of capillary pressure and gravity force. A bridge appears between it and embryo; it decreases with time till the very moment of drop separation. This flow is arbitrary that is bridge keeps its form [13–15]. At the same time the theory of this phenomenon still not fully described, because the classic equations of hydrodynamics describe completely determined process, and kinetics of the bridge between drop and embryo can be rather referred to the theory of catastrophes and bifurcation phenomena that is to nonlinear processes with reverse connection [16].

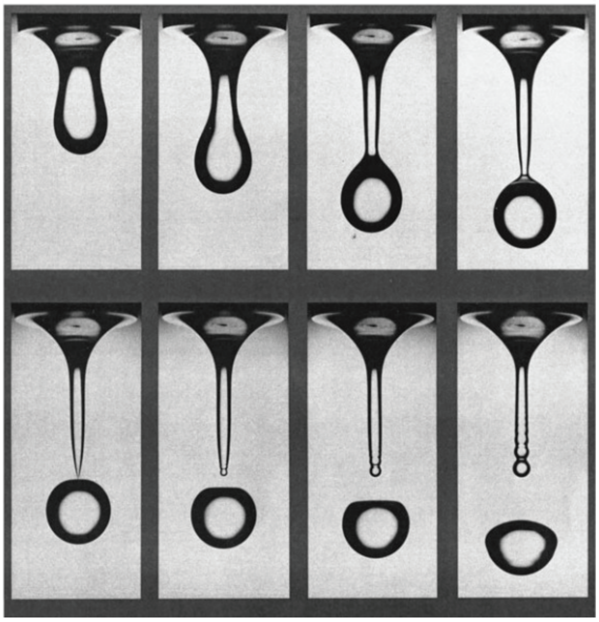


Fig. 1. Stages of real water drop separation: time between scenes is 0,1 s [12]

The one of first attempts to describe the kinetics of bridge rupture was made by the authors [17]. The theory is based on the model, according to which the arbitrary flow of liquid in bridge zone is controlled only by the forces of inertia and surface tension, not depending on viscosity. The bridge radius changes in time according to the stage law with equal index for all liquids.

$$r_{br} \sim \left(\frac{\sigma}{\rho}\right)^{1/3} \times (\tau)^{2/3}, \quad (1)$$

where r_{br} – bridge radius; σ – coefficient of surface tension; ρ – density of liquid; τ – given time.

This law of "two thirds" is proved by the numerous experiments for different liquids [18, 19]. At the same time the question about the initial size of bridge itself, that appears at the first stage of formation and depends on both liquid quality and capillary geometric parameters still open. The problem of formation kinetics (process of creation of embryo, bridge and its rupture) for capsulated hydrophobic liquids, consisted of liquid coat and liquid kernel with different physical characteristics, is more complicated.

2. Materials and Methods

Sodium alginate solutions (AlgNa – ionotropic polysaccharide that is coat-creator) was received by dispersion of the batch of studied substance in demineralized drinking water at t=18…20 ºC with further exposition during (3…4)×60^2 s at t=4…6 ºC. The received solution was placed to vacuum-dessicator and degassed during (30…60)×60 s.

$CaCl_2$ salt was used as a source of Ca^{2+} in the forming medium. To prepare $CaCl_2$ solution, it was dissolved in drinking water at t=18…20 ºC during τ=(8…10)×60 s, the received solution was filtered.

Calcium alginate gels (AlgCa) were received by introduction of AlgNa solutions to the calculated quantity of $CaCl_2$ solution, and the gels with different texture and structural-mechanical parameters were received as a result of it [6].

Extrusion formation of receipt mixtures was carried out on the laboratory and industrial extruder of UGK-20 G trade, of the author production of "Capsular" company (Ukraine) under conditions of slow displacement of aforesaid receipt mixture under pressure with formation of round product (**Fig. 2**).

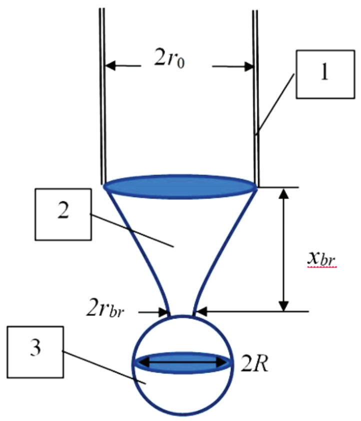
Fig. 2. Photographic representation of industrial sample of head for capsulation "through air"

Capsule head allows get capsules by top-down coaxial extrusive formation of coat-creator and internal content through air in receiving liquid. For that the coat-creator and internal content, for example, sunflower oil, are placed in reservoirs. Then the offered level of capsulated substances is formed in depressurized reservoirs. Then coaxial extrusion of two substances is made, where coat-creator is supplied through the external tube of capsule head, and internal content on the base of hydrophobic substance – through internal one. At such approach there is no chemical interaction between capsule components. The capsule in quasistable state comes into receiving pan with bivalent metal solution through air. As far as the coat creator is ionotropic polysaccharide by its nature, its chemical interaction with sewing bivalent metal takes place in receiving transport medium. The result is the formation of stable structure of capsule.

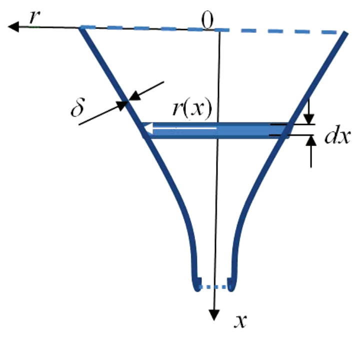
The grounding of kinetic processes of capsulated liquids formation was carried out by theoretical and analytical studies. For this aim there were used the methods of mathematical and statistical modeling, physical laws (law of energy conservation, Archimedes', gravitation, Bond and Frud number) and chemical ones (diffusion of substances, ion-exchange) with further extrapolation of received data on wide diapason of experimental parameters [6, 12].

3. Results

The main theses of the model were formulated, based on observed experimental facts and assumptions that allow use the elementary equations of mechanics of liquids. The process of formation consists of three stages. The first stage is a formation of conic drop embryo, the second one is a formation of spheric drop and bridge between embryo and drop and the third one is arbitrary flow of liquid near the bridge and its rupture (separation moment). The capsulated system consists of kernel and thin coat of two different liquids. All physical properties of liquids (density, coefficient of surface tension) don't change at the process of formation. The loss for viscid friction are absent; the problem is axially symmetric – embryo and drop form at the end of nutrient tube with radius r_0 (**Fig. 3**); the drop form is a sphere with radius R, that must be found. The form of conic embryo can be defined as a function r = f (x). The bridge with output radius r_{br} corresponds to the point of cross of sphere with conic embryo; final equations must allow calculate the duration of all stages of the process.



a



b

Fig. 3. Scheme of geometry embryo-drop: 1 – tube of liquid supply; 2 – embryo of drop, 3 – drop; *a* – scheme of geometry embryo-drop; *b* – scheme of geometry of conic embryo

The photo-monitoring of quasistable capsule formation is presented on the **Fig. 4**. Sunflower oil was used as incapsulator. The water solution of ionotropic polysaccharide was used as film-creator.

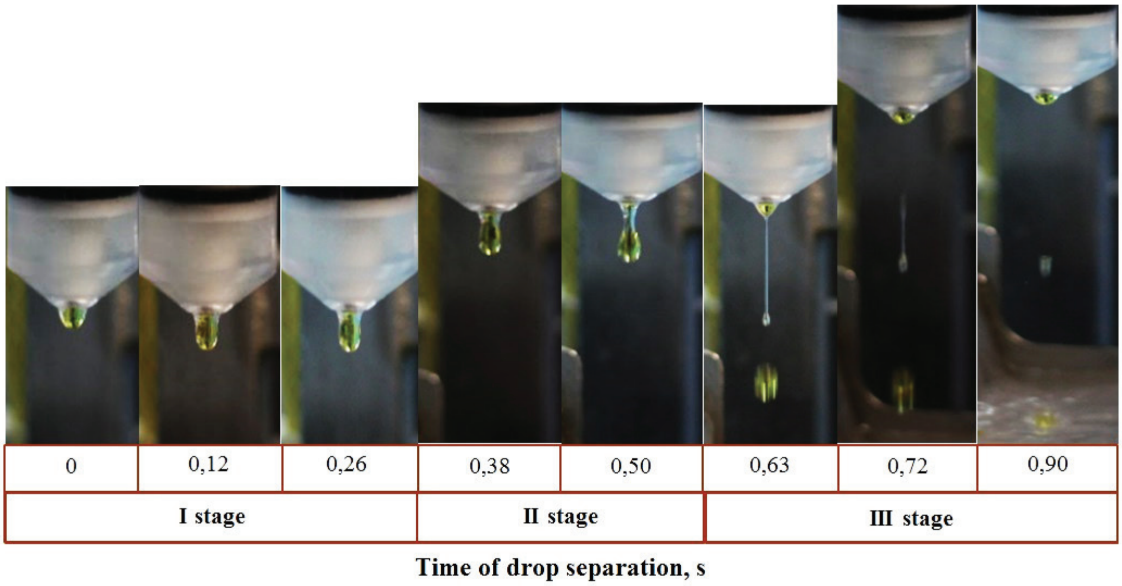


Fig. 4. Stages of formation of quasistable drop of sunflower oil in polymer solution: time of liquid outflow from the drop embryo to the moment of separation – 0,63 s: I – formation of drop embryo; II – formation of spheric embryo and bridge; III – bridge rupture and quasistable drop creation

The stage of embryo creation provides the calculation of drop embryo form, because its geometry determines the capillary potential. The joint action of gravity force and surface tension determine the embryo form –hydrostatic pressure $p_g=\rho_{gx}$ in any cross cut of embryo is balanced by the capillary pressure – $p_{cap}=2\sigma/r$ (**Fig. 3**).

$$dp_{cap} = \rho g dx. \tag{2}$$

Taking into account the fact that this capillary pressure consists of coat capillary pressure and interphase coat-kernel pressure, we get:

$$-2\left[\frac{\sigma_\delta}{(r+\delta)^2}+\frac{\sigma-\sigma_\delta}{r^2}\right]dr = \rho g dx, \tag{3}$$

where σ – coefficient of surface tension of kernel liquid; σ_δ – coefficient of interphase coat-kernel tension ($\sigma>\sigma_\delta$); δ – thickness of coat; g – acceleration of free fall; ρ – given density of liquid system coat-kernel.

$$\rho = \rho_\delta \cdot c_\rho + \rho_c \cdot (1-c_\rho), \tag{4}$$

where ρ_δ – density of coat; ρ_c – density of kernel; c_p – volume part of coat in the volume of capsulated system.

The solution of differentiated equation (3) with starting condition $r(x)\big|_{x=0} = r_0$ is following:

$$\left(1-\frac{r}{r_0}\right)\left[\frac{\sigma-\sigma_\delta}{\sigma_\delta}\frac{r_0}{r}+\frac{1}{\left(\frac{r}{r_0}+\frac{\delta}{r_0}\right)\left(1+\frac{\delta}{r_0}\right)}\right]dr = \frac{\rho g r_0}{2\sigma_\delta}x. \tag{5}$$

Let's simplify this expression taking into account the minimal thickness of coat, taking into account $\delta<r_0$, then get:

$$\frac{x}{r_0}=\frac{2}{Bo}\frac{\sigma}{\sigma_\delta}\left(\frac{r_0}{r}-1\right), \tag{6}$$

$$\frac{r}{r_0}=\frac{1}{2\,Bo\dfrac{\sigma}{\sigma_\delta}\dfrac{x}{r_0}+1}, \tag{7}$$

$$\frac{dx}{dr}=-\left(\frac{r_0}{r}\right)^2\frac{2}{Bo}\frac{\sigma}{\sigma_\delta}, \tag{8}$$

where $Bo=\dfrac{r_0^{\,2}}{l_{cap}^{\,2}}$ – Bond number that indicates the ratio of gravity force to the force of surface tension; l_{cap} – capillary length; $l_{cap}=\sqrt{\dfrac{\sigma}{\rho\cdot g}}$ – typical size, at which surface tension force becomes equal to gravity one.

The equations (6)–(8) describe initial geometry of drop embryo that is the change of embryo radius from its height and vice versa.

To verify physical correctness of received expression, let's find the embryo volume V_{emb}. For that let's write, according to determination of volume of any axially symmetric figure:

$$V_{emb}=\pi\int_0^x r(x)^2\,dx=\pi\frac{x\cdot r_0^{\,2}}{1+\dfrac{Bo}{2}\dfrac{\sigma_\delta}{\sigma}\dfrac{x}{r_0}}. \tag{9}$$

Substituting the expression for embryo height (6) in this formula, we get:

$$V_{emb}=2\pi\frac{\sigma}{\sigma_\delta}\frac{r_0-r}{Bo}r_0^{\,2}. \tag{10}$$

In becomes obvious that within r→0, the volume of drop embryo V_{emb} tends to the value V_{max}:

$$V_{max}=2\pi\frac{\sigma}{\sigma_\delta}\frac{r_0^{\,3}}{Bo}=2\pi\frac{\sigma^2}{\sigma_\delta}\frac{r_0}{\rho g}. \tag{11}$$

If the coat is absent (homogenous liquid in embryo $\sigma_\delta=\sigma$), the value V_{max} in equation (11) exactly coincides with the value of maximal volume that is in balance at the end of tube with radius r_0 under effect of gravity force and the one surface tension that is equal:

$$\rho g V_{max}=2\pi r_0\sigma. \tag{12}$$

Thus, the received equations (6)–(10) remain physically correct.

The change of embryo form that spheric drop is created of takes place under the effect of gravity force that is opposed by the force of surface tension. Let's assume that the drop begins to form at the moment, when the current radius of embryo is equal to the initial radius of bridge. Based on the law of energy conservation, Ag work, realized by gravity force at increase of embryo height is equal to A_σ work against the forces of surface tension at creation of spheric drop:

$$dA_g=p\,dV_{drop}, \tag{13}$$

$$dA_\sigma = \sigma dS_{drop}. \quad (14)$$

Let's find the drop volume:

$$V_{drop} = \frac{4}{3}\pi R^3. \quad (15)$$

The pressure, created by gravity force by the height of liquid drop is equal:

$$p = p_{br} + 2R\rho g, \quad (16)$$

where R – radius of drop; p_{br} – initial hydraulic pressure above the bridge that, taking into account (6), is equal:

$$p_{br} = \rho g x_{br} = \rho g r_0 \frac{2}{Bo}\frac{\sigma}{\sigma_\delta}\left(\frac{r_0}{r_{br}} - 1\right). \quad (17)$$

Integrating (13), taking into account these expressions by the drop radius, we get:

$$A_g = 4\pi\left(\frac{1}{2}\rho g R^4 + \frac{1}{3}p_0 R^3\right) + \text{const}. \quad (18)$$

The constant of integration is determined from initial condition $A_g(R)\big|_{R=r_{br}} = 0.$ So, we get:

$$A_g = 4\pi\left[\frac{1}{2}\rho g(R^4 - r_{br}{}^4) + \frac{1}{3}p_0(R^3 - r_{br}{}^3)\right]. \quad (19)$$

Let's get the expression for the calculation of drop radius R. It becomes obvious that the summary volume of drop and volume of embryo is equal to the maximal volume that can be in balance at the end of tube with radius r_0. That is why, taking into account (10) and (11), let's write:

$$V_{max} = \frac{4}{3}\pi R^3 + V_{emb}. \quad (20)$$

So, we find the connection between the drop radius R with the bridge one r_{br}:

$$R = r_0\left(\frac{3}{2}\frac{\sigma}{\sigma_\delta}\frac{1}{Bo}\frac{r_{br}}{r_0}\right)^{\frac{1}{3}}. \quad (21)$$

Substituting the expression for drop radius (21) and initial hydrostatic pressure (17) in (19), we get the final equation for calculation of the work of gravity force for spheric drop formation.

$$A_g = 2\pi\rho g r_0{}^4\left[\frac{4}{3Bo}\frac{\sigma}{\sigma_\delta}\left(1 - \frac{r_{br}}{r_0}\right)\left(\frac{\sigma}{\sigma_\delta}\frac{3}{2Bo} - \frac{r_{br}{}^2}{r_0{}^2}\right) + \left(\frac{\sigma}{\sigma_\delta}\frac{3}{2Bo}\frac{r_{br}}{r_0}\right)^{\frac{4}{3}} - \left(\frac{r_{br}}{r_0}\right)^4\right]. \quad (22)$$

Then calculate the work of surface tension force for spheric drop formation. Based on (14) let's write:

$$A_\sigma = \int_{S_0}^{S_{drop}} \sigma dS, \quad (23)$$

where S_{drop} – area of drop surface; S_p – area of drop surface that corresponds to the initial radius of bridge r_{br}, taking into account that initial radius at the end of embryo is equal to the one of bridge, we have:

$$S_0 = 2\pi r_{br}^{\ 2},\ \ S_{drop} = 4\pi R^2 - 2\pi r_{br}^{\ 2}.$$

Taking it into account, we get:

$$A_\sigma = 4\pi\sigma\left(R^2 - r_{br}^{\ 2}\right). \tag{24}$$

Substituting the drop radius (21) in this equation, we get the final work of surface tension force:

$$A_\sigma = 4\pi\sigma r_0^{\ 2}\left[\left(\frac{\sigma}{\sigma_\delta}\frac{3}{2\,Bo}\frac{r_{br}}{r_0}\right)^{\frac{2}{3}} - \left(\frac{r_{br}}{r_0}\right)^2\right]. \tag{25}$$

Equaling the work of gravity force (22), and the one of surface tension force (25), we get the equations for determination of the initial bridge radius r_{br0} under condition:

$$A_g(r_{br0}) = A_\sigma(r_{br0}). \tag{26}$$

Obviously, this condition of equality of the works can be realized in defined cut of embryo, depending on physical parameters, included in (22) and (25), that characterize this process. The equation (26) is transcendental as to the output initial radius of bridge r_{br0}, so its numerical value is given as non-dimensional dependence.

Having known the initial radius of bridge, it is possible to calculate the drop radius at the moment of separation according to the equation (21). Thus, the received equations (21) and (26) characterize the geometry of embryo and drop.

Let's determine the time, necessary for embryo and drop formation. Let's base on the offered model and limit ourselves by the assessment of correspondent times according to aforementioned equations for the calculation of the works of gravity force and the one of surface tension. Based on the law of energy conservation, the work of the forces on formation of embryo and drop in time unit is equal to the power of supplying source (parameters of liquid supply in tube). Let's assume, that the parameters of supply in the process of formation of embryo and drop don't change, so the initial time of formation can be calculated as following:

$$\Delta\tau_1 = \frac{\Delta A}{p_0 Q_V}, \tag{27}$$

where $\Delta\tau_1$ – duration of formation of embryo and drop (duration of first and second stage); ΔA – summary work of gravity force and the one of surface tension; p_0 – pressure in supplying tube; Q_V – volume consumption of liquid in supplying tube.

The summary work ΔA consists of the work for the drop formation, determined earlier (23) and the work for the embryo drop formation that can be calculated analogously.

$$dA_{emb} = p dV_{emb} = \rho g x dV_{emb}. \tag{28}$$

Substituting here the expressions for embryo height (6) and its volume (10), we get:

$$dA_{emb} = 4\pi\rho g r_0^{\ 3}\left(\frac{1}{Bo}\frac{\sigma}{\sigma_\delta}\right)^2\left(1 - \frac{r_0}{r}\right)dr, \tag{29}$$

Integrating this equation by the radius from r_0 to r_{br}, we get:

$$A_{emb} = 4\pi \frac{\sigma r_0^2}{Bo} \left(\frac{\sigma}{\sigma_\delta} \right)^2 \left[\ln\left(\frac{r_0}{r_{br}} \right) + \frac{r_{br}}{r_0} - 1 \right]. \tag{30}$$

Thus, having known the summary work of surface tension force (25) and gravity force (30), we can calculate the time of formation of embryo and drop:

$$\Delta\tau_1 = \frac{4\pi\sigma r_0^2}{p_0 Q_V} \left[\left(\frac{\sigma}{\sigma_\delta} \frac{3}{2\,Bo} \frac{r_{br}}{r_0} \right)^{\frac{2}{3}} - \left(\frac{r_{br}}{r_0} \right)^2 + \frac{1}{Bo} \left(\frac{\sigma}{\sigma_\delta} \right)^2 \left[\ln\left(\frac{r_0}{r_{br}} \right) + \frac{r_{br}}{r_0} - 1 \right] \right]. \tag{31}$$

Having known the parameters of liquid supply in forming tube (pressure and consumption) and also the initial radius of bridge, the summary duration of first and second stages of drop formation can be calculated by the equation (31).

Based on these ideas, let's write the equation for the participants of process near the bridge:

$$\frac{\rho \upsilon^2}{2} = \frac{2\sigma}{r}, \tag{32}$$

where υ – speed of liquid flow in bridge zone.

This speed consists of longitudinal υ_x and transversal υ_r components:

$$\upsilon = \sqrt{\upsilon_x^2 + \upsilon_r^2} = \sqrt{\left(\frac{dx}{d\tau} \right)^2 + \left(\frac{dr}{d\tau} \right)^2}. \tag{33}$$

Changing the order of differentiation, let's write:

$$\upsilon = \sqrt{\left(\frac{dr}{d\tau} \right)^2 \left(\frac{dx}{dr} \right)^2 + \left(\frac{dr}{d\tau} \right)^2}. \tag{34}$$

Then let's take into account that the flow is arbitrary that is the bridge form doesn't change with time. In mathematical sense in means the steadiness of embryo form derivative. Taking into account the expression (8), we have:

$$\frac{dx}{dr} = \text{const} = -\left(\frac{r_0}{r_{br0}} \right)^2 \frac{2}{Bo} \frac{\sigma}{\sigma_\delta}. \tag{35}$$

Substituting the last expression in (34), we get the connection of flow speed with the bridge radius:

$$\upsilon = \frac{dr}{d\tau} \sqrt{\left[\left(\frac{r_0}{r_{br0}} \right)^4 \left(\frac{2}{Bo} \frac{\sigma}{\sigma_\delta} \right)^2 + 1 \right]}. \tag{36}$$

Then, substituting this speed in (21), we get the following differential equation of the bridge radius kinetics:

$$\frac{dr}{d\tau} \sqrt{\left(\frac{r_0}{r_{br0}} \right)^4 \left(\frac{2}{Bo} \frac{\sigma}{\sigma_\delta} \right)^2 + 1} = \frac{2}{\sqrt{r}} \sqrt{\frac{\sigma}{\rho}}. \tag{37}$$

The solution of this equation with initial solution $r(\tau)\big|_{\tau=0} = 0$ looks as following:

$$\tau = \frac{1}{3}\sqrt{\frac{\sigma \cdot r^3}{\rho}}\sqrt{\left(\frac{r_0}{r_{br0}}\right)^4 \left(\frac{2}{Bo}\frac{\sigma}{\sigma_\delta}\right)^2 + 1}. \tag{38}$$

Let's note that the received equation differs from the equation (1), offered by [17], by the constant coefficient, taking into account the initial bridge radius and in contrast to the equation (1), allows calculate the duration of bridge thinning from the initial value r_{br0} to null. Thus, the duration of third stage (time of the bridge rupture) is equal to:

$$\Delta\tau_2 = \frac{1}{3}\sqrt{\frac{\sigma \cdot r_{br0}^{\;3}}{\rho}}\sqrt{\left(\frac{r_0}{r_{br0}}\right)^4 \left(\frac{2}{Bo}\frac{\sigma}{\sigma_\delta}\right)^2 + 1}. \tag{39}$$

The kinetic model of formation of capsulated liquids, including the fat-oil ones was elaborated on the base of realized studies. For verification of the offered model, the authors proved the correctness of calculations for their adaptation in real technological process. Thus for relative radius of supplying tube r_0=0,4l_{cap} at increase of relative coefficient of surface tension in 3 times, the drop radius increases in 1,7 times.

This result is a consequence of the fact that the coat increases the resulting force of surface tension that affects the drop kernel (interphase force of molecular interaction is directed inside the drop – $\sigma > \sigma_\delta$). As if "arming" of the drop surface that in such case can endure more pressure of gravity force, takes place.

But to receive more drop radius, it is necessary to decrease the radius of supplying tube. Thus to receive drop with radius R=1,3l_{cap}, the radius of supplying tube must be no more than, 4l_{cap}. This limitation is caused by the fact that at big radius of supplying force, gravity force exceeds the one of surface tension, and drop is not created, laminar flow regime takes place. Within the offered model it means that the condition of equality of gravity force and surface tension force (26) doesn't take place.

The typical time for the processes, controlled by gravity force and surface tension force is a value $\sqrt{l_{cap}/g}$. Taking it into account, let's introduce non-dimensional time $\tau\sqrt{g/l_{cap}}$ and then the equation (39) becomes non-dimensional:

$$\Delta\tau_2^* = \frac{1}{3}Bo^{\frac{3}{4}}\sqrt{\frac{r_{br0}^{\;3}}{r_0^{\;3}}}\sqrt{\left(\frac{r_0}{r_{br0}}\right)^4 \left(\frac{2}{Bo}\frac{\sigma}{\sigma_\delta}\right)^2 + 1}, \tag{40}$$

where $\Delta\tau_2^* = \Delta\tau_2\sqrt{g/l_{cap}}$ – non-dimensional time.

From the equation (40) can be seen, that the time of bridge rupture is a function of only two variables: Bond number (because the initial bridge radius also depends on the number B_o) and relative coefficient of surface tension (σ/σ_δ).

Let's derive the equation (31) that describes the duration of embryo and drop formation to non-dimensional form. This equation includes two unknown values – parameters of strength in supplying tube (p_0, Q_V). Let's take into account that the pressure of p_0 order of capillary pressure that is $p_0=2\sigma/r_0$, and volume consumption of liquid are connected with the speed of flow in supplying tube as $Q_V=\pi r_0^2\times\upsilon_0$. So, taking into account non-dimensional time, the equation (31) looks as following:

$$\Delta\tau_1^* = \frac{2\sqrt{Bo}}{\sqrt{Fr}}\times$$

$$\times\left[\frac{1}{Bo}\left(\frac{\sigma}{\sigma_\delta}\right)^2\left[\ln\left(\frac{r_0}{r_{br0}}\right)+\frac{r_{br0}}{r_0}-1\right]+\left(\frac{3}{2\,Bo}\frac{\sigma}{\sigma_\delta}\frac{r_{br0}}{r_0}\right)^{\frac{2}{3}}-\frac{r_{br0}^{\;2}}{r_0^{\;2}}\right], \tag{41}$$

where $\Delta\tau_1^* = \Delta\tau_1\sqrt{g/l_{cap}}$; Fr=$\upsilon_0^2/(g\times l_{cap})$ – Frud number; υ_0 – speed of liquid supply in supplying tube.

As it flows from the equation (39), non-dimensional time of embryo and drop formation is a function of three variables: Bond number, Frud number and relative coefficient of surface tension – σ/σ_δ.

The influence of relative coefficient on surface tension kernel-coat (σ/σ_δ) is much stronger than Bond number. The decrease of Bond number in 3 times results in increase of the time of drop separation by 25,0 %. Obviously, the change of parameters of liquid supply in supplying tube (Frud number) proportionally changes the time of embryo and drop formation. Thus, the decrease of Frud number by 30,0 %, that corresponds to the decrease of flow speed in supplying tube by 16,0 %, increases the duration of the stage of embryo and drop formation by 16,0 %.

It is important, that the time of embryo and drop formation is much longer than the time of bridge rupture (approximately in 20 times). So, the main factor that limits the time of drop creation and separation is just the stage of embryo and drop formation and not the one of bridge rupture. It means that the speed of instrument for capsules creation according to the principle of arbitrary decay determines the productivity of capillary by capsulation.

4. Conclusions

The kinetic model of process of formation of liquid drops for getting its capsulated form was offered. In our case it is formation of capsule with firm-elastic coat and internal liquid content (kernel) on the base of hydrophobic substance. This model describes all stages of capsulation process – from embryo formation to drop separation.

The theoretical studies were carried out on the base of elaborated accepted models of formation of capsulated liquid and the equations that allow calculate the initial radius of bridge between embryo and drop, radius of drop, duration of embryo formation and time of bridge rupture were received. The received equations are agreed with well-known theory of arbitrary flow in bridge zone and specify the well-known equations due to the presence of initial bridge radius that is a necessary condition at modeling of drop embryo formation stage.

At the stage of modeling of spheric drop and bridge creation, it was theoretically grounded, that the main factor that limits the process of drop creation and separation is just the stage of formation of embryo and drop itself. The time of embryo and drop formation is much more (approximately in 20 times) than the time of bridge rupture. At the modeling of the stage of bridge rupture and creation of quasistable drop, it was established, that the presence of coat in capsulated liquids (increase of relative coefficient of surface tension kernel-coat) essentially influences the sizes of bridge and drop and the time of processes of drop formation and its separation. At that, the increase of relative coefficient of surface tension in 3 times increases the drop radius in 1,6 times and full time of drop formation and separation in 2,5 times.

The received equations can be used in future for experimental verification and industrial approbation of the offered model of liquid drop formation and separation and also at elaboration and assembling of devices for getting of capsulated production and substantiation of power of constructional machines.

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