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NEW INTERPRETATION OF EMULSIFYING MECHANISM

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Abstract. A set of complex theoretical analyses of effects, carried out by the author enabled to create a new physical interpretation of the emulsifying mechanism taking into account the role of basic emulsion parameters, especially absolute viscosity, interfacial tension, density of emulsion phases and especially pressure and temperature. A mathematical description of the process was compiled with a determination of the role of those parameters influencing the characteristic dimension of scattered phase particles. As a result of testing the emulsion of rape oil and water a verified theoretical-experimental model of emulsifying process was elaborated and described by an equation.

Keywords: mechanism of pressure emulgation, emulsion, characteristic dimension, scattered phase

INTRODUCTION

The emulsifying relies upon comminuting the particles of the scattered phase and homogenising the emulsion. This process is commonly used in many industries like pharmaceutical, cosmetic, chemical, petroleum, plastics and especially food industry.

As a result of emulsification the number of the scattered phase balls increases about 200 - 500 times and their total surface increases about 6 - 8 times. For example, the emulsification in food industry increases availability of nutrients, in chemical industry accelerates reactions and allows to obtain a better homogeneity of products, in petroleum industry is used for refining heavy fuels etc.

There are research works carried out in order to use rape oil as an environment - friendly fuel, so that it is fully justified to learn about the possibilities of making water based emulsions of that oil.

Hitherto, there is no explicit interpretation of the emulsifying mechanism and the basic operating parameters of processing are chosen experimentally. Few attempts to explain phenomena occurring during emulsification are incomplete and of descriptive nature, most of them are based on testing milk emulsification at 60°C and therefore cannot be apriori utilised for evaluating emulsifying parameters of other products [1-5].

THEORETICAL

It is generally accepted nowadays that rapid changes in the velocity ϑ and pressure p occur when emulsion enters a narrow hole of a valve. A particle of the dispersed phase is disrupted. The process of disintegration is also affected by other factors, e.g., grinding of the spheres by the walls, implosion of particles leaving the valve, their mutual collisions, etc. (Fig. 1)

PHYSICAL INTERPRETATION OF THE EMULSIFICATION MECHANISM

The present interpretation of the emulsification mechanism is based on the assumption, that the particles of the dispersed phase are sheared while the medium is passing through the emulsifying valve, and thus they are comminuted.

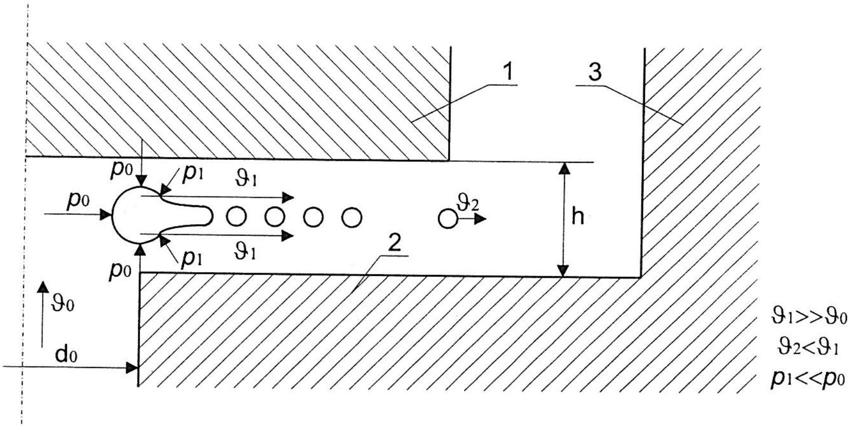

Fig. 1. The model of the mechanism of emulsification under pressure: 1 - valve head, 2 - valve seat, 3 - disrupting ring, ϑ_o - velocity of the medium in the hole of the valve seat, p_o - pressure in the hole of the valve seat, ϑ_1 - velocity of the medium at the entrance into the hole of the valve, p_1 - pressure at the entrance into the hole, ϑ_2 - velocity of the medium at the exit of the hole, d_o - diameter of the hole of the valve seat, h - height of the hole of the emulsifying valve.

A set of complex theoretical analyses of effects, carried out by one of the authors [4] enabled to create a new physical interpretation of the emulsifying mechanism taking into account the role of basic emulsion parameters, especially absolute viscosity - μ, interfacial tension - σ, density of emulsion phases - ρ_s, ρ_{cz} and especially pressure - p and temperature - t [4] (Fig. 2).

MATHEMATICAL MODEL

At moment of comminutation:

$$P_\Sigma = P_\sigma + P_\mu \tag{1}$$

where: P_Σ - resisting force of medium with interaction of scattered phase, P_σ - interfacial tension force, P_μ - friction force cause of viscosity.

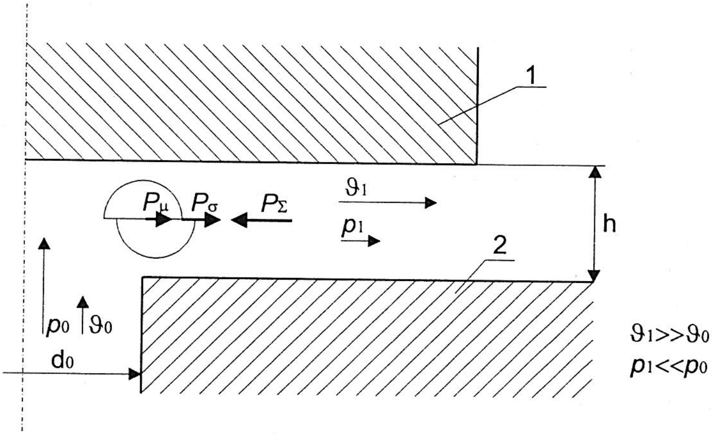

Fig. 2. A new model of the mechanism of emulsification under pressure: 1 - valve head, 2 - valve seat, ϑ_o - velocity of the medium in the hole of the valve seat, p_o - pressure in the hole of the valve seat, ϑ_1 - velocity of the medium at the entrance into the hole of the valve, p_1 - pressure at the entrance into the hole, d_o - diameter of the hole of the valve seat, h - height of the hole of the emulsifying valve, P_Σ - resisting force of the medium interaction of scattered phase, P_σ - interfacial tension force, P_μ - friction force caused by viscosity.

Resisting force of medium P_Σ cause shearing of particles and is manifested in:

- big high velocity gradients of particles,
- changes of directions in particle motion,
- beating the particles of the spheres by the walls,
- mutual collisions of particles,
- rotational motion of particles.

The above effects occur while the medium is passing through the emulsifying valve:

$$P_\Sigma = \tfrac{1}{2}\cdot\tfrac{1}{2}C_x\rho_s\left(\vartheta_{cz}-\vartheta_s\right)^2\frac{\pi d_{cz}^{\;2}}{4} \tag{2}$$

where: d_{cz} - a characteristic dimension of the scattered phase particles, C_x - medium drag coefficient, ρ_s - density of the continuos emulsion phase, ϑ_{cz} - velocity of the particles, ϑ_s - velocity of the continuos phase,

$$P_\sigma = \pi d_{cz}\sigma \tag{3}$$

where: σ - interfacial tension,

$$P_\mu = \mu\frac{d\vartheta}{dx}\frac{\pi d_{cz}^{\;2}}{4} \tag{4}$$

where: μ - absolute viscosity of the scattered phase, $\frac{d\vartheta}{dx}$ - gradient of velocity.

A mathematical description of the process was compiled (Eqs (1)-(4)) with determining the role of those parameters influencing characteristic dimensions of the scattered phase particles:

$$d_{cz} = \frac{16\sigma}{C_x\rho_s\left(\vartheta_{cz}-\vartheta_s\right)^2-4\mu\dfrac{d\vartheta}{dx}}\cdot \tag{5}$$

Equation 5 was analysed for various values of ϑ_{cz} - ϑ_s:

- the process goes smoothly, comminuting follows under influence of the difference of between velocity of continuos phase and scattered while passing through the medium of emulgation in the gap of the valve conditioned by the difference in density levels of the two phases density, then:

$$\vartheta_{cz}-\vartheta_s = \varphi\sqrt{\frac{2p}{\rho_{cz}}}-\varphi\sqrt{\frac{2p}{\rho_s}} \tag{6}$$

where: ρ_{cz} - density of the scattered phase of emulsion, φ - coefficient of discharge, p - pressure.

- the process of comminuting goes rapidly, then:

$$\vartheta_{cz}-\vartheta_s = \varphi\sqrt{\frac{2p}{\rho_{cz}}} \tag{7}$$

and characteristic values of the velocity gradient $\frac{d\vartheta}{dx}$, and a number of mathematical relations were obtained:

- a change in the velocity level $d\vartheta$ occurs at the half of the valve gap height, at the same time it reaches velocity value of the flux in the middle of the gap; for a smooth process:

$$\frac{d\vartheta}{dx} = \frac{2\left(\vartheta_{cz}-\vartheta_s\right)}{h} \tag{8}$$

then:

$$d_{cz} = \frac{1}{p\varphi^2}\cdot\frac{\sigma}{\left[\dfrac{C_x\rho_s}{8}\left(\dfrac{1}{\rho_{cz}}+\dfrac{1}{\rho_s}-\dfrac{2}{\sqrt{\rho_{cz}\rho_s}}\right)-\dfrac{\pi\mu d_o}{V}\left(\dfrac{1}{\sqrt{\rho_{cz}\rho_s}}-\dfrac{1}{\rho_s}\right)\right]} \tag{9}$$

where: d_o - diameter of the hole of the valve seat, V - capacity of the emulgator, and for a rapid process:

$$\frac{d\vartheta}{dx} = \frac{2\vartheta_{cz}}{h} \tag{10}$$

then:

$$d_{cz} = \frac{\sigma}{p\varphi^2\left(\dfrac{1}{8}C_x\dfrac{\rho_s}{\rho_{cz}}-\dfrac{\pi\mu d_o}{\sqrt{\rho_{cz}\rho_s}}\right)} \tag{11}$$

- the change of the velocity value occurs at the half of the valve gap height, at the same time in the middle of the gap the value of analytical velocity is equal to the double velocity value of the flux; for a smooth process:

$$\frac{d\vartheta}{dx}=\frac{4(\vartheta_{cz}-\vartheta_s)}{h} \tag{12}$$

then:

$$d_{cz}=\frac{1}{p\varphi^2}\cdot\frac{\sigma}{\left[\frac{C_x\rho_s}{8}\left(\frac{1}{\rho_{cz}}+\frac{1}{\rho_s}-\frac{2}{\sqrt{\rho_{cz}\rho_s}}\right)-\frac{2\pi\mu d_o}{V}\left(\frac{1}{\sqrt{\rho_{cz}\rho_s}}-\frac{1}{\rho_s}\right)\right]} \tag{13}$$

and for a rapid process:

$$\frac{d\vartheta}{dx}=\frac{4\vartheta_{cz}}{h} \tag{14}$$

then:

$$d_{cz}=\frac{\sigma}{p\varphi^2\left(\frac{1}{8}C_x\frac{\rho_s}{\rho_{cz}}-\frac{2\pi\mu d_o}{V\sqrt{\rho_{cz}\rho_s}}\right)} \tag{15}$$

- a change in the velocity value $d\vartheta$ moves on the distance which is equal to the dimension of an emulgated particle of the scattered phase, for a smooth process:

$$\frac{d\vartheta}{dx}=\frac{\vartheta_{cz}-\vartheta_s}{d_{cz}} \tag{16}$$

then:

$$d_{cz}=\frac{8\sigma+2\mu\varphi\left(\sqrt{\frac{2p}{\rho_{cz}}}-\sqrt{\frac{2p}{\rho_s}}\right)}{C_x\rho_s p\varphi^2\left(\frac{1}{\rho_{cz}}+\frac{1}{\rho_s}-\frac{2}{\sqrt{\rho_{cz}\rho_s}}\right)} \tag{17}$$

and for a rapid process:

$$\frac{d\vartheta}{dx}=\frac{\vartheta_{cz}}{d_{cz}} \tag{18}$$

then:

$$d_{cz}=\frac{2\rho_{cz}\left(4\sigma+\mu\varphi\sqrt{\frac{2p}{\rho_{cz}}}\right)}{C_x\rho_s p\varphi^2} \tag{19}$$

- a change in the velocity value $d\vartheta$ occurs at the distance which is equal to a half of the emulgated particle dimension, for a smooth process:

$$\frac{d\vartheta}{dx}=\frac{2(\vartheta_{cz}-\vartheta_s)}{d_{cz}} \tag{20}$$

then:

$$d_{cz}=\frac{8\sigma+4\mu\varphi\left(\sqrt{\frac{2p}{\rho_{cz}}}-\sqrt{\frac{2p}{\rho_s}}\right)}{C_x\rho_s p\varphi^2\left(\frac{1}{\rho_{cz}}+\frac{1}{\rho_s}-\frac{2}{\sqrt{\rho_{cz}\rho_s}}\right)} \tag{21}$$

and for a rapid process:

$$\frac{d\vartheta}{dx}=\frac{2\vartheta_{cz}}{d_{cz}} \tag{22}$$

then:

$$d_{cz}=\frac{4\rho_{cz}\left(2\sigma+\mu\varphi\sqrt{\frac{2p}{\rho_{cz}}}\right)}{C_x\rho_s p\varphi^2} \tag{23}$$

- a change in the velocity value $d\vartheta$ occurs at the distance which is equal to the double dimension of the emulgated particle, for a smooth process:

$$\frac{d\vartheta}{dx}=\frac{\vartheta_{cz}-\vartheta_s}{2d_{cz}} \tag{24}$$

then:

$$d_{cz}=\frac{8\sigma+\mu\varphi\left(\sqrt{\frac{2p}{\rho_{cz}}}-\sqrt{\frac{2p}{\rho_s}}\right)}{C_x\rho_s p\varphi^2\left(\frac{1}{\rho_{cz}}+\frac{1}{\rho_s}-\frac{2}{\sqrt{\rho_{cz}\rho_s}}\right)} \tag{25}$$

and for a rapid process:

$$\frac{d\vartheta}{dx}=\frac{\vartheta_{cz}}{2d_{cz}} \tag{26}$$

then:

$$d_{cz} = \frac{\rho_{cz}\left(8\sigma + \mu\varphi\sqrt{\frac{2p}{\rho_{cz}}}\right)}{C_x \rho_s p \varphi^2}. \quad (27)$$

The above Eq. (27) gave the best correlation with available results [4]:

Parameters of the analysis, which are put into the elaborated mathematical model, described by a derived theoretical Eq. (27) show that a characteristic dimension of a scattered phase particle value depends on the:

- process parameter:
  - emulgation pressure p,
  - temperature t,
- physical properties of emulsion:
  - interfacial tension σ; $\sigma = f(t)$,
  - absolute viscosity of the scattered phase μ; $\mu = f(t)$,
  - density of the scattered phase of emulsion ρ_{cz},
  - density of the continuos phase of emulsion ρ_s,
  - medium drag coefficient C_x, $C_x = f$(shape of particle, t, properties of emulsion),
- parameters of the emulgator constitution:
  - diameter of the hole of the valve seat d_o,
  - emulgator capacity V,
  - coefficient of discharge φ; $\varphi = f(\mu$ valve gap parameters).

In the above model (Eq. (27)), grinding of spheres by the walls, implosion of particles leaving the valve, their mutual collisions, etc. are not included. Its necessary to supplement mathematical models (Eq. (27)) of emulgation mechanism with experimentally assigned correction factors.

DESCRIPTION OF THE EXPERIMENT

One per cent emulsion of rape oil in water was studied. Temperature relation of the interfacial tension was studied using a method of a pendant drop.

Studies on the particle size dc as a function of pressure and temperature were carried out using an apparatus specially designed for this purpose at the Department of Food Industry Engineering of the Technical University of Lublin. The set for the measurements of emulsification pressure in a high-pressure chamber consists of a PM-250/0-25 MPa - type tensiometric pressure sensor, a MTS-03 tensiometric DC bridge, a V-540 digital voltmeter, and a X-Y recorder. The temperature measurement set consists of a TTFe (Fe-Co) thermoelectric sensor, a MTS-03 tensiometric DC bridge, a 0°C temperature standard, a V-540 digital voltmeter, and a X-Y recorder [4].

The value of d_{cz} was determined by means of a microscopic method at a 900x magnification, according to the Polish Standard PN/75-A-86059.

RESULTS AND DISCUSSION

The experimentally determined relation between particle size d_{cz} and pressure and temperature of emulsification are plotted in Fig.3.

The analysis shows, that experimental data coincide with theoretical calculation at 60 °C, but this is not the case for 20 and 40 °C.

As a result of testing emulsion of rape oil and water a verified theoretical-experimental model of the emulsification process was elaborated and described by an equation:

$$d_{cz} = \frac{2\rho_{cz}\left(4\sigma + \frac{\mu\varphi}{k}\sqrt{\frac{2p}{\rho_{cz}}}\right)}{C_x \rho_s p \varphi^2} \quad (28)$$

where: k - correction factor ($k = 5.12 - 0.052t$ for the studied emulsion).

Experimentally assigned relation $k = f(t)$ for rape oil and water emulsion can be used to analyse other emulsions containing water and different oils with similar parameters.

It was found out, that in the whole range of the tests, i.e., at pressure 0.5-16 MPa and temperature 20-60 °C (Fig. 4) the mathematical description presented is very accurately conforming with the results of experimental tests.

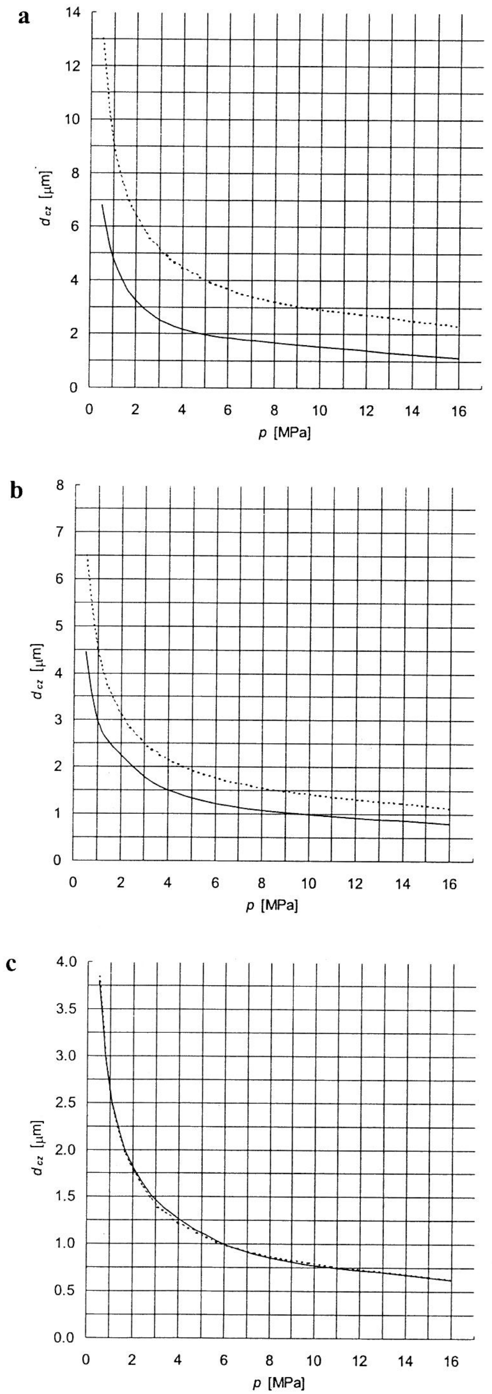

Fig. 3. Experimentally determined relation between particle size d_{cz} and pressure and temperature of emulsification - solid lines, dashed lines calculated from Eq. (27), for the following temperatures: a) 20, b) 40, and c) 60 °C.

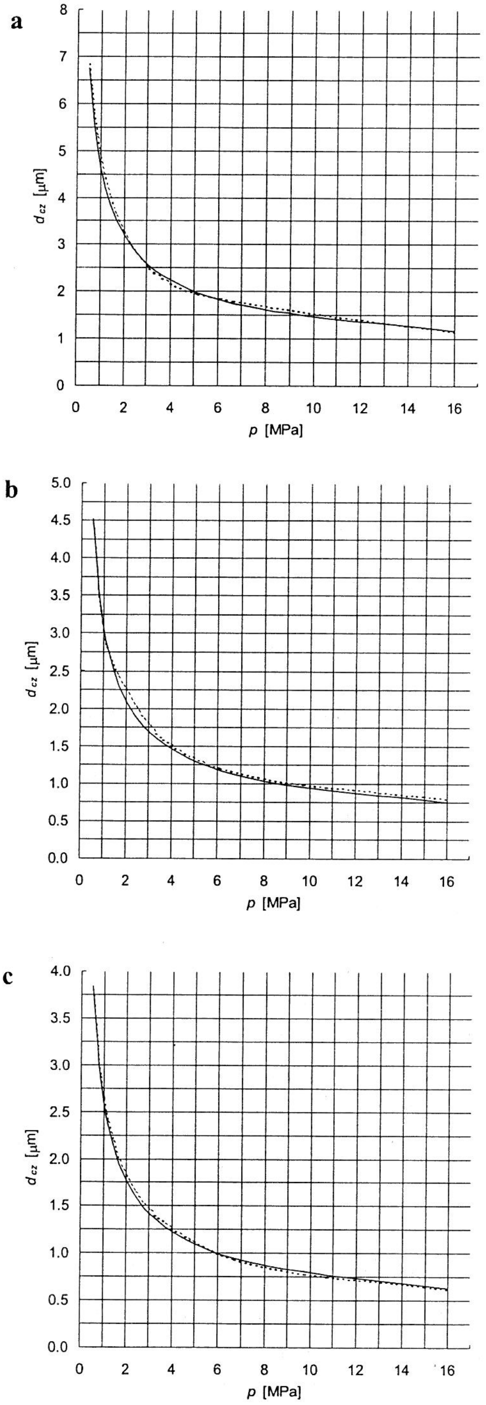

Fig. 4. Relation between particle size d_{cz} and pressure and temperature of emulsification calculated from Eq. (28) - solid lines, dashed lines - experimentally determined for the following temperatures: a) 20, b) 40, and c) 60 °C.

CONCLUSIONS

The above physical interpretation and the following theoretical and empirical model of the mechanism of comminution of emulsion make it possible to visualise the effect of the main process parameters, especially of pressure and temperature and of properties of the dispersed phase - coefficient of dynamic viscosity, interfacial tension, and density on the particle size of the dispersed phase in the studied oil-in-water emulsion. This mathematical model makes it possible to determine the pressure necessary to homogenise the emulsion and, thus to determine the proper construction and working parameters of an emulsifier.

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