An original continuous process for double emulsions preparation using static mixers: Focus on the viscosity

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An original continuous process for double emulsions preparation using static mixers: Focus on the viscosity

Noureddine Lebaz[1*]; Kristy Touma[1]; Nida Sheibat-Othman[1]

[1] University of Lyon, Université Claude Bernard Lyon 1, CNRS, LAGEPP UMR 5007, F-69100, Villeurbanne, France

Abstract

A novel method for the preparation of water-in-oil-in-water (W/O/W) double emulsions is proposed and evaluated in this work. It is based on the classical two-step method in which the inner water-in-oil (W/O) emulsion is prepared using a high shear device (first batch step). This inner emulsion is then dispersed continuously in an aqueous phase using in line static mixers as second emulsification step for the formation of double emulsions. This somehow semi-continuous preparation method is evaluated when varying the viscosity of the three phases (from 1 to 100 mPa s) and the internal aqueous phase fraction (from 1 to 40 wt. %). Under the investigation conditions, the use of static mixers is shown to be efficient for the formation of double emulsions with monomodal droplet size distributions and high encapsulation efficiency despite the shear thinning behavior of the inner emulsions. A correlation was established to relate the viscosity of the inner (W/O) emulsion with the fraction of the inner phase, that was found to be independent of the viscosity of the inner water phase. Moreover, it was possible to control the range of variation of the droplets size of the double emulsion from some tens to hundreds of micrometers while the residence time is less than a second. This fast and efficient double emulsion preparation process constitutes a promising alternative to classical batch processes.

Keywords: Double emulsions, static mixers, apparent viscosity, droplet breakage, droplet size distribution.

[*] Corresponding author. Address : LAGEPP, Université Claude Bernard Lyon 1, bât 308G ESCPE-Lyon, 43 bd du 11 Novembre 1918, Villeurbanne 69622 France. Tel.: +33 04 72 43 18 55; Fax: +33 04 72 43 16 99
Email address: noureddine.lebaz@univ-lyon1.fr (Noureddine Lebaz)

1 Introduction

Double emulsions (DEs), also known as liquid membranes, are complex systems in which the droplets of the dispersed phase themselves contain smaller droplets [1]. They may be water-in-oil-in-water (W/O/W) or oil-in-water-in-oil (O/W/O) stabilized by a set of lipophilic and hydrophilic surfactants dissolved in the intermediate and the external phases. They are employed for instance for setting up low-fat food products [2], encapsulating pharmaceutical active substances inside a single carrier for their sustained release [3] or the extraction of pollutants for wastewater treatment [4]. They also may constitute an intermediate step, such as in interfacial polymerization or other surface solidification processes for the preparation of capsules [5]. Among the possible applications of DEs, the medical and pharmaceutical applications are highly demanding, with narrow specifications and a strict regulation of the production processes and end-use properties frames. Owing to their dual structure, involving both water-in-oil (W/O) and oil-in-water (O/W) emulsions that have challenging requirements, DEs present a higher complexity than single emulsions. Indeed, a higher number of phenomena may occur during their preparation and storage and their formulation is more complex[6]. Their formulation in a continuous mode, which is aimed at the industrial scale, is rarely addressed.

Double emulsions have been described since 1925 [7]. The two-step emulsification process for preparing DEs was first reported in 1976 by Matsumoto et al. [8] and since then, it became the most prevalent preparation method [3]. Based on this method, different processing techniques were then reported for preparing double emulsions, mainly including high-speed shearing (rotor-stator), high-pressure homogenization (HPH), ultrasonication, membranes and microfluidics [9–11].

In the first step of DE preparation, the rotor-stator device is typically used for the preparation of the inner emulsion [12]. This high-speed shearing technique (driven by mechanical forces, shear stress and cavitation forces) allows the preparation of fine emulsions with droplet sizes usually in the micrometer range. In the second step, the dispersion of the inner emulsion in the outer continuous phase is usually exposed to more moderate dispersing conditions, or to shorter mixing times, to avoid the destabilization of the double emulsion (i.e. extraction of inner droplets). Most of the techniques reported in literature operate in batch mode, i.e. commonly in stirred tanks. One of the disadvantages of batch operation is that it makes the process scale-up challenging. This is due to the non-uniform dissipation of the mechanical energy in the medium, with local intense shearing conditions near the rotating element (or near the sonication probe in

the case of ultrasonication where significant physical shearing is caused by acoustic cavitation). This non-uniformity, increases with the scale-up, and directly impacts the emulsification efficiency, leading to a broad droplet size distribution [13]. Alternatively, the high-shearing device may be associated with another impeller to slightly improve the circulation and uniformity of the emulsion inside the stirred tank.

The development of membranes and microchannels is attractive since they ensure efficient continuous formation of the outer DE droplets with negligible disturbances of the inner phase (i.e. escape or coalescence of inner droplets) [9]. The microfluidic-based technique (driven by shear and extensional stress forces) is adapted for the preparation of highly reproducible droplets (with controlled size and morphology), but, it delivers very low flow rates (of the order of milliliter per minute at most) and generates droplets larger than 10 μm [14]. Membrane emulsification is an intensified continuous process allowing the production of size-controlled emulsions based on shear forces and can deliver higher flow rates. However, membrane processes may undergo fouling and deterioration during the operation, which alter their efficiency. Also, the high operating cost (specific type of membranes, cyclic regeneration, material aging, high pressure drops due to resistance to permeation, …) limits the implementation of this process at large scales [15]. High pressure homogenization is also frequently used for the generation of relatively fine emulsions and can be adapted to continuous operation. But, it usually requires a pre-emulsification step, and usually several cycles are needed to reach a small droplet size which in the case of double emulsions may lead to the loss of the encapsulated ingredient by leakage [16].

Static, or motionless, mixers play an important role in process mixing. They have been used in various unit operations such as absorption, scrubbing, reaction enhancement and emulsification [17,18]. They generate intense homogeneous turbulence without any moving parts. They consist of complex structured rigid elements usually inserted into cylindrical pipes. Their geometrical characteristics promote chaotic mixing behavior by splitting and redistributing the flow streamlines sequentially, following radial and tangential directions to the main flow [19]. The resulting turbulence and shear stress forces cause droplet breakage in liquid-liquid dispersions. Therefore, static mixers are conceptually feasible for use in double emulsions preparation, but no relevant studies on this application have been reported so far.

We have recently investigated both experimentally and numerically the preparation of single emulsions by the use of SMX+ static mixer in different conditions [20–22]. The choice of SMX+ (by Sulzer®) mixing elements is motivated by their high mixing efficiency with low

pressure drop compared to other static mixers [23]. For single emulsification, these mixers showed very interesting capabilities [24]. Unlike stirred tanks for instance, the energy dissipation rate in these mixers is uniformly distributed in the free volume occupied by the fluid leading to an efficient production of O/W emulsions (with a narrow monomodal droplet size distribution) even at high viscosity of the two phases [19]. Indeed, the advantage of using static mixers over stirred tanks is more pronounced with increased viscosity of the continuous phase. In this case, emulsification in stirred tanks leads to a bimodal size distribution due to the fact that mixing between the high energy dissipation zone around the impeller and the other zones is reduced, while static mixers may still generate narrow droplet size distributions [20]. Compared to classical emulsification techniques, static mixers also offer additional advantages like their compactness, narrow residence time distribution, reduced maintenance requirements, and enhanced safety [25].

Hence, the aim of this study is to investigate the preparation of double emulsions using static mixers for the second emulsification step. For the first step, requiring intense shearing, a rotor-stator device is employed. Different process parameters including the viscosity of the three phases and the internal aqueous phase fraction are investigated, and their role quantified in terms of outer droplet size distribution, apparent viscosity and encapsulation efficiency.

2 Material and experimental methods

2.1 Material

To prepare the W/O/W double emulsions, silicone oil (provided by Sigma-Aldrich, Germany at different viscosities) is used as the intermediate phase after mixing with Abil® EM97S (offered by Evonik, Germany) as hydrophobic surfactant. The inner and outer phases are composed of ultrapure water (Synergy unit system, Millipore, France) and glycerol (VWR Chemicals, France) as viscosity enhancer. Polysorbate 20 (Tween®20, Sigma-Aldrich, Germany) is used as hydrophilic surfactant and is dissolved in the external aqueous phase. Sodium chloride (Sigma-Aldrich, Germany) is dissolved in the internal aqueous phase as tracer and regulator of osmotic pressure.

2.2 Double emulsion preparation

The two-step method is adopted for the W/O/W double emulsions preparation, at room temperature, as depicted in Figure 1. In the first step, an aqueous solution, containing sodium chloride at a concentration of 0.1 M, is mixed with silicone oil in which the lipophilic surfactant

(Abil EM97S, at a concentration of 2 wt. %) is previously dissolved. The mixing is ensured by an IKA T 18 digital ULTRA-TURRAX® at 12 000 rpm for 4 min. The preparation conditions of the inner emulsion are kept constant, except the viscosity of the two phases and the internal aqueous phase fraction.

In the second step, the inner emulsion is mixed with the external continuous aqueous phase by pumping them separately through a set of SMX+ static mixers using MCP-Z Ismatec gear pumps. The fraction of the dispersed phase is kept at 1 wt. % by controlling the flow rate of the two phases. For stability enhancement of the flow rates, the junction between the two phases is ensured using a syringe needle for the dispersed phase, which is introduced parallel to the tube of the continuous aqueous phase. The external aqueous phase contains the hydrophilic surfactant (Tween® 20) at a concentration of around 2 g L^{-1}.

At the upstream of the static mixers, a pressure gauge (Keller LEO1: 0-3 bar, ± 3 mbar, Germany) is installed for pressure drop measurement during the emulsification process. A total of 20 SMX+ elements were used for the dispersion of the inner emulsion. For each emulsification experiment, a sample is withdrawn at the outlet of the mixers for droplet size distribution(DSD) and conductivity measurements. Another sample is withdrawn after only 5 elements to evaluate the efficiency of the remaining elements independently. The set of experiments carried out at different conditions is summarized in Table 1.

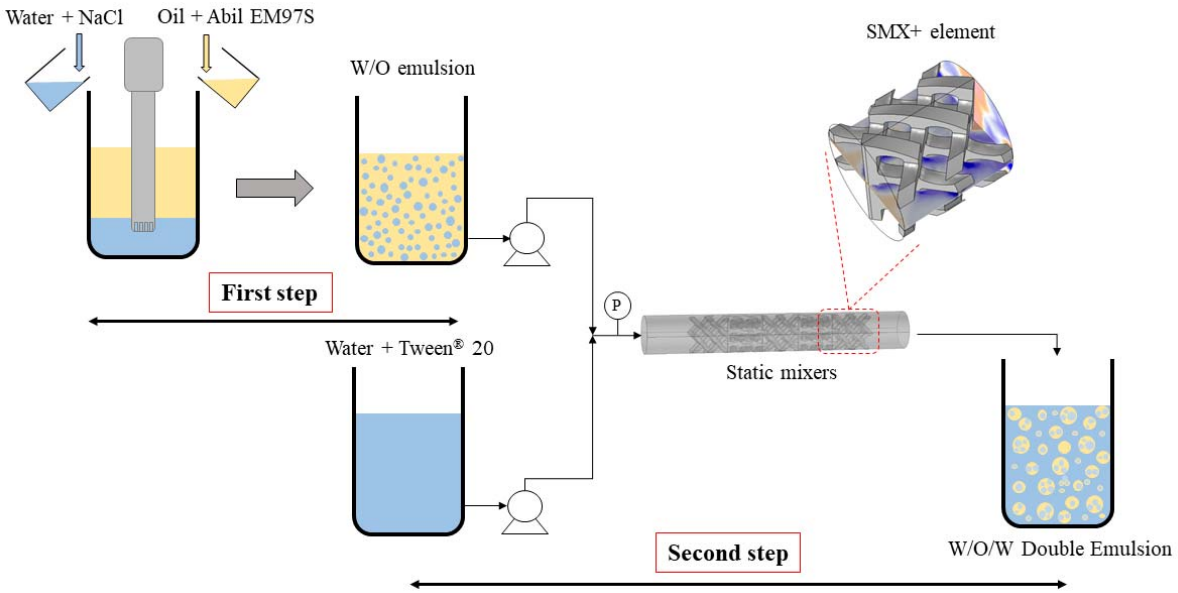

Figure 1: Experimental set-up for the preparation of W/O/W double emulsions using a two-step method based on a high shear device (Ultra-Turrax) and static mixers.

Table 1: Experiments carried out for the preparation of the W/O/W double emulsions.

N°	μ_{wi} [mPa.s]	μ_o [mPa.s]	μ_d [mPa.s]	μ_c [mPa.s]	ϕ_i [wt. %]	ΔP [bar]	Re_h [-]
1	1	5	30	1	40	0.25	1000
2	1	10	53	1	40	0.25	1000
3	1	20	148	1	40	0.25	1000
4	1	100	370	1	40	0.25	1000
5	5	5	26	1	40	0.25	1000
6	5	10	69	1	40	0.25	1000
7	5	20	118	1	40	0.25	1000
8	5	100	337	1	40	0.25	1000
9	10	5	31	1	40	0.25	1000
10	10	10	45	1	40	0.25	1000
11	10	20	93	1	40	0.25	1000
12	10	100	362	1	40	0.25	1000
13	20	5	26	1	40	0.25	1000
14	20	10	61	1	40	0.25	1000
15	20	20	96	1	40	0.25	1000
16	1	10	53	5	40	0.60	300
17	1	10	53	10	40	1.86	300
18	1	10	32	1	30	0.25	1000
19	1	10	19	1	20	0.25	1000
20	1	10	8.1	1	10	0.25	1000

The experiments shown in Table 1 are carried out at a hydraulic Reynolds number higher than 260, which ensures turbulent emulsification [26]. The hydraulic Reynolds number (Re_h) is calculated as:

$$Re_h = \frac{\rho_c u_s D_h}{\varphi \mu_c} \quad (1)$$

Where ρ_c is the apparent continuous phase density (kg m^{-3}), D_h is the hydraulic diameter of the pipe equipped with the mixing elements (m), φ is the porosity of the mixers, μ_c is the apparent continuous phase viscosity (Pa s), and u_s is the superficial velocity in the empty pipe given by (m s^{-1}):

$$u_s = \frac{4Q}{\pi D^2} \quad (2)$$

Where Q is the volumetric flow rate of the fluid (m^3 s^{-1}) and D is the empty pipe internal diameter (m) ($D_h = 4\varphi/a_g$ with a_g being the mixer specific area). The mean turbulent energy dissipation rate $\bar{\varepsilon}$ is accessible experimentally through the measurement of the pressure drop induced by the static mixers:

$$\bar{\varepsilon} = \frac{\Delta P u_i}{\rho_c L_s} \quad (3)$$

where L_s is the total length of the mixing elements and u_i is the interstitial velocity ($u_i = u_s/\varphi$). The characteristics of the static mixers are reported in Lebaz & Sheibat-Othman (2019) [22].

2.3 Characterization of the emulsions

Right after the first preparation step, the DSD of the obtained W/O simple emulsions is measured by means of dynamic light scattering (Malvern Zetasizer Nano ZS®) which is adapted to the micro-scale of the water droplets. During the second emulsification step, the DSD of the samples withdrawn after 20 elements is measured using laser diffraction (Mastersizer 3000, Malvern Instruments, France). The DSD measurement in the different cases is achieved after significant dilution in the corresponding continuous phase, and the measurement is repeated three times for each sample. Moreover, a direct observation of the prepared double emulsions is achieved with an optical microscope (Leica© DM2000 LED) for the visualization of the inner and outer droplets.

As reported in our recent studies, the efficiency of emulsification through static mixers depends strongly on the viscosity of the dispersed and continuous phases[20,24]. In the case of double emulsification, the inner emulsion constitutes the dispersed phase. Hence, one should estimate the apparent viscosity of the inner emulsion, which depends on the nature of the aqueous and oil phases, the concentration of the surfactant and more importantly the internal dispersed phase fraction, with a possible effect of the internal droplets size. For this, the inner emulsion viscosity is measured using an MCR 302 rheometer (Anton Paar, France) equipped with a 25 mm plate-plate geometry under a shear rate ranging from 0 to 1 000 s^{-1}.

The interfacial tension of the outer droplets is obtained by a Drop Shape Analysis System DSA10 Mk2 (Krüss GmbH, Germany). For this, a pendant drop of the inner W/O emulsion is immersed in a cuvette containing an aqueous phase with the composition of the considered formulation (composed of water, hydrophilic surfactant and possibly glycerol).

Finally, one important parameter during the preparation of double emulsions is the encapsulation efficiency. The released amount caused by the emulsification in the second step is monitored by electrical conductivity measurement using a Transmitter M200 probe (Mettler-Toledo). The conductivity is measured for the DE samples taken after 20 mixing elements.

3 Results and discussion

3.1 Inner emulsions DSD

The inner W/O emulsions are prepared using an Ultra-Turrax at 12 000 rpm during 4 min for all the experiments described in Table 1. Figure 2 illustrates the obtained inner DSD of pure water as inner phase, with different oil phase viscosities. It can be seen that the droplet size is below 10 µm for all cases, and the distributions become broader and shift towards bigger sizes when the viscosity of the continuous phase (i.e. the oil) increases. This is because the mixing rate and time of the rotor-stator are kept constant in these formulations, while for more viscous fluids one needs more energy input to generate equivalent turbulence. However, in all the tests, only slight differences are observed in the DSD.

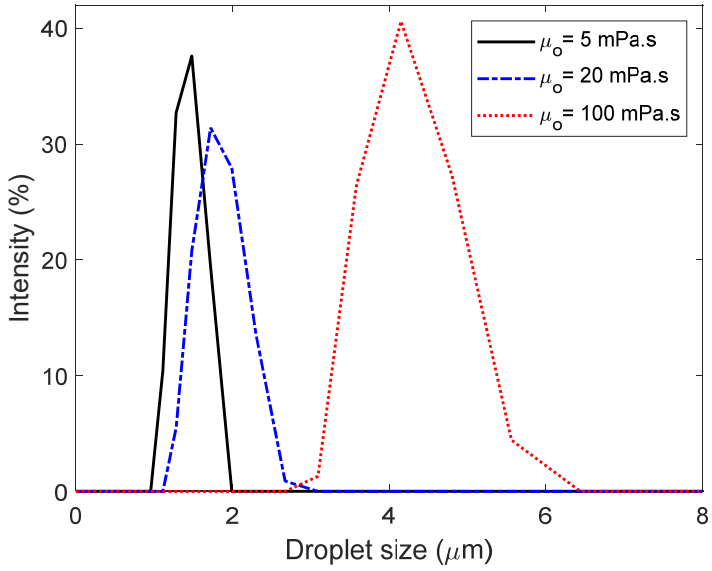

Figure 2: Droplet size distribution of the inner aqueous droplets ($\mu_{wi} = 1$ mPa s) with varying viscosity of the oil phase.

3.2 Inner emulsions rheology

Regarding the rheological behavior of the W/O inner emulsions, Figure 3 gives the evolution of the apparent viscosity as a function of the shear rate when varying the internal phase fraction

and the viscosities of the two phases. Globally, except for the very dilute case ($\phi_i = 1$ %), the emulsions show a shear thinning behavior: i.e. a high apparent viscosity is measured at low shear rates and it stabilizes to a relatively constant viscosity at high shears. It is worth noticing that the inner emulsions conserve their integrity after shearing at 1 000 s^{-1}. This was confirmed by droplet size measurements which gave the same results before and after shearing. As the turbulence intensity in the mixers is very high (ε between 100 and 2 000 m^2 s^{-3}), high shear rates are expected to dominate ($\dot{\gamma} \approx \sqrt{\varepsilon/\nu} > 10^4$ s^{-1}). In these specific conditions, the apparent viscosity may be considered to be constant. In the remaining parts of the paper, the apparent viscosity of the inner emulsions is taken at a constant shear rate of 1 000 s^{-1}.

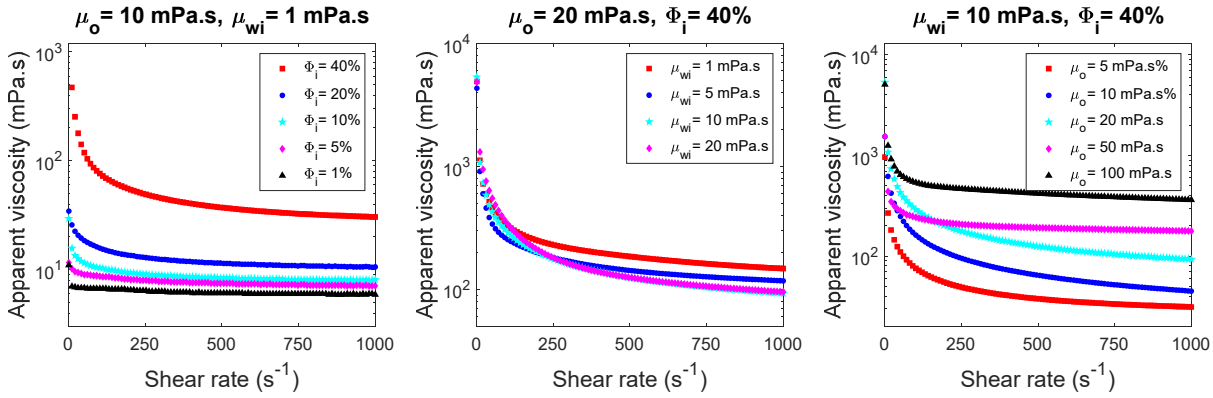

Figure 3: Apparent viscosity of the inner emulsion as a function of the shear rate: Impact of the dispersed phase fraction, and the viscosities of the internal aqueous phase and the oil.

If we focus on the viscosity obtained at high shear rates, Figure 3 shows that the apparent viscosity is highly dependent on both the oil viscosity and the internal phase fraction, but little on the inner droplets (water) viscosity. At $\phi_i = 40$ %, increasing the internal phase viscosity from 1 to 20 mPa.s causes only a slight decrease of the apparent viscosity. This may be related to the droplet size distribution of inner droplets which becomes broader and tends towards bigger sizes as shown by Figure 2. Indeed, it is well known that for concentrated emulsions, a reduction in droplet size leads to an increase in the apparent viscosity and the shear-thinning character becomes stronger [27].

Figure 4 shows the evolution of the apparent viscosity of the W/O inner emulsions when changing the internal phase fractions (each curve with the same oil and water viscosities). In the different cases, the apparent viscosity is exponentially increasing with the aqueous internal phase fraction, whatever the viscosity of the continuous oil phase (μ_o) (which was varied from

5 to 100 mPa s) or that of the internal phase (i.e. water, varied from 1 to 20 mPa s). The curves are plotted in two different ways to clearly show the effect of the viscosity of the continuous or dispersed phases. For instance, the increase of the continuous phase viscosity (μ_o) induces an increase of the apparent viscosity of the emulsion, as revealed by the three subplots on the top of Figure 4. On the other hand, increasing the viscosity of the dispersed phase (μ_{wi}) has a minor effect on the apparent viscosity as revealed by the three subplots on the bottom of Figure 4, and as reported earlier in Figure 3.

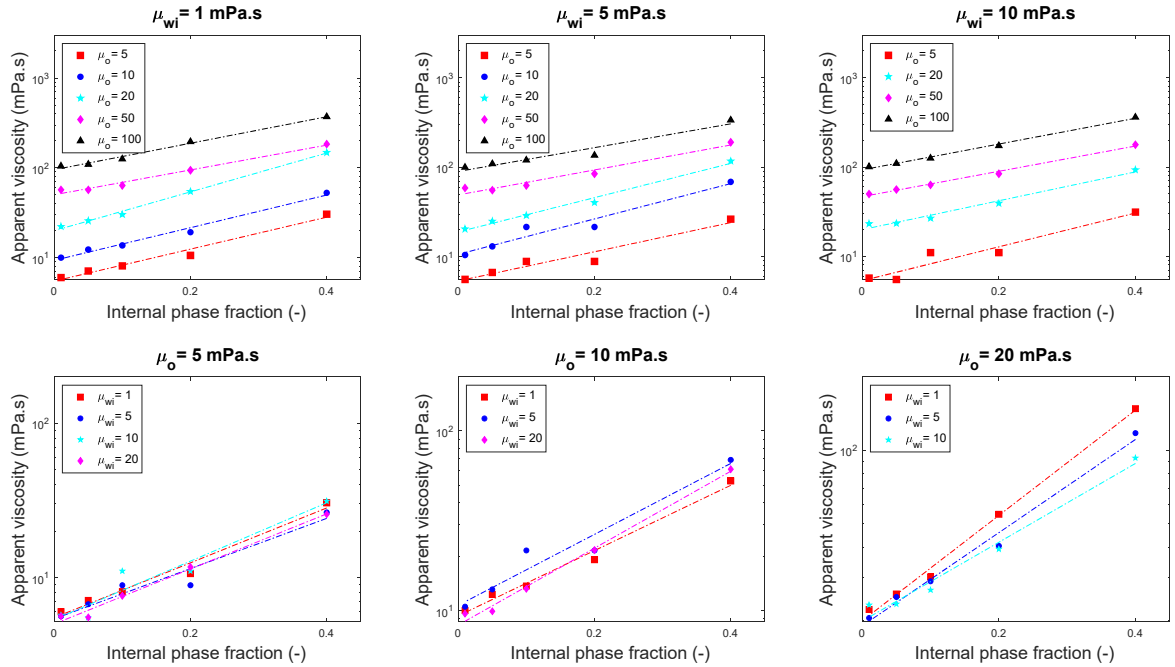

Figure 4: Apparent viscosity of the inner W/O emulsions as a function of the internal phase mass fraction (ϕ_i): Regrouped by the viscosity of the internal aqueous phase μ_{wi} (three subplots on the top) or by the viscosity of the oil phase μ_o (three subplots on the bottom). The hatched strait lines are only indicative.

The apparent viscosity reported here is in agreement with the literature [28,29]. A commonly adopted approach for a straightforward comparison between emulsions prepared in different cases is to use the relative emulsion viscosity, which is the ratio between the apparent viscosity of the emulsion to the viscosity of its continuous phase ($\mu_r = \frac{\mu_d}{\mu_o}$). Figure 5 depicts the evolution of μ_r when varying μ_{wi} and μ_d.

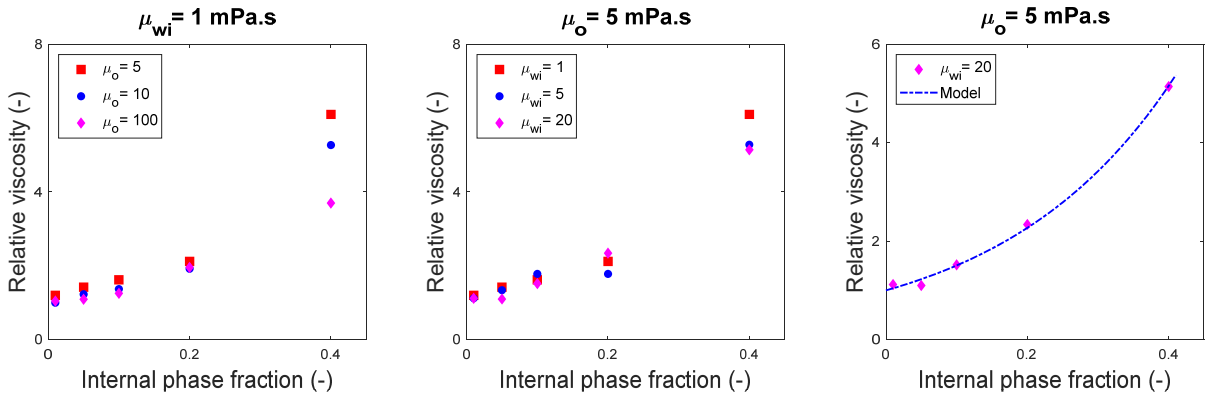

Figure 5: Relative viscosity (μ_r) evolution as a function of the internal phase fraction (ϕ_i): Effect of the oil phase viscosity (first subplot), effect of the internal phase viscosity (second subplot) and typical viscosity trend with Richardson correlation (last subplot).

It is clear from Figure 5 that the relative viscosity increases importantly with the internal phase fraction. At low internal phase fraction ($\phi_i \leq 20$ %), μ_r is independent of the viscosities of the two phases. However, at high internal phase fraction, μ_r decreases with the increase of the oil phase viscosity (first subplot), probably because of the increase of the inner droplet size as discussed above. The effect of μ_{wi} is almost negligible.

Different models are proposed in the literature for the prediction of the relative viscosity as a function of the internal phase fraction [30]. Richardson [31] proposed the following correlation:

$$\mu_r = e^{K\phi_i} \quad (4)$$

Where *K* is a constant having values between 3 and 5 in their case.

As example, Figure 5 (last subplot) shows a comparison between the experimental data ($\mu_o = 5$ mPa.s and $\mu_{wi} = 1$ mPa.s) and the correlation of Richardson. In this specific case, the fitting parameter *K* is identified to be equal to 4.1. It is obvious that this correlation will give good estimates of the relative viscosity only for low internal phase fractions ($\phi_i \leq 20$ %).

3.3 Static mixers efficiency for double emulsions preparation

The inner W/O emulsions (prepared in the previous section) are then pumped in parallel with the aqueous continuous external phase through the static mixers to form W/O/W double emulsions. Figure 6 shows optical microscope images at different magnifications of a double emulsion at the outlet of the process (downstream of 20 mixing elements in series). It is evident from the aspect of the droplets that they are encapsulating smaller aqueous droplets which

impact their turbidity since pure silicone oil droplets in water are transparent. In Figure 6-a, even the inner droplets are discernable because of the high magnification (×100). These optical microscope images confirm the effective formation of W/O/W double emulsions in a continuous mode using static mixers.

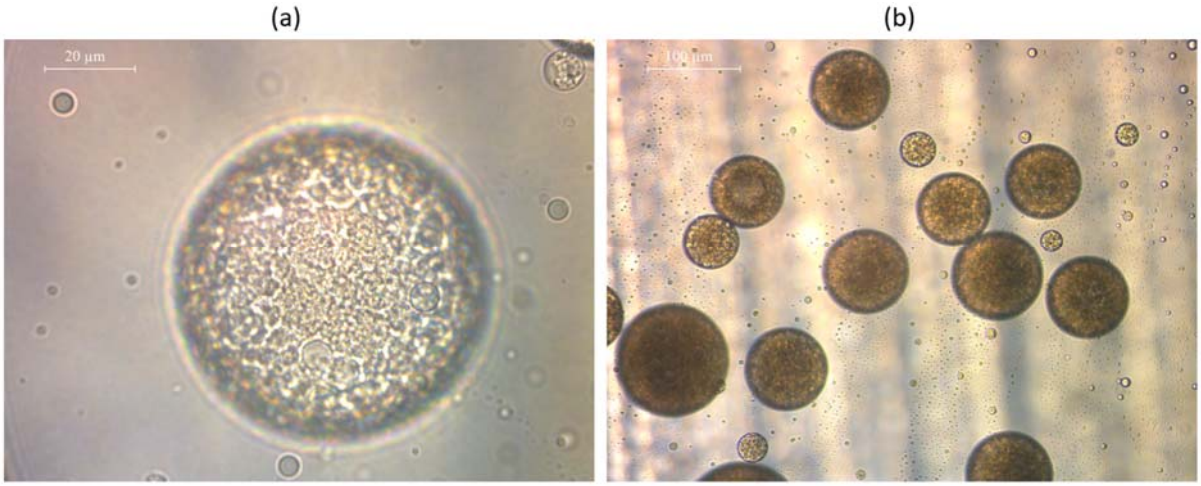

Figure 6: Optical microscope images of the W/O/W double emulsion at the outlet of the static mixers: (a) a unique outer droplet with a multitude of inner droplets inside (magnification × 100) and (b) outer droplets with different sizes encapsulating water droplets (magnification × 20)

3.4 Outer emulsions: experimental results

To evaluate the efficiency of the process to form W/O/W double emulsions, the outer DSD is measured after 5 and 20 static mixing elements by laser diffraction under different operating conditions. Figure 7-a shows the impact of the number of static mixers on the outer DSD. The results are given for two different oils, with a great variation of the viscosity ($\mu_o = 5$ and 100 mPa.s). In both cases, even after 5 mixing elements, the outer droplets of the double emulsion are formed but with a bigger size and wider distribution. When increasing the number of mixing elements to 20, the outer DSD becomes narrower and tends towards smaller sizes because the residence time increases. In the case of $\mu_o = 5$ mPa.s, the mean droplet size (d_{43}) decreases from 113 µm to 92 µm, while in the case of $\mu_o = 100$ mPa.s it decreases from 191 µm to 173 µm. As expected, this behavior is observed for all the experiments of Table 1, demonstrating the ability of the static mixers to homogeneously break up the inner emulsions into small droplets with monomodal distributions. Note that the equilibrium of the DSD would be reached

after different numbers of mixers, depending on the operating conditions (e.g. viscosity and fractions of the different phases, total flow rate, etc.), but the equilibrium time is out of the scope of this study. Regarding the encapsulation efficiency, the electrical conductivity is not impacted during the droplet breakage. In fact, its variation between 5 and 20 mixing elements does not exceed 5 % in all experiments. This demonstrates that the inner droplets release during the formation of the outer droplets is negligible because of the very short residence time inside the mixers (less than 1 second). Hence, static mixers are not only efficient for the formation of double emulsions but also allow to get a very high encapsulation efficiency.

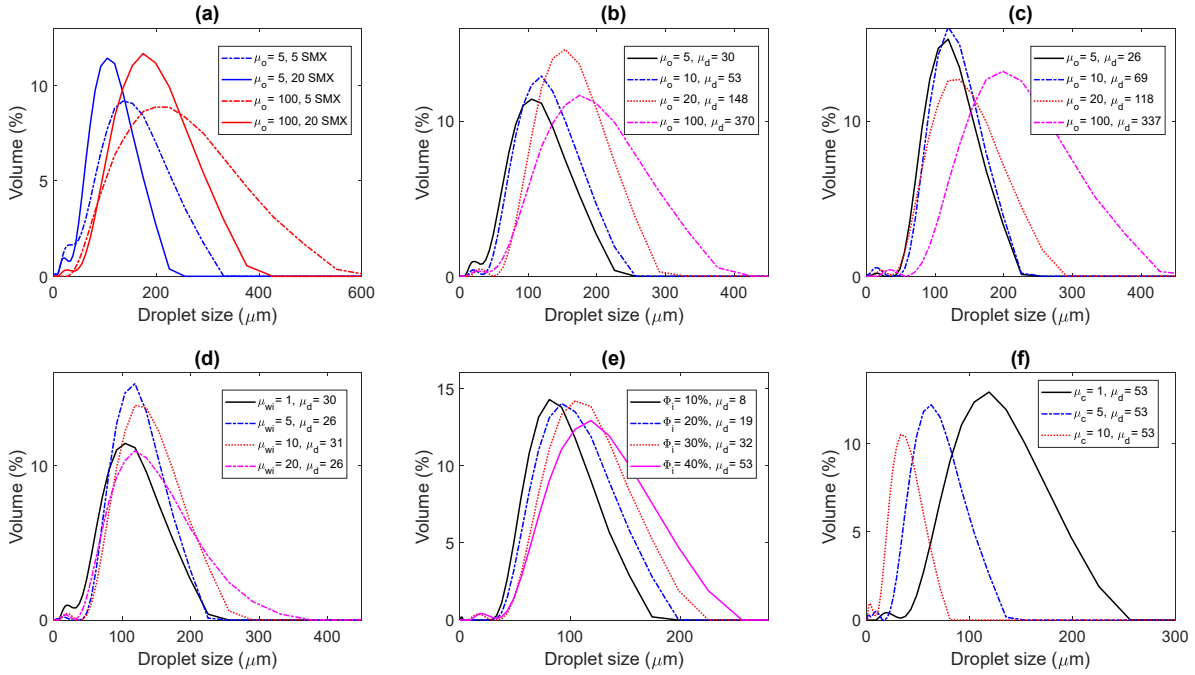

Figure 7: W/O/W DSD when varying different experimental parameters: (a) Effect of the number of static mixing elements (i.e. residence time) for two oil viscosities ($\mu_o = 5$ and 100 mPa s), (b) Effect of the oil viscosity at $\mu_c = \mu_{wi} = 1$ mPa s, (c) Effect of the oil viscosity at $\mu_c = 1$ mPa s and $\mu_{wi} = 5$ mPa s, (d) Effect of the internal aqueous phase viscosity (at $\mu_c = 1$ mPa s and $\mu_o = 5$ mPa s), (e) Effect of the internal phase fraction (with $\mu_c = \mu_{wi} = 1$ mPa s, $\mu_o = 10$ mPa s) and (f) Effect of the external aqueous phase viscosity (at $\mu_{wi} = 1$ mPa s and $\mu_o = 10$ mPa s).

Figure 7-b and Figure 7-c show the effect of the oil viscosity on the outlet DSD at two different internal aqueous phase viscosities (i.e. $\mu_{wi} = 1$ and $\mu_{wi} = 5$ mPa s, respectively). In both cases, the internal phase fraction is kept at $\phi_i = 40$ % and the outer phase viscosity at $\mu_c = 1$ mPa s. As expected, the increase in the oil viscosity affects directly the apparent viscosity of the inner emulsion and by the way the breakage efficiency by the static mixers. So, the outer DSD becomes broader and moves towards bigger sizes. For instance, as shown in Figure 7-b,

the mean droplet size changes from 92 µm when $\mu_o = 5$ mPa s to 173 µm when $\mu_o = 100$ mPa s. The same trend is observed in Figure 7-c. Remember that μ_{wi} only had a slight effect on the apparent viscosity of the inner droplets. Therefore, the increase of the internal aqueous phase viscosity from $\mu_{wi} = 1$ to $\mu_{wi} = 20$ mPa s does not have a remarkable effect on the outer DSD as shown in Figure 7-d.

Regarding the effect of the internal aqueous phase fraction, Figure 7-e shows the results when ϕ_i is varied from 10 to 40 wt. %, at $\mu_c = \mu_{wi} = 1$ mPa s and $\mu_o = 10$ mPa s. As expected, the variation of ϕ_i impacts the outer DSD, which is explained by the increase of the apparent viscosity of the inner emulsion from 8.1 mPa s at $\phi_i = 10$ % to 53 mPa s at $\phi_i = 40$ %. This increase of the inner emulsion viscosity makes the droplet breakage less efficient, so the mean droplet size increases from 79 µm to 107 µm. It can therefore be seen that the two parameters affecting the apparent viscosity of the inner emulsion (i.e. ϕ_i and μ_o) have similar effects on the breakage of the outer droplets.

In the case of increasing the viscosity of the outer continuous phase from $\mu_c = 1$ to 10 mPa s, it can be seen that the DSD of the double emulsion is strongly affected (Figure 7-f). The DSD becomes narrower and its mean size decreases from 107 µm to 30 µm. This trend is due to the increase of the energy dissipation rate within the static mixers. Indeed, at $\mu_c = 5$ mPa.s and $\mu_c = 10$ mPa.s, the hydraulic Reynolds number is kept constant at 300 by increasing the flow rate, so leading to an exponential increase in the energy dissipation rate. Note that except for these two cases, all the other experiments are conducted at Re_h=1 000 to ensure the same energy dissipation rate. Indeed, ensuring Re_h=1 000 was not feasible for these two experiments, as the used pumps cannot deliver so high flow rates to ensure a such high Re_h with the viscosities $\mu_c = 5$ or $\mu_c = 10$ mPa s.

It is worth noticing that because the same concentration of surfactants (lipophilic and hydrophilic) is used in all the investigated cases, the interfacial tension between the dispersed and continuous phases was found to be almost constant and very low in the different experiments ($\sigma = 0.6$ mN m^{-1}). Hence, the interfacial tension has the same impact on droplet breakage / coalescence in all experiments. The differences shown in Figure 7 in terms of DSD are therefore mainly caused by the apparent viscosity of the inner emulsion, its internal phase fraction and the hydrodynamics of the continuous phase.

To sum-up, the different experimental results in Figure 7 show a coherent evolution of the outer DSD of the double emulsions with respect to the investigated parameters and their ranges of

variation. The static mixers are efficient as a second-step method for the preparation of double emulsions leading to the formation of monomodal DSDs with mean sizes ranging from tens to hundreds of microns, depending on the operating conditions.

3.5 Double *versus* simple emulsions

As it was demonstrated that the internal fraction (between $\phi_i = 1$ % and 40 %) affects the apparent viscosity of the inner emulsion, it is important to evaluate its effect on droplet breakage during the formation of double emulsions. Figure 8 compares the DSDs of single (i.e. $\phi_i = 0$ %) and double emulsions obtained at the outlet of 20 mixing elements at two different continuous phase viscosities ($\mu_c = 1$ and 5 mPa s). The idea is to see if the apparent dispersed phase viscosity in double emulsions (which is itself an emulsion) has exactly the same impact as in single emulsions (which is only oil). The experimental data for the single emulsions shown in Figure 8 are taken from Lebaz and Sheibat-Othman [20].

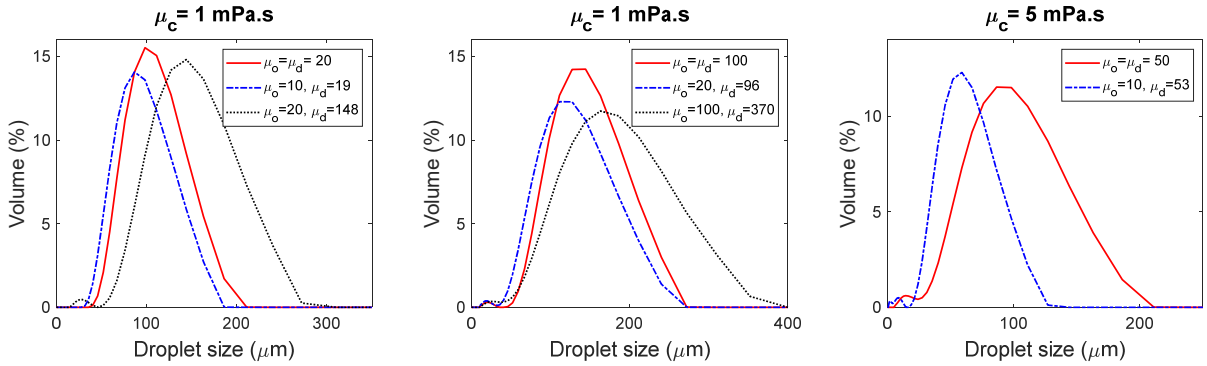

Figure 8: Comparison of the emulsification efficiency for single O/W (continuous line) and double emulsions W/O/W (dashed or dotted lines): Effect of dispersed phase and oil viscosities (given in mPa s).

In all the cases, and as expected, the double emulsion leads to a bigger droplet size compared to a single emulsion prepared with the same oil (two first subplots). This is due to the increase in the apparent viscosity of the inner emulsion in the case of double emulsions. Interestingly, at the same apparent viscosity of the dispersed phase, droplet breakage is more efficient in the case of double emulsions (i.e. breakage of the inner W/O emulsion) than the pure oil. This character is amplified when the energy dissipated in the system is increased (last subplot in Figure 8). The enhanced droplet breakage in double emulsions compared to single emulsions can be explained by the interfacial tension between the continuous aqueous phase and the oil phase, which is lowered by the presence of the lipophilic surfactant in the case of double

emulsions. Indeed, the interfacial tension strongly decreases from around 6 mN m^{-1} in the case of simple emulsions to 0.6 mN m^{-1} for double emulsions.

4 Conclusions

In this study, a novel semi-continuous two-step method is investigated for the effective production of W/O/W double emulsions. This method is based on a classical high-shear rotor stator device for the preparation of the inner W/O emulsion, followed by static mixing elements which were found to efficiently disperse the inner emulsion into small droplets to form the double emulsion. This is the first time that static mixers are reported as a part of a double emulsification process and showed remarkable performances. As a remarkable result, in specific cases, the static mixers may reduce the droplet mean diameters to some tens of microns with a narrow droplet size distribution. This is typically not possible when using stirred tanks or high shear devices with large volumes.

The first preparation step allowed to prepare W/O emulsions with a mean droplet size of some microns and a narrow droplet size distribution in the different investigated cases. At this stage, it was shown that the oil viscosity and the internal phase fraction strongly impact the rheological behavior of the inverse emulsion. Increasing the inner fraction of water exponentially increases the apparent viscosity of the W./L emulsion. Also, a shear thinning behavior is observed, especially at high internal phase fractions (>10 wt. %). However, the influences of the internal phase viscosity and the inner droplet size distribution on the apparent viscosity of the emulsion are negligible. This can be due to the reduced variation interval of these two parameters.

In the second preparation step, static mixers are shown to be efficient for the continuous formation of double emulsions with monomodal droplet distributions in the different tested cases and a high encapsulation efficiency as well. The double emulsion DSD is shown to be sensitive to different parameters such as the fraction and viscosity of the inner emulsion and the viscosity of the continuous phase. A particularly interesting observation is that, in double emulsions, even though increasing the inner fraction of water exponentially increases the apparent viscosity of the inner emulsion (which may render the droplet breakage harder), but due to the use of an inner lyophilic surfactant the interfacial tension of the outer droplets decreases drastically compared to single emulsions, which permits the production of smaller droplets.

Using static mixers as a part of DE preparation process is shown to be feasible technically, efficient under a large panel of operating conditions, and time saving since the preparation period corresponds to the fluid residence time inside the mixers which does not exceed 1 second. As a perspective, a fully continuous preparation process would be a further step for scaling up the DE preparation. Modeling the droplet breakage process is also interesting to be able to predict new formations from the operating and formulation conditions. Finally, the comparison with different types of mixers would be very useful to optimize the process design.

Nomenclature

a_g	Mixer specific surface area	$m^2\ m^{-3}$
D	Internal diameter of the empty pipe	m
D_h	Hydraulic diameter of the pipe equipped with the mixers	m
d_{43}	Volume-based mean droplet size	m
K	Constant	-
L_s	Total length of the mixing elements	m
ΔP	Pressure drop	Pa
Q	Volumetric flow rate	$m^3\ s^{-1}$
Re_h	Hydraulic Reynolds number	-
u_i	Interstitial velocity	$m\ s^{-1}$
u_s	Superficial velocity	$m\ s^{-1}$

$\dot{\gamma}$	Shear rate	s^{-1}
ε	Energy dissipation rate	$m^2\ s^{-3}$
$\bar{\varepsilon}$	Mean energy dissipation rate	$m^2\ s^{-3}$
μ_c	Dynamic viscosity of the continuous aqueous phase	Pa s
μ_d	Apparent dynamic viscosity of the inner emulsion (dispersed phase)	Pa s

μ_o	Dynamic viscosity of the oil phase	Pa s
μ_r	Relative viscosity of the inner emulsion	-
μ_{wi}	Dynamic viscosity of the inner aqueous phase	Pa s
ν	Kinematic viscosity of the continuous phase	$m^2 s^{-1}$
ρ_c	Continuous phase density	$kg\ m^{-3}$
σ	Interfacial tension	$N\ m^{-1}$
φ	Global porosity of the static mixers	-
ϕ_i	Internal aqueous phase weight fraction	-

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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