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APPLICATIONS OF PRESSURE EMULSIFICATION MODEL

A mathematical model, created for description of the mechanism of interaction between basic parameters of high pressure dispersion of emulsions, is presented in this paper. The model is applied for the analysis of the influence of physical properties of emulsions, quantitative content of dispersed emulsion phase and parameters of emulsification, pressure and temperature, on the characteristic dimension of particles of the dispersed phase. The model makes it possible to determine appropriate process parameters, especially the pressure necessary to obtain the required dispersion of the emulsion and to define construction and exploitation parameters of high-pressure emulsification valve.

NOMENCLATURE

C_x – aerodynamic resistance coefficient,
D – valve diameter, m,
d_{cz} – characteristic dimension of dispersed-phase particles, m,
d_0 – valve seat orifice diameter, m,
h – valve gap height, m,
k_{Sv} – coefficient dependent on concentration of the dispersed phase,
k_t – emulsifying temperature coefficient,
l – valve gap length, m,
N – power necessary for emulsifier, W,
p – emulsification pressure, Pa,
p_0 – pressure at the entrance to the valve seat orifice, Pa,
p_1 – pressure at the valve seat orifice outlet, Pa,

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S_v	–	concentration of the dispersed phase, %,
t	–	process temperature, °C,
V	–	emulsifier efficiency, m^3s^{-1},
υ_0	–	fluid flow velocity at the entrance to the valve seat orifice, ms^{-1},
υ_1	–	fluid velocity at the valve seat orifice outlet, ms^{-1},
η	–	mechanical efficiency coefficient,
φ	–	capacity effectiveness coefficient,
μ	–	absolute viscosity coefficient of dispersed phase of emulsion, Pas,
ρ_{cz}	–	density of the dispersed phase, kgm^{-3},
ρ_s	–	density of the continuous phase, kgm^{-3},
σ	–	interfacial tension, Nm^{-1}.

1. Introduction

Emulsions are produced or processed in various industries such as food, pharmaceutical, cosmetic, chemical or petrochemical industry [1÷3, 15÷18, 27, 29]. For example, the use of emulsions in the food industry, in applications such as production of homogenized milk [2, 3, 9, 25, 26, 30], cream [2, 4, 26], ice-cream [5] or mayonnaise, increases the bioavailability and improves the taste of end products [25, 30]. In pharmaceutical industry, emulsification is used to scatter the dispersed phase of products appearing in the form of ointments, oily emulsion, oil-based vaccines, whereas in the cosmetic industry, emulsification is utilized during production of creams, shampoos, polishes, soaps, bleaches etc., thus allowing significant improvement of the performance of dispersed components. In the chemical industry (paints, oils or glues), emulsification accelerates reactions due to enhanced homogeneity of the used products. In the petroleum industry, emulsification is used, for example, to improve the parameters of heavy fuels. Recently, research efforts have been addressed to exploit various vegetable oils as renewable ecological fuel [10, 33], and to search for the possibilities of creating such emulsions.

Emulsification is a process allowing dispersion of particles of the scattered emulsion phase. Their number usually increases about 200 to 500-fold, and their total area increases 6–8-fold [6, 7, 16, 21, 23, 24, 28]. This process is highly energy-consuming, because of the necessity to use specified temperature range and high pressures (e.g. for the water oil emulsion, temperature 20–60°C and pressure up to 20 MPa) required for proper functioning of pressure emulsifier. The efficiency of emulsifiers is very high (up to 0.01 m^3/s). The emulsifier power ranges from 10 kW, corresponding to an efficiency of 0.0005m^3/s, to approximately 200 kW corresponding to an efficiency of 0.01m^3/s [16, 20].

Pressure emulsification involves scattering of the particles of a dispersed emulsion during its high-speed flow through narrow gap between the valve and the valve seat (Fig. 1) [14, 16, 18, 19, 25]. Determination of the features of dispersing module of a pressure emulsifier necessary for determining basic construction parameters, such as valve seat orifice diameter d_0 and gap height h (Fig. 1), is based on the required value of characteristic particle dimension d_{cz}, efficiency of emulsifier V and parameters of emulsion ingredients [8, 12, 13, 20, 24, 31, 32].

The emulsifying valve is a key element, essentially contributing to the process of pressure emulsification. Therefore, it is necessary to optimize the procedure for the calculation of construction parameters of emulsifying valves in order to attain dispersion level of scattered emulsion phase at a required efficiency and with the lowest energy consumption.

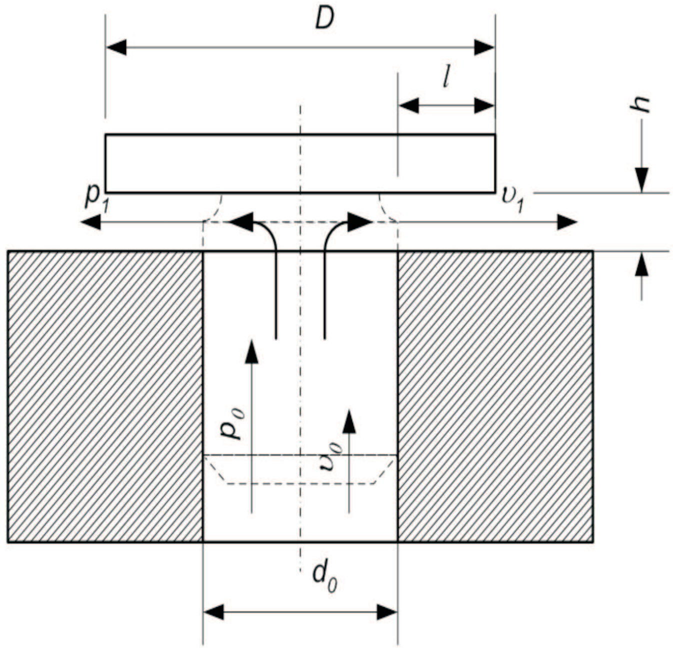

Fig. 1. Pressure emulsifying valve D – valve diameter, d_0 – valve seat orifice diameter, υ_0 – fluid flow velocity at the entrance to the valve seat orifice, p_0 – pressure at the entrance to the valve seat orifice, υ_1 – fluid flow velocity at the valve seat orifice outlet, p_1 – pressure at the valve seat orifice outlet, h – gap height, l – gap length

2. Mathematical model of pressure emulsification

The mathematical model of pressure emulsification, formulated by the author [14÷19, 22], is based on the assumption that during emulsification the basic parameters are: the characteristic dimension d_{cz} of dispersed-phase particles, the absolute viscosity coefficient μ of dispersed phase of the emulsion, the densities ρ_{cz} and ρ_s of the dispersed and continuous phases, respectively, the emulsification pressure p, the interfacial tension σ, the aerodynamic resistance coefficient C_x, and the capacity effectiveness coefficient φ. The parameters μ, σ, ρ_{cz} and ρ_s are functions of process temperature t. The final expression of the model relating the characteristic dimension d_{cz} of dispersed-phase particles to the concentration S_v of the dispersed phase is given in the form:

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

Determination of the best parameters of an emulsion, especially determining the level of emulsified phase dispersion, is essential for the optimization of a production process and for establishing the emulsion content. This allows one to establish a correlation between the construction parameters of the emulsifying valve, emulsion parameters such as physical properties of emulsion and percentage share of the phase of dispersed emulsion, and emulsification parameters, for example pressure and temperature. This procedure forms the basis for the process of increasing the effectiveness of designing the working elements of pressure emulsifiers.

3. Experimental results

Oil-in-water emulsions containing 1, 1.8, 9, 12 or 18% of dispersed phase were selected for this study. The densities of the constant phase, the densities of the dispersed phase, the dynamic viscosity and the interfacial tension of the emulsions as a function of temperature are as follows:

ρ_{cz} [kg/m^3] = 921.4945−0.6054 t;
ρ_s [kg/m^3] = 1000.8871−0.0598 t−0.0039 t^2;
μ [Pa·s] = 0.158−0.0043 t+3.375E−5 t^2;
φ = 0.9753−4.6604E−9 p+ 8.5897E−18 p^2;
σ [N/m^3] = 0.0239321−0.0000905 t+ 0.0000002 t^2.

Investigations of the impact of pressure, temperature and contents of the dispersed phase in emulsion on the value of the characteristic dimension d_{cz} of particles in the dispersed emulsion phase were conducted by means of the apparatus, shown in Fig. 2, built at the Lublin University of Technology [25]. Author used the pressure emulsifier CHO-03M (efficiency up to $8.61 \cdot 10^{-5}$ m^3/s) produced in FMiUPS in Bełżyce, equipped with a one-step emulsifying head and with a flat emulsifying valve (Fig. 3). The maximum working pressure of the emulsifier was 16 MPa.

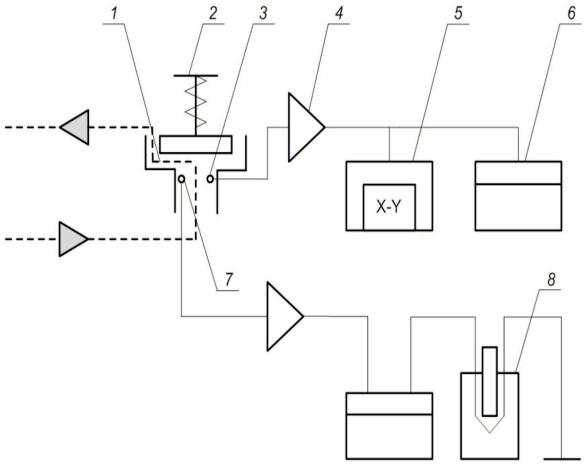

Fig. 2. Outline of the apparatus for investigations of influence of parameters of emulsifying pressure, pressure, temperature and contents of the dispersed phase in emulsion on the value of the characteristic dimension d_{cz} of particles of dispersed phase 1 – gap between the valve and the valve seat, 2 – knob of the pressure control of emulsifying, 3 – tensometric sensor of the pressure PM– 250 type / 0 – 25 MPa, 4 – permanent-power-driven small tensometric bridge MTS-03 type, 5 – X-Y recorder, 6 – digital voltmeter V– 540 type, 7 – thermoelectric TTFe sensor (Fe-Co), 8 – standard of temperature 0°C water – ice

The results of investigations presented here indicate that the value of the characteristic dimension d_{cz} of dispersed-phase particles decreases with an increase in the emulsifying pressure p. The value of the characteristic dimension d_{cz} of the particles also decreases with an increase in the emulsifying temperature t. However, the value of the characteristic dimension d_{cz} increases when the fraction S_v of the dispersed phase increases. For example, in the case of emulsion containing 9% of the dispersed phase at t = 40°C, an increase in the emulsifying pressure p from 4 MPa to 8 MPa (Fig. 4) leads to a decrease in the value of the characteristic dimension d_{cz} of the particles from 1.57 μm to 1.13 μm. However, at the pressure p = 4 MPa, an increase in the process temperature t from 20°C to 60°C decreases the value of the characteristic dimension d_{cz} of the particles from 2.17 μm to 1.22 μm.

Figure 5 demonstrates the relationship between characteristic dimension d_{cz} of dispersed-phase particles and dispersed-phase content S_v in the emulsion for different emulsifying pressures p at emulsifying temperature t = 20°C. The value of characteristic dimension d_{cz} of dispersed-phase

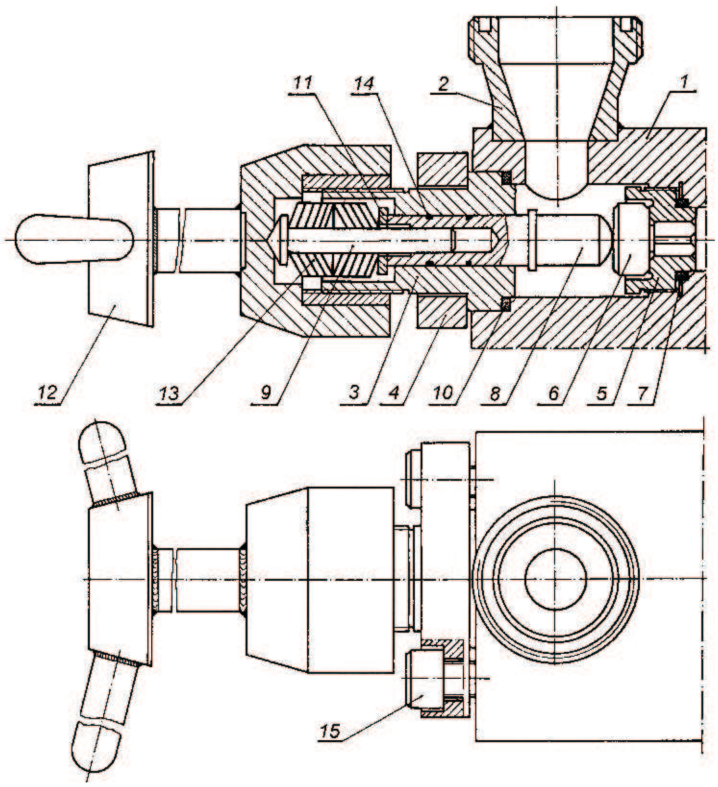

Fig. 3. Construction of emulsifying head of pressure emulsifier CHO- 03 M [11] 1 – body of the block, 2 – outlet connector pipe, 3 – running unit, 4 – fixing plate, 5 – valve seat, 6 – valve, 7 – seal, 8 – piston, 9 – tappet, 10 – seal of the unit, 11 – pad of the spring, 12 – knob, 13 – spring, 14 – sealing ring, 15 – fixing screw

particles decreases with an increase in emulsifying pressure. The value of characteristic dimension d_{cz} of dispersed-phase particles also decreases with increasing temperature of the process. Moreover, the value of characteristic dimension d_{cz} increases when the fraction of dispersed phase in the emulsion increases.

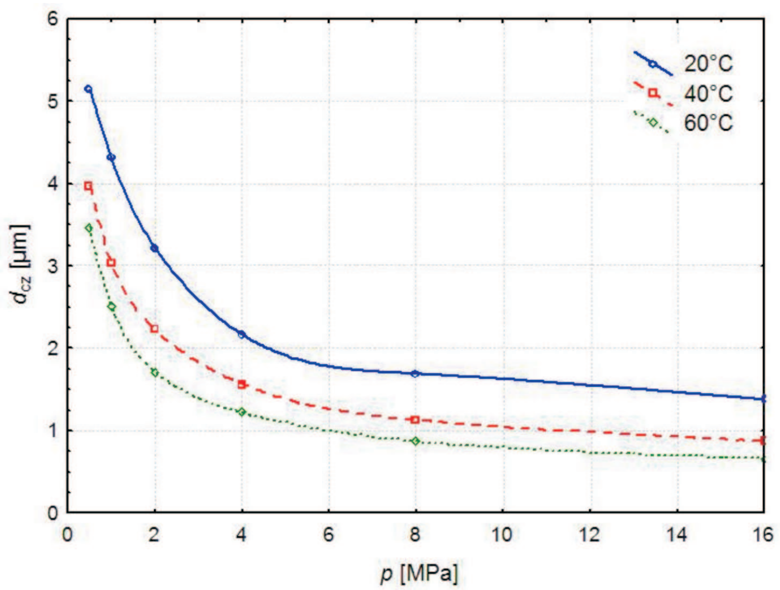

Fig. 4. Dependence of characteristic dimension d_{cz} of dispersed-phase particles on emulsifying pressure p. Data are shown for S_v = 9% of dispersed phase. Temperatures of emulsifying are: t = 20, 40 and 60°C

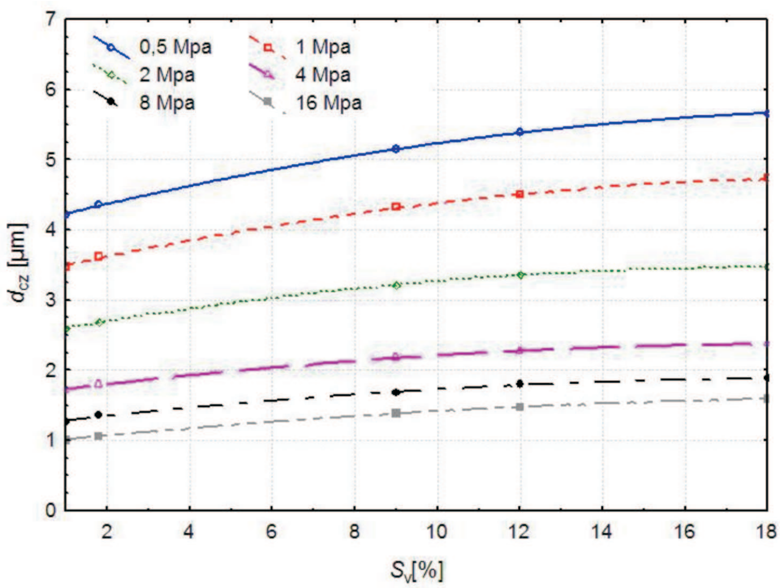

Fig. 5. Relationship between characteristic dimension d_{cz} of dispersed-phase particles and dispersed-phase content S_v in emulsion. Emulsifying temperature t = 20°C, and emulsifying pressures p = 0.5, 1, 2, 4, 8 and 16 MPa

4. Discussion

Equation 1, based on the mathematical model described above for the mechanism of pressure emulsification, was used to analyze the experimental data. The data can be described by the following generalized equation:

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

where:
$k_{Sv} = \square(S_v)$
$k_t = 6.3775 - 0.046t + 8.748\text{ E } -5t^2$
$k_{Sv} = 0.9529 + 0.0594S_v - 0.0013S_v^2$
One can rewrite the above equation in the form:

$$p = \frac{4\rho_{cz}k_{S_v}\left(\mu^2/4 + 2\sigma d_{cz}C_x\rho_s/k_{S_v} + \frac{\mu}{2}\sqrt{\mu^2/4 + 4\sigma d_{cz}C_x\rho_s/k_{S_v}}\right)}{d_{cz}^2 C_x^2\rho_s^2\varphi^2} \tag{3}$$

Eq. (3) may be used to calculate the emulsifying pressure p necessary to obtain the required value of the characteristic dimension d_{cz} for dispersed-phase particles. The diameter d_0 of the orifice in the valve seat, necessary to obtain the required characteristic dimension d_{cz} of dispersed-phase particles and to achieve the assumed efficiency V of the emulsifier, can be calculated from the relation [11, 21]:

$$d_0 = 0,00257\frac{V^4\sigma^3}{d_{cz}^3\phi^6\nu^4 p^3} \tag{4}$$

The height h of the emulsifying valve gap is given by [11, 25]:

$$h = \frac{V}{\pi d_0\phi\sqrt{2gp/\gamma}} \tag{5}$$

The power N necessary for the pressure emulsifier to work is calculated from the relation [11, 25]:

$$N = \frac{Vp_0}{\eta}, \quad W \tag{6}$$

where:
η – mechanical efficiency coefficient, $\eta = 0.75$

As an illustration of the application of the above approach, we consider the case of a desired characteristic dimension $d_{cz} = 2$ μm of dispersed-phase particles containing 2% of the dispersed phase, at efficiency of the emulsifier V = 0.003 m^3/s and the temperature of emulsifying t = 40°C. These parameters require an emulsifying valve (Fig. 6, 7) with the diameter d_0 of opening in the valve seat equal to 16 mm and the working pressure p = 1.9 MPa. Experimental tests used to verify the above procedure revealed that, in this specific case of emulsification, at t = 40°C and p = 1.9 MPa, the value of the characteristic dimension d_{cz} of dispersed-phase particles was 1.98 µm, the efficiency V = 0.00298 m^3/s and the power necessary for the emulsifier N = 7.58 kW. The characteristics that define the construction-exploitation parameters of the emulsifying valve and determine the power demand of the emulsifier necessary for scattering of the dispersed-phase particles are presented in Fig. 8.

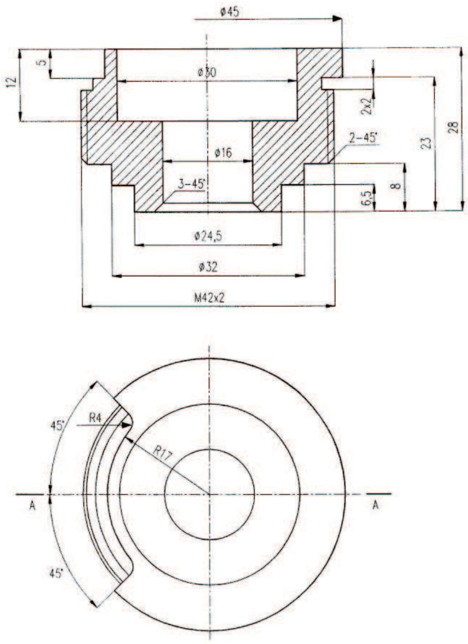

Fig. 6. Emulsifying valve seat

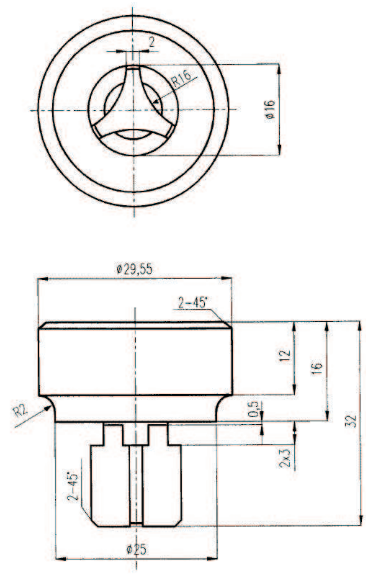

Fig. 7. Emulsifying valve

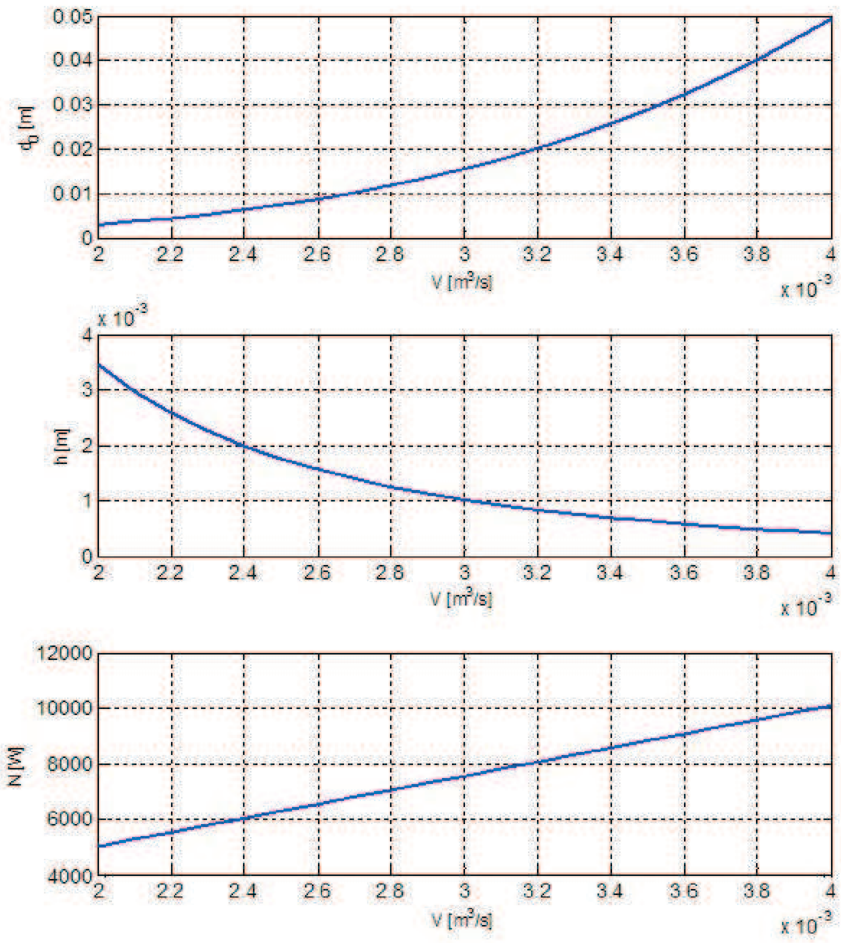

Fig. 8. Characteristics of establishing construction-exploitation parameters of emulsifying valve and determining the power demand of the emulsifier necessary for scattering of the dispersed-phase particles

5. Conclusions

1. The results presented above, including consideration of the biphasic interactions between the basic parameters of emulsifying process and the fraction of the dispersed phase in emulsion, could be the basis for setting guidelines for effective realization of pressure-emulsifying process in the range of the studied parameters.
2. The pressure emulsification model, developed and verified here, demonstrates the relationship among the working characteristics of structural elements of an emulsifier, the basic process parameters, the properties of

emulsion, the content of dispersed phase in the emulsion and the necessary value of the characteristic dimension of dispersed-phase particles.

3. The model of emulsification process and the results of analysis of the experimental results make it possible to establish and verify the parameters of an emulsifying valve, which are required to obtain a desired value of the characteristic dimension of dispersed-phase particles within a defined range of process efficiency, applied pressure and temperature. This model provides grounds for eliminating the most detailed and expensive phase of designing the process of pressure emulsification via experimental estimation of the relationship between the characteristic dimension of dispersed-phase particles and the emulsification parameters.

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Aplikacje modelu ciśnieniowego wytwarzania emulsji

S t r e s z c z e n i e

Opracowany przez autora mechanizm współoddziaływania podstawowych parametrów procesu ciśnieniowego rozpraszania emulsji, fizycznych właściwości emulsji, ilościowego udziału fazy rozproszonej emulsji oraz parametrów procesu emulgowania, ciśnienia i temperatury stanowił podstawę dla sformułowania matematycznego modelu procesu uwzględniającego wpływ tych parametrów na wartość wymiaru charakterystycznego cząstek fazy rozproszonej rozpraszanej emulsji. Daje to możliwość ustalania racjonalnych parametrów procesu a w szczególności ciśnienia, niezbędnego do uzyskania wymaganego rozproszenia emulsji oraz określanie parametrów konstrukcyjnych i eksploatacyjnych wysokociśnieniowych zaworów emulgujących.