Energy Efficiency of Different Emulsification Methods:  
A Comparative Evaluation

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Since emulsification for the production of O/W emulsions is a process associated with a gain in interfacial energy, its energy efficiency was defined as the ratio between the interfacial energy acquired and the energy consumed during emulsification. The energy efficiency thus defined could then be comprehensively correlated with the energy consumed by three different emulsification processes, - rotor-stator homogenization, high-pressure homogenization, and membrane emulsification. This correlation suggests that membrane emulsification resembles a high-pressure process from the viewpoint of energy consumption.

Keywords: O/W emulsion, energy efficiency, membrane emulsification, high-pressure emulsification

1. Introduction

Emulsification is widely used in the food, pharmaceutical, and agricultural fields [1]. Emulsions used in the food sector are, generally, categorized as oil-in-water (O/W) emulsions, such as milk and mayonnaise, or water-in-oil (W/O) emulsions, such as butter and margarine. Multiple emulsions of the O/W/O and W/O/W types, on the contrary, have a limited use in the food industry. Since O/W emulsions displaying smaller oil droplet sizes and narrower size-distributions have higher dispersion stability, the preparation of emulsions with these features is greatly desired [2]. Given that a large amount of energy should be supplied in order to prepare emulsions displaying small oil droplet sizes [2, 3], methods with a large energy output - e.g., colloid mill, rotor-stator homogenizer, high-pressure homogenizer, and ultrasonic homogenizer - are frequently used in industrial emulsification [4, 5]. However, emulsification is usually an energy-consuming process such that the efficiency of the equipment’s energy usage is expected to be low.

It is, therefore, highly desirable to develop an efficient method to prepare O/W emulsions displaying smaller oil droplet sizes with a lower input of energy. For that purpose, the relationship between the energy input in emulsification and the mean oil droplet size or oil droplet size distribution has been examined [4–8]. However, these analyses were not systematic thus hindering the comprehensive interpretation of the results [9].

Membrane emulsification has attracted widespread attention due to its lower energy consumption compared to other emulsification methods. In fact, the dispersion stability and oil droplet size distribution of the O/W emulsions prepared through this method have been extensively studied [12–14]. However, only a few studies have dealt with the energy efficiency of the membrane emulsification process [9].

In this context, we investigated the relationship between the total interfacial energy of O/W emulsions and the energy input for rotor–stator homogenization, high-pressure homogenization, and membrane emulsification with a particular focus on emulsification efficiency and energy density [4, 15].

2. Materials and Methods

2.1 Materials

Distilled water and trioctanoylglycerol (abbreviated C₈TG; Sigma-Aldrich, St. Louis, MO, USA) were used as the water and oil phases, respectively. Sodium dodecyl sulfate (SDS; Wako Pure Chemical Industries, Ltd., Osaka, Japan) and polyoxyethylene (20) sorbitan mono-
laurate (Tween 20; Sigma–Aldrich) were used as the hydrophilic surfactants.

2.2 Preparation of the O/W emulsions
Oil and water phases were mixed at a weight ratio of 1:9 or 2:8 and at the surfactant concentration of 5 or 10 g/L, which was much higher than the critical micelle concentrations of the surfactant. The mixture was vigorously mixed using a rotor–stator homogenizer with a 12-mm–diameter generator shaft (Polytron TP1300, Kinematika, Switzerland) at a rotational speed of 5000 rpm for 5 min to produce a coarse O/W emulsion.

The coarse emulsion was further treated with a high-pressure homogenizer (PEL-20, Nanomizer, Aichi, Japan) at a pressure of 45 to 150 MPa to produce a fine O/W emulsion. The coarse emulsion was also membrane-emulsified by passing it through a Dismic 25CS080AN membrane (Advantec, Tokyo, Japan) with a mean pore size of 0.8 μm under nitrogen pressure to produce another fine O/W emulsion.

2.3 Measurement of the oil droplet size distribution and interfacial tension
The oil droplet size distribution was measured using a laser diffractive particle-size analyzer (SALD-2200, Shimadzu, Kyoto, Japan). The interfacial tension, \(\sigma\) (usually assumed to be synonymous with the interfacial energy) between water and C8TG was measured using a CBVP-A3 surface tensiometer (Kyowa Interface Science, Saitama, Japan) based on the Wilhelmy method.

2.4 Estimation of power consumption and energy efficiency during emulsification
The Sauter mean radius of an oil droplet in an O/W emulsion, \(d_{32}\), was evaluated from the oil droplet size distribution. The specific surface area of the oil droplet, \(a\), was estimated as \(a=\frac{3}{d_{32}}\). After subtracting the surface energy of the coarse emulsion, the surface energy acquired during emulsification, \(E_s\), was estimated by Eq. (1),

\[
E_s = aV_o\sigma
\]  

where \(V_o\) is the volume of the oil phase. Since the surface of an oil droplet is not covered with surfactant molecules immediately after its formation, the interfacial tension between C8TG and water containing no surfactant, \(2.52 \times 10^{-2} \text{ J/m}^2\), was used as the \(\sigma\) value.

The energy input during emulsification, \(E_a\), was calculated by taking into consideration the volume of the oil phase. As such, the \(E_a\) for emulsification using the rotor–stator homogenizer was calculated with the following equation

\[
E_a = IVt r_0
\]

where \(I\) is the electric current, \(V\) the voltage, \(t\) the time for emulsification, and \(r_0\) the volumetric fraction of oil phase in the O/W emulsion. The \(E_a\) values for emulsifications using the high-pressure homogenization and membrane-emulsification methods were calculated through Eq. (2–b)

\[
E_a = pV_o
\]

where \(p\) is the pressure applied during the emulsification and \(V_o\) the volume of oil phase.

The energy efficiency during emulsification, \(\eta\), was estimated by Eq. (3)

\[
\eta = E_g/E_a
\]

The power consumed during emulsification, \(W_e\), was estimated based on the total volume of the O/W emulsion through Eq. (4)

\[
W_e = E_a/(tr_0)
\]

3. Results and Discussion
The energy density, \(E_v\) [4] is a useful parameter for comparing the energy efficiency among different emulsification methods [11]. It is defined as the energy consumed during emulsification per unit volume of emulsion and can be calculated by using Eq. (5)

\[
E_v = W_e/(V_{OW}/t)
\]

where \(V_{OW}\) is the volume of O/W emulsion and \(E_v\) has units of Pa [4]. In high-pressure homogenization and membrane emulsification, the energy density is given by the pressure applied during emulsification. The relationship between energy density and \(d_{32}\) has been extensively investigated [4, 5, 15, 16], and the energy efficiency is assessed to be higher when smaller oil droplets are formed at a specific energy density. Therefore, we also plotted the \(d_{32}\) values of the oil droplets in the O/W emulsions prepared by the three different emulsification methods against their respective energy densities (data not shown). Although previous works reported the existence of a weak correlation between the \(d_{32}\) value and the energy density for a specific emulsification method [4, 15], we observed the existence of no such correlation for
the three different emulsification methods considered here.

Considering that emulsification is a process involving a gain of interfacial energy, we defined the energy efficiency during emulsification, \( \eta \), by Eq. (3). The \( \eta \) values for all the three emulsification methods examined in this study were low, especially the \( \eta \) value for the emulsification by the rotor–stator homogenizer. The low \( \eta \) values indicate that emulsification is an energy-consuming process.

The \( \eta \) values were plotted against the \( E_v \) values for the three emulsification methods (Fig. 1). Table 1 summarizes the emulsification method, emulsifier type and its concentration, oil content in the emulsions, as well as the symbols used in Fig. 1. For comparison purposes, the \( \eta \) values for membrane emulsification and high-pressure homogenization obtained, respectively, by van der Zwan et al. [16] and Jafari et al. [7] are also shown in that figure. The \( \sigma \) value between water and hexadecane, which is necessary to evaluate the \( \eta \) value for the membrane emulsification, was cited from Oh and Shah [17], and that between water and \( d \)-limonene for the high-pressure homogenization was assumed to be \( 2.5 \times 10^{-2} \) J/m\(^2\). All the plots in Fig. 1 lie on a curve roughly expressed by Eq. (6), indicating that the energy efficiency, \( \eta \), is a useful parameter for the comprehensive comparison of the performance of different emulsification methods,

\[
\eta = 347 E_v^{-0.582} \quad (9 \times 10^5 < E_v < 1.5 \times 10^8 \text{ Pa}) \quad (6)
\]

The plots cited from van der Zwan et al. [16] were slightly deviated from the line. This deviation might be ascribed to the uncertainty of the assumed value of interfacial tension. From that curve, we can estimate the \( d_{32} \) values of the oil droplets in the O/W emulsion when the power consumed during emulsification is measured or estimated and the \( \sigma \) value is known.

While in membrane emulsification, the oil droplets are formed by passing the oil phase through numerous pores at a reduced velocity, in high-pressure homogenization, those droplets are formed by passing the oil phase through fewer or even a single pore at a very high velo-

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**Table 1** Conditions for the preparation of O/W emulsions, and the definition of symbols in Fig. 1

| Emulsification method          | Surfactant | Surfactant concentration [g/L] | Oil-phase concentration [% (w/w)] | Symbol | Reference |
|-------------------------------|------------|--------------------------------|-----------------------------------|--------|----------|
| Membrane emulsification       | Tween 20   | 5                              | 5                                 | ○      | [16]     |
|                               |            | 5                              | 10                                | ○      |          |
|                               |            | 10                             | 10                                | □      |          |
| SDS                           | 5          | 10                             | △                                 |        |          |
|                               | 5          | 20                             | ▽                                 |        |          |
|                               | 10         | 10                             | ▲                                 |        |          |
|                               | 10         | 20                             | ▼                                 |        |          |
| High-pressure homogenization   | Tween 20   | 5                              | 10                                | ●      | This work |
|                               |            | 10                             | 10                                | ■      |          |
| SDS                           | 5          | 10                             | ▲                                 |        |          |
|                               | 5          | 20                             | ▼                                 |        |          |
|                               | 10         | 10                             | ▲                                 |        |          |
|                               | 10         | 10                             | ▼                                 |        |          |
| Capsul                        | 10         | 15                             | ●                                 |        | [7]      |
ity. Although these emulsification methods appear to be largely different, they both involve the production of oil droplets by passing the oil phase through pores with similar energy consumptions.

The energy efficiency values obtained during emulsification using the rotor–stator homogenizer were very low and, therefore, are not shown in Fig. 1. Just as an indication, these values are located 7 on the axis and −4 on the ordinate of the double logarithmic scale.

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Nomenclature

- $a$: specific surface area of an oil droplet [m$^2$/m$^3$]
- $E_a$: energy input during emulsification [J/m$^2$]
- $E_g$: surface energy acquired during emulsification [J/m$^2$]
- $E_v$: energy density [Pa]
- $I$: electric current [A]
- $p$: pressure applied during emulsification [Pa]
- $r_0$: volumetric ratio of the oil phase in an O/W emulsion
- $t$: time for emulsification [s]
- $V$: voltage [V]
- $V_o$: volume of the oil phase [m$^3$]
- $V_{OW}$: volume of the O/W emulsion [m$^3$]
- $W_e$: power consumed during emulsification [W]
- $\eta$: energy efficiency during emulsification
- $\sigma$: interfacial tension [N/m = J/m$^2$]

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