

**THE STUDY ON OIL DROPLET SIZE DISTRIBUTION
IN O/W EMULSIONS PREPARED
BY THE USE OF THE ASYMMETRIC MEMBRANE***

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Key words: membrane emulsification, oil droplet size distribution, milk protein concentrate, whey protein concentrate.

A b s t r a c t

This paper analyses the impact of two types of emulsifiers originating from milk: milk protein concentrate (MPC) and whey protein concentrate (WPC), on droplet size distribution using an asymmetric membrane process. The results indicated that the size, span and uniformity of oil droplets in emulsions depend on the velocity of shear stress on the internal surface of a membrane channel and on the physical and chemical parameters of the medium used as an emulsifier. The use of WPC produced an emulsion with optimum (the lowest) parameters of oil droplet size distribution. Switching from WPC to MPC resulted in an increase in the average characteristic diameter of the emulsion droplets and simultaneously caused widening of the distribution and a reduction in the uniformity index.

**STUDIA NAD ROZKŁADEM WIELKOŚCI KULECZEK TŁUSZCZOWYCH EMULSJI
TYPU O/W OTRZYMANÝCH Z WYKORZYSTANIEM MEMBRAN ASYMETRYCZNYCH**

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Słowa kluczowe: emulgowanie membranowe, rozkład wielkości kuleczek tłuszczowych, koncentrat białek mleka, koncentrat białek serwatkowych.

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Abstrakt

W publikacji analizowano wpływ dwóch typów emulgatorów: koncentratu białka mleka (MPC) i koncentratu białek serwatkowych (WPC) na rozkład wielkości kuleczek tłuszczowych w emulsjach uzyskanych z wykorzystaniem membran asymetrycznych. Wielkość kuleczek tłuszczowych, równomierność i ich rozstęp w emulsjach uzyskanych metodą membranową najbardziej zależą od prędkości zmian naprężeń na powierzchni wewnętrznej kanałów membrany oraz właściwości fizycznych i chemicznych medium wykorzystywanego jako emulgator. Zastosowanie WPC pozwoliło na otrzymanie emulsji charakteryzującej się optymalnymi (najmniejszymi) parametrami rozkładu wielkości kuleczek tłuszczowych. Zmiana WPC na MPC spowodowała wzrost wielkości średnic średnic charakteryzujących daną emulsję oraz zwiększenie zakresu zmienności rozmiaru kuleczek tłuszczowych emulsji oraz redukcję indeksu równomierności.

Introduction

Emulsions are heterogeneous dispersive systems that are composed of several phases: a continuous phase and one or several phases that are dispersed in it. They are widely used in different industrial branches, such as the pharmaceutical, cosmetic, petrochemical, agricultural and food industries. In the majority of applications it is attempted to obtain an average size of droplets in the dispersed phase of below 1 μm and to achieve the highest uniformity of the dispersed phase possible (URBAN et al. 2006). A smaller size of droplets in the dispersed phase has an impact on the optical properties of a produced emulsion such as clarity and colour (LEE et al. 2013). In the case of emulsions in which the dispersed phase contains biologically active compounds, the average size of particles impacts their bioavailability (SCHUCHMANN and SCHUBERT 2003). The degree of dispersion of the dispersed phase (defined as the ratio of the surface of a dispersed phase to its volume) and droplet size distribution in the dispersed phase depend on the method and conditions of emulsification. Providing the size of droplets and their distribution that are proper for each emulsion depends on such factors as the volume of supplied mechanic energy, the type and concentration of an emulsifier, physical properties of the dispersed phase and continuous phase and physical parameters of the process itself (e.g. pressure and temperature) (MCCLEMENTS 1999). The average droplet size, the difference between the maximum and minimum diameter of droplets of the dispersed phase and the degree of their dispersion are considered as the significant parameters characterizing a given emulsion.

Physical stability is an important descriptor of an emulsion quality and it is defined as the capacity of the emulsion to maintain the same properties for a long period of time. This feature is associated with rheological properties such as viscosity, texture and lubricity. In the case of food emulsions, import-

ant features include sensory properties like colour, taste and smell. Interfacial tension at the border between the continuous and dispersed phases is one of the factors that impact the stability of an emulsion. Its reduction prevents such faults of an emulsion as coalescence, flocculation or inversion of the phases. In an emulsion, superficially active substances of an amphiphilic nature selected based on the substrates forming an emulsion are responsible for the interfacial tension at the border between the phases (BEROT et al. 2003). In the food industry, this role is most often taken by amphiphilic macromolecules such as proteins. Proteins, as emulsifiers, allow for a reduction of the surface tension and constitute a component of the macromolecular layer which is formed during emulsification process, which determines the stability of the entire arrangement (FLOURY et al. 2000). The studies on ultra-high pressure homogenization (UHPH) carried out by HEBISHY et al. (HEBISHY et al. 2013) are an example of the increase in the stability of an emulsion due to a reduction of droplet size. The reduction of droplet size during the UHPH process (over 100 MPa) produced a vegetable oil emulsion with similar viscosity to an emulsion produced with a colloidal mill. The droplet size was, however, smaller, which resulted in an increase in protein concentration on the surface of dispersed molecules and effectively prevented coalescence of lipid droplets (HEBISHY et al. 2013).

The properties of an emulsifier have an impact on the average size of the dispersed phase. Petersen and Ulrich (2013) compared the size of droplets in an emulsion produced with maize oil with low-molecular emulsifiers: Polysorbate 20 and sodium caseinate. The use of Polysorbate 20 contributed towards a smaller size of droplets and higher stability of the produced emulsion.

During production of emulsions in emulsifying machines, droplets of the dispersed phase are formed as a result of supplying mechanical energy to the system. In food emulsions, it is most often attempted to produce a dispersed oil phase in water (o/w type emulsions) or vice-versa (w/o type emulsions). Deformation and consequent fragmentation of oil droplets in the aqueous phase also occur during such processes as mixing, pumping, spraying or extruding under conditions of both laminar and stormy flow (WINDHAB et al. 2005).

In order to produce an emulsion with a proper size of droplets in the dispersed phase, high-pressure homogenizers, rotor-stator machines, membrane techniques and ultrasound homogenizers are used (SCHUCHMANN and SCHUBERT 2003, SCHULTZ et al. 2004, URBAN et al. 2006). The correlation between the size of droplets in the dispersed phase and the method of emulsification was demonstrated by SIDDIQUI (2011). The author compared the average size of droplets of sunflower oil in an emulsion produced with soy lecithin as an emulsifier that was dispersed in a high-pressure homogenizer,

a silverson rotor-stator device and a silverson impinging jet and an ultrasonic device (SIDDIQUI 2011). The smallest average size of droplets in the dispersed phase (3 μm) was detected in the emulsions produced with a high-pressure homogenizer. Emulsifying in an ultrasonic device generated the emulsion with the size of droplets between 3 and 10 μm . A similar range of variability (from 4 to 15 μm) was produced with an impinging jet system, whereas the largest droplets (15 to 45 μm) were detected in the emulsions homogenized in a silverson rotor-stator device (SIDDIQUI 2011). In their publication, PERRIER-CORNET and GERVAIS (2005) also demonstrated that the size of droplets in an emulsion and its homogeneity depended on the method of emulsification. The use of a high-pressure jet generates smaller particles, yet with lower uniformity than the emulsion produced with a micro-fluidizer. According to those authors, a nature of the flow generated at the spot of jet decompression could have a strong impact on the shape of a curve depicting the volume distribution of the tested droplets (PERRIER-CORNET and GERVAIS 2005).

Membrane techniques are gaining increasing popularity as emulsifying modalities (VAN DER GRAAF 2005, CHARCOSSET 2009, HEBISHY et al. 2013). During emulsification with membranes, different mechanisms of droplet formation in the dispersed phase are involved than with the above methods. The phase that is dispersed is pushed through the pores in a membrane to the continuous phase flowing along the surface of a membrane. At the ends of the pore tubules, droplets of the dispersed phase are formed and thrown by shear stress into the liquid flowing along a membrane (CHARCOSSET et al. 2004). According to many authors, there is a close relationship between the size of pores in a membrane and the size of droplets in the dispersed phase (JOSCELYNE and TRAGÅRDH 2000, BEROT et al. 2003, NAZIR et al. 2010). The use of a membrane with a larger pore size reduces larger droplets in the dispersed phase in both oil/water (O/W) and water/oil (W/O) emulsions (NAKASHIMA et al. 2000). The distribution of droplet size in the emulsions produced with membrane techniques also depends on the speed of adsorption of an emulsifier on the surface of droplets. Berot et al. demonstrated that O/W emulsions generated with membrane techniques using protein as an emulsifier had a higher size of droplets than those produced with SDS as an emulsifier which has a higher rate of the changes in surface tension at the border of the phases (BEROT et al. 2003). Shear stresses found in the continuous phase near the surface of a membrane are an important factor determining the size distribution of the dispersed phase. According to VLADISAVLEVIC and SCHUBERT (2003), the size of a droplet generated with membrane emulsification decreases with an increase in shear stresses below 30 Pa. A further increase in the velocity of flow and, consequently, in shear stresses caused an increase in their magnitude. Further studies into optimizing the process of membrane emulsification are thus warranted.

The objective of the studies was to investigate the impact of the protein type and concentration, flow efficiency of the continuous phase and transmembrane pressure on the distribution of droplet size in the dispersed phase in rapeseed oil emulsions generated with the membrane emulsification technique.

Material and Methods

The O/W emulsions with 30% dry matter content were prepared and they contained the following components of the continuous phase: demineralized water, milk protein concentrate MPC 75 (Z.P.M. MLECZ Wolsztyn, Poland) or whey protein concentrate WPC 80 as emulsifying agents and maltodextrin N (dextrose equivalent – DE 7–13) – MLT from PEPEES JSC Starchworks Lomza. Milk protein concentrate MPC 75 and whey protein concentrate WPC 80 were chosen base on the preliminary experiments during which different types of MPC and WPC concentrate were tested. The dispersed phase was composed of refined rapeseed oil from EOL Poland. The mass fraction of oil in the dry matter of emulsion was $x = 0.3$ w/w. The other part constituted a mixture of protein concentrates and maltodextrin in the proportion of 0.3 proteins + 0.4 MLT or 0.1 proteins + 0.6 MLT depending on the experiment design (Table 1).

Table 1
Independent variables considered in the experiment design

Independent variable	Lower level “-1”	Upper level “+1”
X_1 – protein concentration in emulsion solids [w/w]	0.10	0.30
X_2 – kind of protein concentrate	MPC 75	WPC 80
X_3 – circulation flow-rate of the continuous phase [$\text{dm}^3 \text{ s}^{-1}$]	0.111	0.222
X_4 – transmembrane pressure [kPa]	300	500

The experimental emulsions were produced with a membrane emulsification technique on a post whose design is presented in Figure 1. An INSIDE CéRAM™ asymmetric, one-channel ceramic membrane with an internal diameter of 0.006 m and length 0.3 m manufactured by TAMI Industries (France), is the main component of the system. According to the specification provided by the manufacturer, the nominal diameter of pores in the membrane was 0.8 μm . The schematic diagram of the experimental setup is presented in Figure 1. Dispergation of rapeseed oil in the aqueous phase was run in the membrane module (D). During emulsification, the aqueous phase was pumped into the internal membrane channel (D) from the feed container (A) with

a two-stage circulatory pump system (*B*). The regulating valve (*H*) was used to regulate the intensity of flow of the continuous phase. Oil was pumped out of the pressure container (*E*) into the outer part of membrane module. The samples of emulsion for PSD analyses were collected through the drainage valve (*I*).

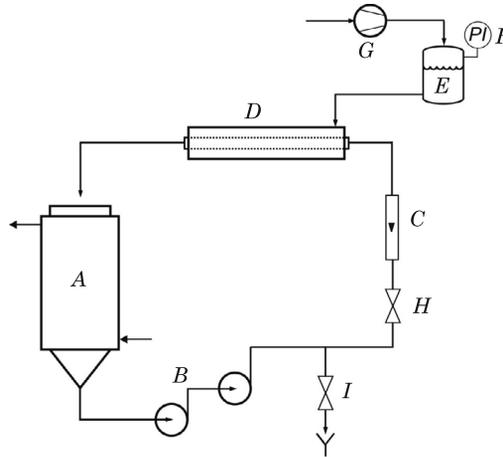


Fig. 1. Schematic diagram of the experimental setup: *A* – continuous phase supply tank with a heating/cooling coat, *B* – pump system, *C* – flowmeter, *D* – membrane module, *E* – pressurized oil tank, *F* – pressure gauge, *G* – air compressor, *H* – control valve, *I* – drainage valve

The process of emulsification was run at $30^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ (a measurement with a HI 935005 one-channel thermometer with a *K*-type probe) at the input pressures of oil pumping and jets of flow volume of the continuous phase (Table 1). The volume jet corresponded to the shearing velocity of the internal surface of membrane channel in the range of $\gamma = 3800$ to 11000 s^{-1} , which was calculated from the following equation:

$$\gamma = \frac{8u}{d} \quad (1)$$

where:

γ – shear rate [s^{-1}]

u – flow velocity [m s^{-1}],

d – diameter of the membrane channel [m].

Particle size distribution of oil droplets in the emulsions was assessed by laser diffraction analysis using a particle size analyzer *Mastersizer 2000* (*Malvern Instruments Ltd Great Britain*). The measurements resulted in a data set comprising: percentile readings of equivalent diameters: $d_{0.1}$, $d_{0.5}$, $d_{0.9}$ – i.e. diameters of the droplets at which 10, 50 or 90% of the sample is smaller

than the size measured, d_{32} – volume-surface mean diameter (so-called Sauter diameter) and d_{43} – weight-volume mean diameter. The distribution width was expressed as span value calculated as (JOSCELYNE and TRÄGÅRDH 1999):

$$Span = \frac{d_{0.9} - d_{0.1}}{d_{0.5}} \tag{2}$$

and its uniformity as the ratio:

$$\frac{\sum v_i |d(v,0.5) - d_i|}{d(v,0.5)\sum v_i} \tag{3}$$

where:

$d(v,0.5)$ is the median size of the distribution and d_i and v_i are respectively the mean diameter of, and result in, size class i (MALVERN MANUAL 2005).

These magnitudes have been analyzed as dependent variables in the full factorial experiment type 2^4 according to (MAŃCZAK 1976). The independent variables considered in the experiments are summarized in Table 2. The experiment design matrix (Table 2) was generated and analysed by the DOE module of *StatSoft, Inc.* [2011]. *STATISTICA (data analysis software system), version 10* software.

Table 2
Full factorial experiment design matrix type 2^4

Standard No. of experiment	Independent variables				Dependent variable vector y_i
	X_1	X_2	X_3	X_4	
1	-1	-1	-1	-1	y_1
2	-1	-1	-1	+1	y_2
3	-1	-1	+1	-1	y_3
4	-1	-1	+1	+1	y_4
5	-1	+1	-1	-1	y_5
6	-1	+1	-1	+1	y_6
7	-1	+1	+1	-1	y_7
8	-1	+1	+1	+1	y_8
9	+1	-1	-1	-1	y_9
10	+1	-1	-1	+1	y_{10}
11	+1	-1	+1	-1	y_{11}
12	+1	-1	+1	+1	y_{12}
13	+1	+1	-1	-1	y_{13}
14	+1	+1	-1	+1	y_{14}
15	+1	+1	+1	-1	y_{15}
16	+1	+1	+1	+1	y_{16}

Results and Discussion

The emulsions produced during the experiments contained oil droplets with diameters significantly higher than the nominal diameter of pores in the membrane (Figure 2).

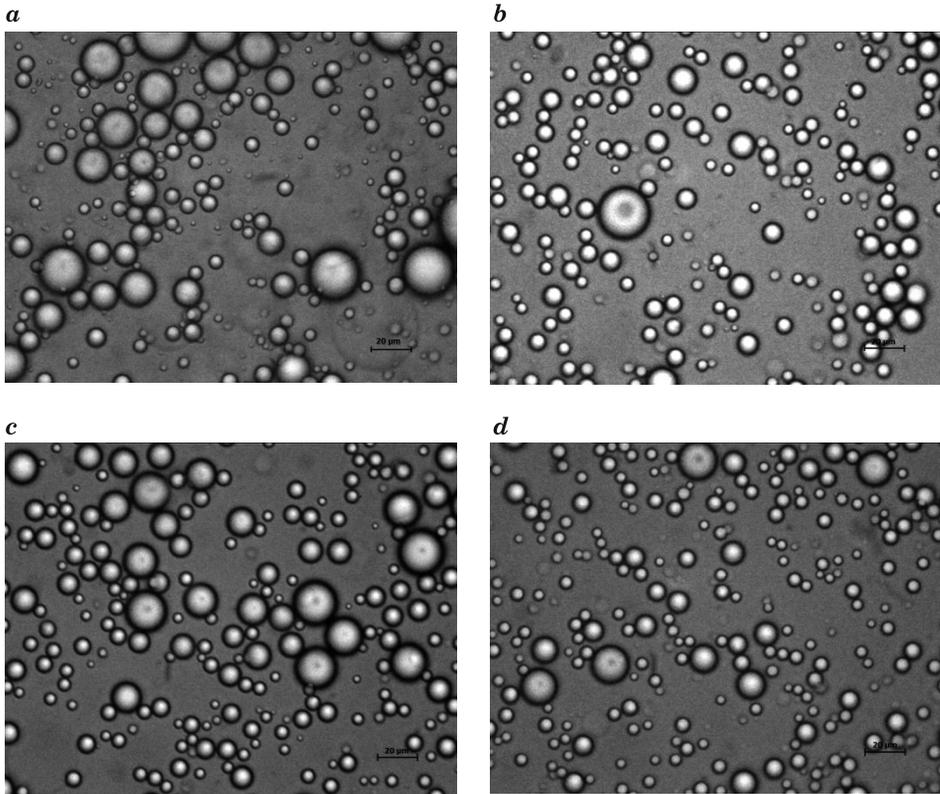


Fig. 2. Examples of emulsions; structure from experiments: *a* – no. 2; *b* – no. 4; *c* – no. 8; *d* – no. 11 (photomicrographs from light microscope taken at lens 5×40)

Although the smallest droplet size detected by laser during PSD measurements in the individual experiments ranged from 0.68 to 5.37 μm , their number in the sample was small and thus the diameter $d_{0.1}$, below which droplets constituted 10% of the volume, was 4.50–12.13 μm . Droplets of 9.87–30.04 μm represented by the size $d_{0.5}$ constituted the main fraction.

In the majority of cases, a monomodal distribution was generated (Figure 3).

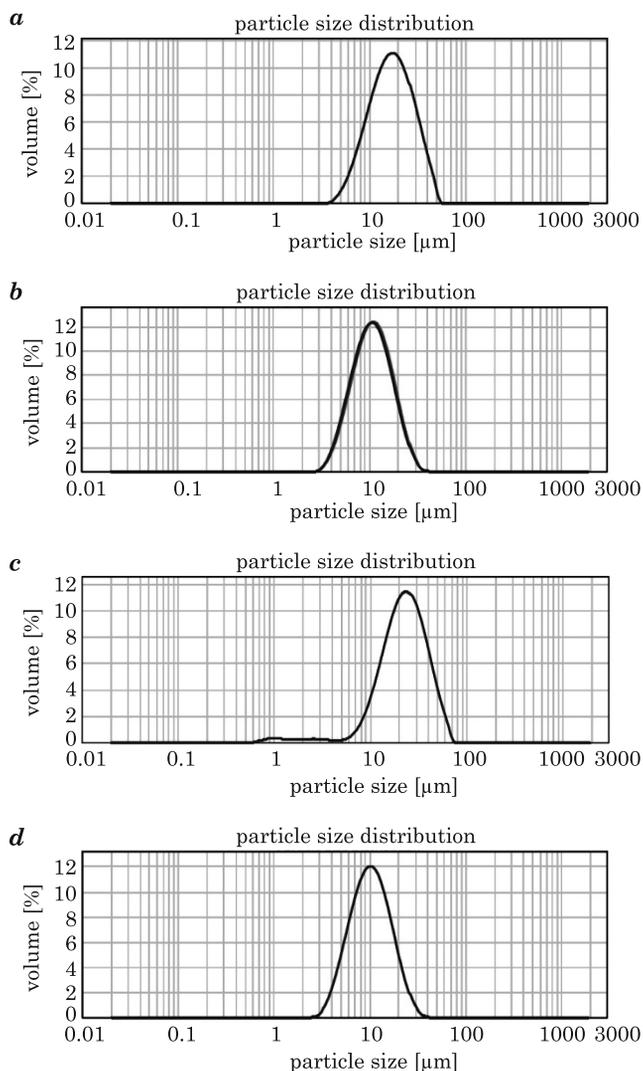


Fig. 3. Examples of particle size distribution from experiments: *a* – no. 2; *b* – no. 4; *c* – no. 8; *d* – no. 11

Only in experiments 3, 5 and 6, apart from the main fraction of droplets with a diameter of 3-50 μm , was the second weak peak observed and it corresponded to the presence of droplets with diameters over 50 μm . The general characteristics of variability in the results of droplet size distribution measurements in the produced emulsions are presented in Table 3.

Table 3

Overall variability characteristics of oil droplet size distribution in the emulsions

Dependent variable	Droplet diameter d [μm]				Variability coefficient $v(y)\%$
	min	max	average	standard deviation $s(y)$	
$d_{0,1}$	4.50	12.13	7.71	2.21	28.7
$d_{0,5}$	9.87	30.04	16.97	6.06	35.7
$d_{0,9}$	18.53	125.84	40.32	26.36	65.4
d_{32}	8.49	25.13	13.36	4.27	31.9
d_{43}	11.33	51.55	21.81	10.43	47.8
<i>Span</i>	1.033	3.785	1.783	0.674	37.8
<i>Uniformity</i>	0.321	1.120	0.601	0.223	37.1

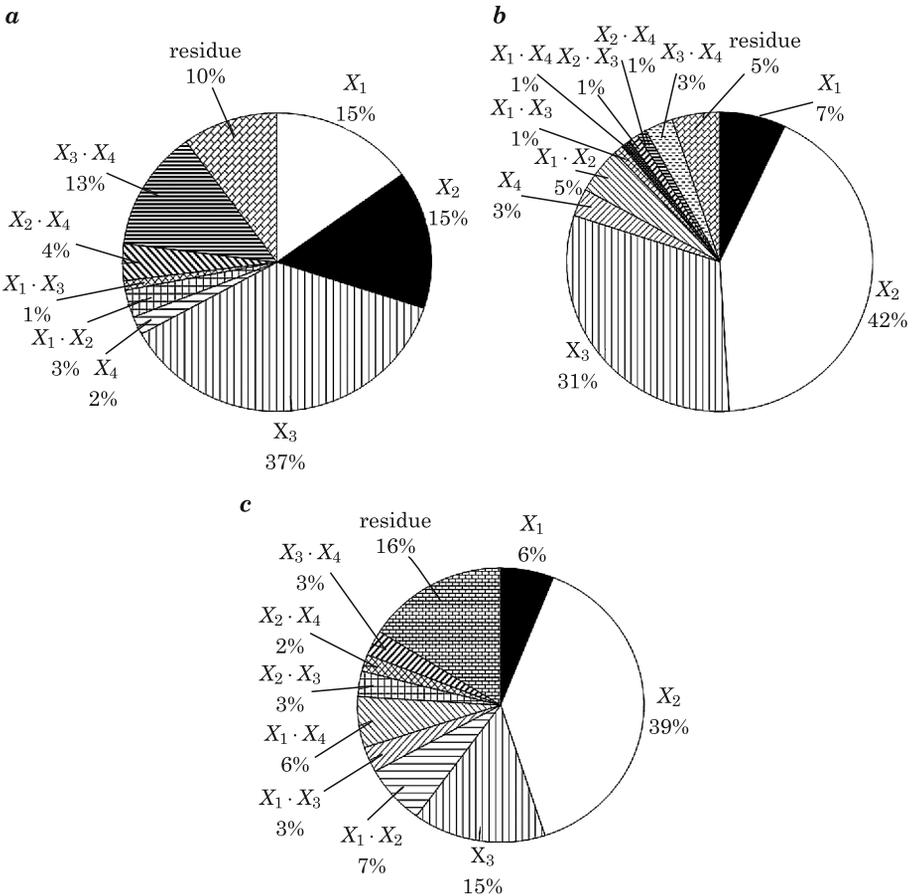


Fig. 4. The results of the variance analysis of “percentile” diameters of oil droplets expressed as percentage of total sum of squares explained by the particular effects: a – $d_{0,1}$; b – $d_{0,5}$, c – $d_{0,9}$

Both the presence of small diameter droplets and large droplets ($d_{0.9}$) in the emulsions resulted in varied parameters describing the span and uniformity of size distribution (Table 3). This variability could have been caused by the changes of initial sizes in a two-factor experiment (Tables 1 and Table 2), which is indicated by the analysis of variance involving all initial values in the experiment.

A graphic depiction of the results of analysis of variance carried out for the variability of percentile diameter of oil droplets is presented on Figure 4. The following factors had the greatest impact on the droplet size, defined as the percentile readings of equivalent diameters $d_{0.1}$, $d_{0.5}$, and $d_{0.9}$: protein concentration in the emulsion solids, kind of protein concentrate, and circulation flow-rate of the continuous phase. The role of these three factors in elucidating the variability of particle size distribution of the values $d_{0.1}$, $d_{0.5}$, and $d_{0.9}$ was 67%, 80% and 60%, respectively. The impact of individual process factors X_1 – X_4 and their interactions on the size of $d_{0.1}$, $d_{0.5}$, $d_{0.9}$ descriptors (Figure 4) in the tested emulsions was 90% explained (at 10% share of the residual sum of squares (SS)), 95% (at 5% residual (SS)) and 84% (at 16% residual (SS)), respectively. The interactions of independent variables did not have any significant impact on the value of individual descriptors of droplet size distribution parameters in the produced emulsions. Interaction of the independent variables had no significant effect on the value of the droplet size distribution descriptors $d_{0.1}$, $d_{0.5}$, $d_{0.9}$. For the interaction of X_1X_4 factors, it was within 0–6%, for X_1X_2 1–7%, for X_3X_4 : from 3 to 13% only for $d_{0.1}$ (Figure 4a). The impact of interactions of X_1X_3 , X_2X_3 , X_2X_4 factors on the analyzed descriptors of droplet size distribution was minor and below 5%.

A graphic depiction of the results of analysis of variance for the surface-based diameter (Sauter) d_{32} and volume-based diameter d_{43} is presented in Figure 5.

The following factors exerted the greatest impact on these values: protein concentration in the emulsion solids, the kind of protein concentrate and the circulation flow-rate of the continuous phase. The role of linear effects of all investigated process factors and their interactions on the size of Sauter's diameter (Figure 5a) and the volume-based diameter d_{43} (Figure 5b) of the tested emulsions was 87% and 90% explained, respectively. The total share of all variable conjugations that were important for d_{32} and d_{43} was 20% and 18%, respectively.

The results of a variance analysis for the variability in span and uniformity of droplet size distributions in the emulsions (generated with variable concentrations of WPC and MPC proteins), different shearing forces (resulting from varied efficiency in the flow of a liquid through the membrane channel) and variable pressure of oil supply (Figure 6), unambiguously indicate that these

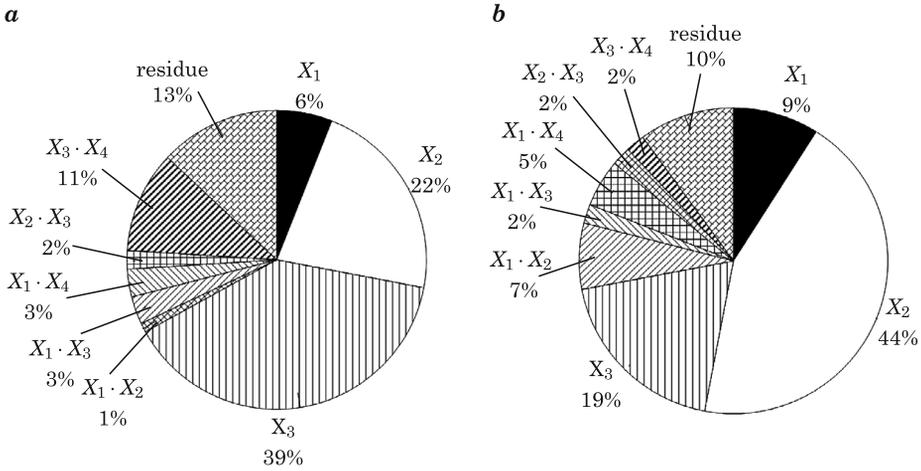


Fig. 5. The results of the variance analysis of: *a* – surface based (Sauter) diameter d_{32} ; and *b* – volume based diameter d_{43} ; explained by the particular effects under consideration

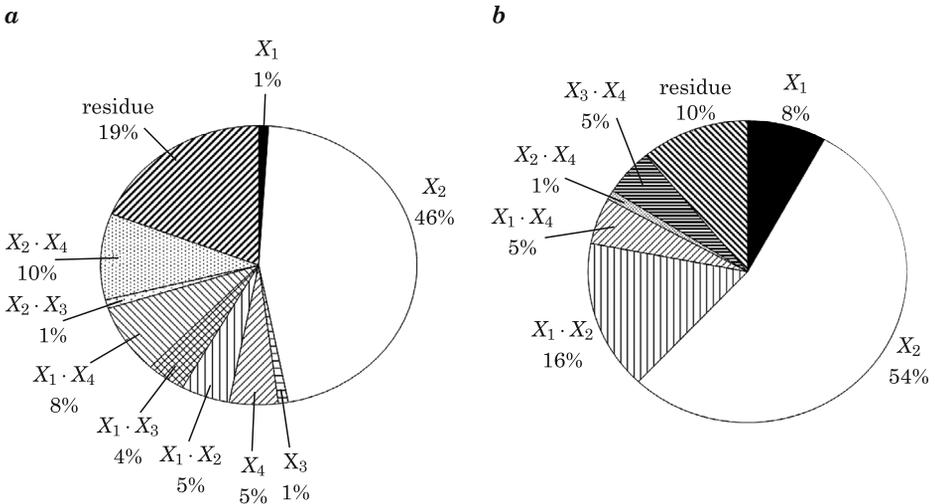


Fig. 6. The results of the variance analysis of: *a* – span of droplets size distribution; *b* – uniformity of the droplets size distribution; expressed as percentage of sum of squares explained by the particular effects under consideration

distribution features mainly depend on the type of protein used as an emulsifier (X_2). This observation is consistent with the research results of CHARON et al. (2011) and YE (2011). They used a different biopolymers as emulsifiers and received differing size distributions of droplets in emulsions produced.

The relations depicted on Figure 5 and Figure 6 are presented in more detail with the following regression equation:

$$\hat{y}_j = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_{12}X_1X_2 + B_{13}X_1X_3 + B_{14}X_1X_4 + B_{23}X_2X_3 + B_{24}X_2X_4 + B_{34}X_3X_4 \tag{4}$$

where:

- \hat{y}_j – denotes the estimated dependent variable
- X_i – standardized independent variable
- B_0 – is the average y_j value in the experiment
- B_{1-4} – are the linear regression coefficients for independent variables
- B_{12-34} – are the regression coefficients for the interactions of independent variables.

Numerical values of regression coefficients are collected in Table 4.

Table 4

Regression coefficients in the equation (4)

Variable		Droplet diameter d [μm]					Span	Uniformity
		$d_{0.1}$	$d_{0.5}$	$d_{0.9}$	d_{32}	d_{43}		
Coefficients	X_0	7.712*	16.967*	40.316*	13.357*	21.814*	1.783*	0.600*
	X_1	-0.842*	-1.591*	-6.390	-0.998	-3.028	-0.129	-0.038
	X_2	0.833*	3.787*	15.728*	1.959*	6.702*	0.880*	0.142*
	X_3	-1.293*	-3.263*	-9.845	-2.565*	-4.366*	-0.155	0.001
	X_4	0.322	1.093	-1.741	0.109	-0.009	-0.290	-0.060
	X_1X_2	-0.358	-1.315	-6.675	-0.307	-2.745	-0.286	-0.048
	X_1X_3	0.232	0.420	4.714	0.757	1.443	0.245	0.018
	X_1X_4	0.074	0.581	6.129	0.659	2.159	0.376	0.075
	X_2X_3	0.011	-0.494	-4.768	-0.509	-1.584	-0.144	-0.023
	X_2X_4	0.439	0.623	-3.297	0.177	-0.231	-0.422	-0.045
	X_3X_4	0.768	1.059	4.536	1.400	1.522	0.031	-0.023
	R^2	0.902	0.949	0.839	0.866	0.904	0.812	0.789

* Asterisk denotes effects significant at $p = 0.05$

They correspond with the variability of independent variables within limits $\langle -1, +1 \rangle$ according to Table 1 as follows:

$$X_1 = \frac{C - 0.20}{0.10} \tag{5}$$

$$X_2 = -1 = \text{WPC} \tag{6}$$

$$X_2 = +1 = \text{MPC}$$

$$X_3 = \frac{U - 0.167}{0.10} \quad (7)$$

$$X_4 = \frac{p - 0.40}{0.10} \quad (8)$$

The results presented in (Table 4) clearly show that the most important factors influencing droplet size distributions in emulsions obtained using membrane as the dispersing system are: kind of protein used as the surface active agent and the flow-rate of the liquid in the membrane channel. Switching from WPC to MPC results in an increase of every characteristic diameter of the droplets in the emulsions and simultaneously causes widening of the distribution and a reduction in the uniformity index. It is thus concluded that the use of whey proteins in producing and stabilizing emulsions with a membrane technique is more beneficial than using total milk proteins (MPC), which is probably associated with the size of molecules or micelles in the aqueous phase and the kinetics of their adsorption on the interfacial surface (TCHOLAKOVA et al. 2004, RAYENER et al. 2005, YE 2011). Under the conditions of the conducted experiment, the investigated change of proteins in the dry matter of an emulsion had a significant impact only on diameters $d_{0.1}$ and $d_{0.5}$.

MCCARTHY et al. (2012) used whey protein concentrate (WPC-75) to stabilize sunflower o/w emulsions. They have demonstrated the relationship between the concentration of this emulsifier in the dry matter and the diameters of the emulsion formed during the emulsification of the dispersed phase. Based on results of this, researchers can be concluded that increasing the protein concentration favors the formation of small droplets of the dispersed phase.

The factor X_3 had a comparably significant impact on the size of oil droplets in the produced emulsions. This value determines the shearing velocity on the surface of a membrane, eqn. (1) and, consequently, the magnitude of shearing stresses that make oil droplets tear away from the margin of pores in a membrane (RAYNER et al. 2005).

For all analyzed dependent variables, the impact pressure at which oil was fed into an emulsion was statistically insignificant at $p = 0.05$.

The analysis of relations between all investigated diameters of oil droplets in the emulsions and the conditions of emulsification indicates that the median d_{32} and the Sauter's d_{32} and Herdan's d_{43} diameters react most strongly to the changes introduced to the parameters of the process.

Conclusions

1. The possibility of manufacturing of the o/w emulsions stabilized by milk-originated proteins using regular asymmetric ceramic membranes has been demonstrated.

2. Oil droplet diameters in the emulsions are more than 10-times greater than nominal pore size in the membrane and are influenced by the process variables.

3. The greater is the velocity of continuous phase / emulsion the smaller oil droplets are produced by this technique.

4. Whey proteins as the stabilizing agent enable better oil droplet size distribution than may be obtained with milk protein concentrate.

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