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Oil-in-Water and Water-in-Oil Emulsions

Heike P. Schuchmann, Karsten Köhler, Freddy Aguilar, and Andreas Hensel

20.1

Emulsion Basics

20.1.1

Definitions, Major and Minor Ingredients

Emulsions are part of the product range in the chemical and petrochemical industries, and also in the pharmaceutical, cosmetic and food industries. Widespread and well known are food emulsions such as milk and dairy products, mayonnaise, spreads, sauces and dressings. However, emulsions are also found in vanishing cream, ointments and lotions, detergents, surface coatings (e.g. of paper), bitumen and as intermediate products in a wide range of product technology [1].

An emulsion is a disperse system of at least two immiscible liquids, e.g. water and oil. One of these phases is finely dispersed and forms droplets in the other phase. Depending on the droplet phase, oil-in-water (o/w) and water-in-oil- (w/o) types of emulsion exist. Droplet sizes usually range from 0.1 to 1 μm in mini- or submicron emulsions and from 1 to several tens of μm in (macro-) emulsions.

Microemulsions of droplet sizes $<0.1 \mu\text{m}$ will not be covered here, since product and emulsifier composition, stability and process technology differ from those in mini- and macroemulsion technology.

Macro- and miniemulsions are thermodynamically unstable. If not stabilized, the droplets tend to flocculate, coalesce, sediment or cream [2–4]. Other instabilities, such as Ostwald ripening and phase inversion, are also known. At worst, an emulsion will break, i.e. the two phases will separate completely. A product becoming unstable will lose its quality within a short period of time and thus cannot be commercialized. Therefore, even in natural emulsion-based products, amphiphilic molecules are found (e.g. lecithin and proteins in egg yolk and milk and artificial surfactants and emulsifiers in cosmetics and chemical products. They adsorb at the droplets' interfaces and stabilize them against flocculation and coalescence. Adsorption and stabilization mechanisms depend on the molecular structure of a surfactant or an emulsifier as depicted in Figure 20.1. Stabilization mechanisms are summarized in

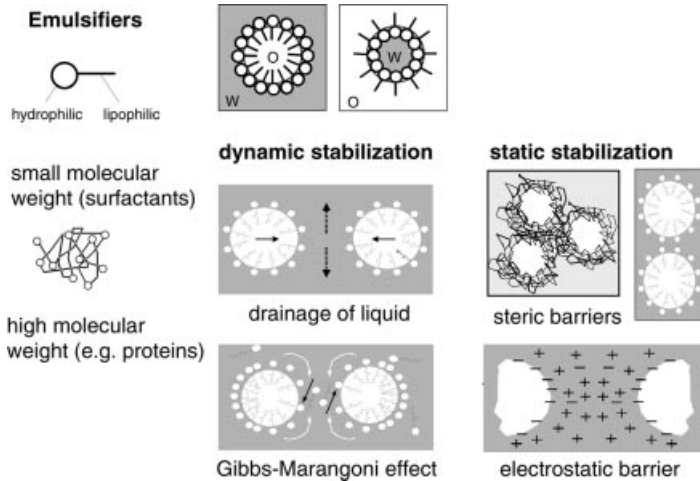


Figure 20.1 Emulsifiers and stabilization principles.

detail elsewhere [1, 4]. In addition to stabilizing an emulsion, the emulsifier often influences the product properties, such as its viscosity, especially if the molecules are of high molecular weight.

Thickeners, high molecular weight molecules soluble in the continuous phase, enhance its viscosity. They stabilize emulsions by slowing the droplet mobility. Flocculation, sedimentation or creaming and coalescence are either slowed or completely inhibited. Typical thickeners are (modified) starches and proteins for foods or glycerine or polyethylene oxides in non-food products.

Nanoparticles, being much smaller than the droplets and mainly wetted by the continuous phase, may also stabilize emulsion droplets [5, 6]. Emulsions thus stabilized are called “pickering or particle-stabilized emulsions (PSE)”.

20.1.2

Emulsion Properties and Their Design

Important quality properties of emulsion-based products are the physical and microbiological stability, rheological properties (such as consistency, viscosity, texture and spreadability), sensorial qualities (such as color, taste and mouth feel) and the distribution of active ingredients, their dissolution rate and bioavailability. They are influenced on the one hand by the formula (type and concentration of main phases and additives). On the other hand, the droplets' size distribution has an important impact on the properties of an emulsion. Often, the formula of an emulsion is constrained by marketing, recipe and/or legislation. Thus, the droplet size distribution depicts an important parameter influencing the product properties [7]. A basic factor in emulsion product design is therefore the knowledge of property functions (describing how its properties are influenced by its microstructure [8, 9]) and process functions (influence of process design and parameters on product microstructure).

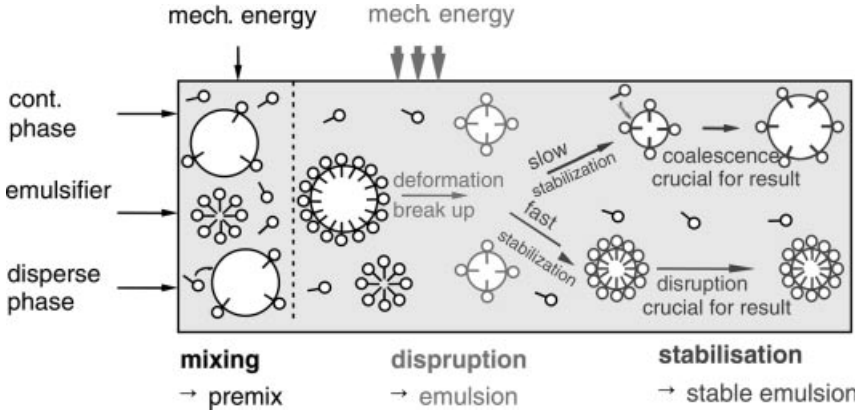


Figure 20.2 Scheme of principle of mechanical emulsification.

20.1.3

Principle of Emulsification

Emulsification combines the creation of fine droplets and their stabilization. In mechanical emulsification processes, emulsion droplets are created by first premixing the hydrophilic and lipophilic phases. The coarse droplets in the emulsion pre-mixes are then finely dispersed to the micrometer range or even smaller by deforming and disrupting them at high specific energies. In addition, droplets of micrometer size may also be formed directly by pressing the inner phase of the emulsion through channels of microporous systems (such as microporous membranes or microchannel devices). Whether directly formed or disrupted, the small droplets have to be stabilized against coalescence by adsorbing emulsifier molecules (Figure 20.2). Even when stabilized fairly rapidly, coalescence of newly created droplets is found to occur in nearly all technical emulsification processes [10, 11]. Due to coalescence, droplet diameters in emulsions are always larger than those that are predicted by disruption theory.

20.2

Emulsification Process Functions

20.2.1

Droplet Disruption Theory

Droplets are disrupted if they are deformed over a period of time t_{def} that is longer than a critical deformation time $t_{\text{def, cr}}$ and if the deformation (described by the Weber number We or capillary number Ca) exceeds a critical value [3]:

$$We > We_{\text{cr}} \quad \text{and} \quad t_{\text{def}} > t_{\text{def, cr}} \quad (20.1)$$

with

$$We = \frac{\sigma}{p_c} \quad (20.2)$$

$$p_c = \frac{4\gamma}{x} \quad (20.3)$$

$$t_{\text{def, cr}} = \frac{\eta_d}{\sigma - p_c} \quad (20.4)$$

where σ is the external tension responsible for droplet deformation, p_c the capillary pressure, γ the interfacial tension, x the droplet diameter and η_d its viscosity.

Droplet-deforming tensions are supplied by the continuous phase and act on the droplet interfaces. The emulsification machine itself only serves for the flow conditions required. Laminar shear flow, elongational flow, turbulent flow and cavitation-induced microturbulences are usually found in industrial emulsification machines.

20.2.2

Droplet Disruption in Turbulent and Laminar Flow

In *turbulent flow*, droplets are deformed and disrupted mostly by inertial forces that are generated by energy-dissipating small eddies. Due to internal viscous forces, droplets try to regain their initial form and size [12]. Two-dimensionless numbers, the turbulent Weber number We_{turb} and the Ohnsorge number Oh , characterize the tensions working on droplets in deformation and break-up:

$$We_{\text{turb}} = \frac{C^2 P_v^{2/3} \rho_c^{1/3} x^{5/3}}{\gamma} \quad (20.5)$$

$$Oh = \frac{\eta_d}{(\gamma \rho_d x)^{1/2}} \quad (20.6)$$

where C is a constant, P_v the volumetric power density, ρ_c the continuous phase density and ρ_d the droplet density. For very long deformation times, limits can be given for the droplet diameter after disruption in homogeneous isotropic turbulent flow [13]:

For low-viscosity droplet phases:

$$x_{\text{max}}|_{Oh \rightarrow 0} \propto \rho_c^{-1/5} \gamma^{3/5} P_v^{-2/5} \quad (20.7)$$

For highly viscous droplet phases ($\eta_d < 10 \text{ mPa s}$ [11, 12]):

$$x_{\text{max}}|_{Oh \rightarrow \infty} \propto \rho_c^{-1/2} \eta_d^{3/4} P_v^{-1/4} \quad (20.8)$$

The droplet deformation and relaxation time t_{def} depends on the turbulent velocity u' [2, 14]:

$$t_{\text{def}} = \frac{\eta_d}{\rho_c u^2 - \rho_c} = \frac{\eta_d}{C P_V^{2/3} x^{2/3} \rho_c^{1/3} - 4\gamma/x} \quad (20.9)$$

In continuous industrial emulsification, the residence time t_{res} in the zones of high power dissipation is in the order of milliseconds to tenths of a second, also influencing droplet disruption, as determined empirically [15]:

$$\bar{x} \propto t_{\text{res}}^{-0.3} \quad (20.10)$$

Since the exponents of residence time t_{res} and power density P_V are of the same order of magnitude (0.25–0.4), t_{res} and P_V may also be mathematically summarized to the volumetric energy density or specific disruption energy E_v [11, 16]. Thus the mean droplet diameter \bar{x} after droplet disruption in turbulent flow can be calculated by the process function:

$$\bar{x} \propto E_v^{-0.25 \dots 0.4} \eta_d^{0 \dots 0.75} \quad (20.11)$$

with

$$E_v = P_V t_{\text{res}} = \frac{E}{V} = \frac{P}{\dot{V}} = \Delta p_h \quad (20.12)$$

where E and P are the energy and power, respectively, being supplied by the emulsification machine, V the emulsion volume, \dot{V} the emulsion volume throughput and Δp_h the homogenizing pressure (in the case of high-pressure homogenization). The higher the energy density in disruption processes, the smaller is the mean droplet diameter achievable. Droplets of a low viscosity are more easily deformed and disrupted than droplets of higher viscosities.

Droplet disruption due to *laminar shear flow* has been widely investigated (e.g. [3, 17]). However, it is restricted to a narrow range of viscosity ratios (between disperse and continuous phase η_d/η_c for single droplet disruption or between the disperse phase and the emulsion η_d/η_e for emulsions [18] (Figure 20.3). *Laminar*

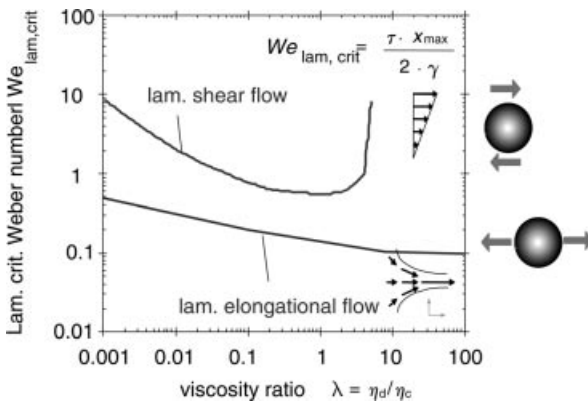


Figure 20.3 Droplet disruption in laminar shear and elongational flow: critical Weber number $We_{\text{cr, lam}}$ as a function of viscosity ratio η_d/η_c (single droplets [17]) or η_d/η_e (emulsions [18]).

elongational flow is of advantage if highly viscous disperse phases have to be disrupted [19]. The process functions for droplet disruption in laminar flow are as follows:

Laminar shear flow:

$$x_{1,2} \propto E_V^{-1} f(\eta_d/\eta_e) \tag{20.13}$$

Laminar elongational flow:

$$x_{1,2} \propto E_V^{-1} \tag{20.14}$$

Pure laminar shear and elongational flow are realized in special machines, most of them being on the laboratory scale (e.g. [19–24]). A mixture of laminar shear and elongational flow is found, for example, in porous media or packed beds from e.g. spheres [25] or micromixers. Laminar elongational flow is successfully applied in microstructured high-pressure homogenization valves, where it adds to the effect of turbulent droplet disruption by pre-deforming the droplets. Hence the droplet disruption efficiency can be significantly increased, especially for droplets of high viscosity [7, 26–28].

20.2.3

Droplet Formation and Detachment at Membrane Surfaces

In droplet disintegration processes, only a negligible part of the energy (<1%) is used for droplet disintegration itself, most of the energy being converted into heat. Producing droplets of the required size directly by a droplet-forming process is much more efficient [29]. This can be realized, e.g. by pressing the disperse phase through microporous systems, such as a membrane or microchannels. In order to form droplets, the capillary pressure has to be overcome. Forces acting on droplets in emulsification in microporous systems are the lifting force F_A , the gravitational force F_G , the impetus force F_I , the dynamic lifting force F_{dA} , the surface parallel resisting force $F_{W,c}$, the stream resisting force $F_{W,Tr}$, the inertial force F_T , the surface tension force F_γ and the static pressure force F_{stat} (Figure 20.4).

Transmembrane pressure drop:

$$\Delta p_{tm} = p_d - p_c = \Delta p_{pore} + p_{cap} \tag{20.15}$$

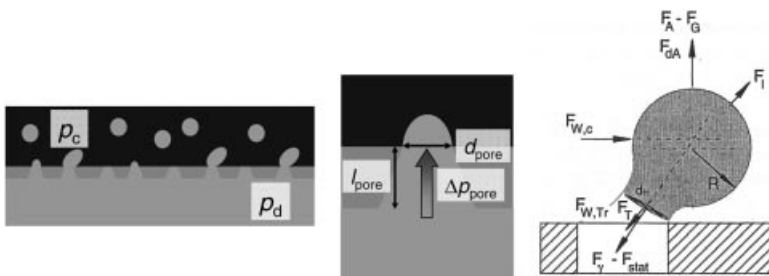


Figure 20.4 Droplet formation at the surface of micropores and forces acting on droplets in emulsification in microporous systems [31].

Capillary pressure:

$$p_{\text{cap}} = 4\gamma/d \quad (20.16)$$

Effective transmembrane pressure difference:

$$\Delta p_{\text{pore}} = \frac{32\eta l_{\text{pore}} V}{d_{\text{pore}}^2} \quad (20.17)$$

Relevant process parameters are the continuous phase wall stress, the diameter of the membrane pores and the trans-membrane pressure difference (Equation 20.17) [29]. For a given membrane, the sum of trans-membrane pressure difference and wall stress, being proportional to the specific energy E_v , and also the disperse phase fraction ϕ , govern the emulsification result (e.g. given as a Sauter diameter $x_{1,2}$):

$$x_{1,2} \propto \phi E_v^{-1} \quad (20.18)$$

No dependence on the dispersed phase viscosity is found. However, the dispersed phase flux depends closely on the dispersed phase viscosity [30].

20.3

Emulsification Processes

20.3.1

Conventional and Innovative Techniques

Emulsions can be produced by a wide range of industrially applied processes. Most often, droplets are formed and disintegrated mechanically (Figure 20.5). Rotor–stator devices and high-pressure homogenizers are emulsification techniques have been

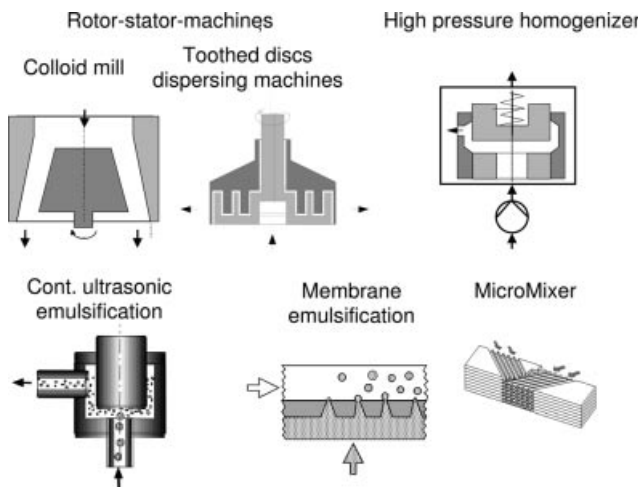


Figure 20.5 Emulsification devices (mechanical emulsification).

applied for decades. Even so, process optimization by enhancing droplet disruption efficiency is currently a relevant topic. Membrane, microchannel and continuous ultrasonic emulsification are techniques that have been under investigation within the last 15 years. Further, emulsions of very small droplet size, <100 nm, can be produced by a heating–cooling process twice passing the phase inversion temperature (PIT). These PIT emulsions are applied e.g. in cosmetic formulas [31, 32], but also work for specific emulsion-based formulations of active ingredients [33].

Optimizing the efficiency of droplet formation, disintegration and stabilization is the domain of microengineered devices. Here, micromixers, optimized high-pressure homogenizer nozzles and specific microfluidic devices such as microchannels are under investigation.

20.3.2

Microengineered Devices

20.3.2.1 High-pressure Homogenization Nozzles

High-pressure homogenizers have traditionally been used in the dairy industry. These machines are operated continuously at throughputs of up to several thousand liters per hour. They consist essentially of a high-pressure pump and a homogenizing nozzle. The pump creates the pressure, which is then converted within the nozzle to kinetic energy, which is responsible for droplet disintegration. The design of the homogenizing nozzle influences the flow pattern in the nozzle and hence droplet disruption [27]. Recent developments in high-pressure homogenization have concentrated on nozzle design [34, 35]. Microengineering is one of the tools applied. Examples of new homogenizing nozzles are opposing jets (e.g. Microfluidizer [36, 37]), jet dispersers [38] and a simple orifice valve [26] and developments based on it [39–43] (Figure 20.6). Droplet disruption in high-pressure homogenizers is predominantly due to inertial forces in turbulent flow, shear forces in laminar elongational flow and cavitation [2, 26, 39, 41, 42, 44].

20.3.2.2 Membranes, Microporous and Microchannel Systems

In conventional membrane emulsification, droplets are formed at the membrane surface and detached from it by wall shear stress of the continuous phase (Figure 20.8, middle) [29, 45, 46]. In addition to tubular membranes made from ceramics such as aluminum oxide, special porous glasses such as SPG (Shiratsu Porous Glass) membranes and polymers such as polypropylene [29, 47, 48], flat filter membranes made of PTFE [49, 50], nylon [51] and silicon [30, 51–55] have been used in emulsification. Silicon membranes are produced by microengineering techniques. This technology offers the possibility to influence precisely the structure of a membrane (arrangement of pores, pore shape, size and distance, porosity, surface characteristics, as shown in Figure 20.7). Very thin active layers reduce the pressure drop without losing mechanical stability.

The membrane's surface wetting behavior has a major influence: If the membrane is wetted by the continuous phase, emulsions of very narrow droplet size distributions are produced with mean droplet sizes in the range of three times the mean pore

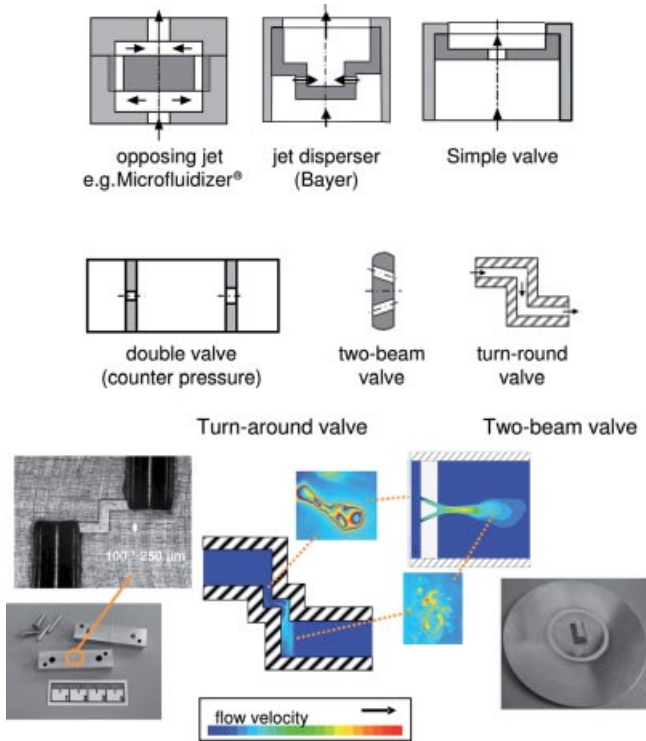


Figure 20.6 Recent developments in high-pressure homogenizing nozzles and microengineered valves.

diameter of the membrane [29]. The pressure to be applied should ideally be slightly above the capillary pressure [30, 47, 48]. Membrane emulsification reduces the shear forces acting in droplet formation. Hence it is the method of choice in the production of double emulsions or emulsions containing active ingredients [45, 58].

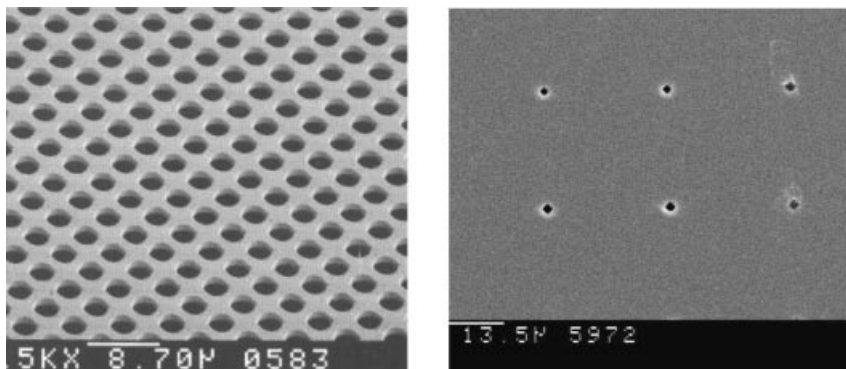


Figure 20.7 Microsieves as an example of microengineered membranes (source: Aquamarijn).

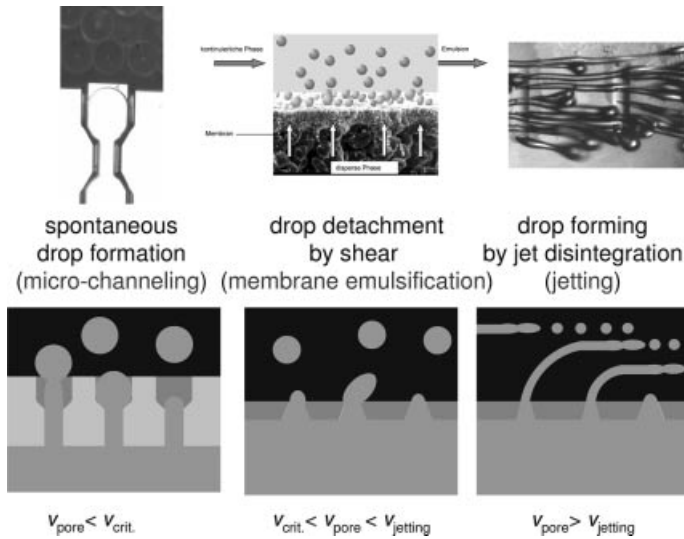


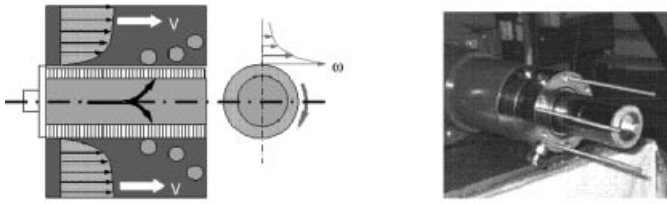
Figure 20.8 Conventional and innovative membrane emulsification principles: spontaneous droplet formation at microchannels (left), droplet formation and detachment at conventional membranes (middle) and jet formation at microengineered microsieves (right) as a function of dispersed phase pore velocity v_{pore} .

In conventional membrane emulsification, the process starts at a disperse phase content of zero. Increasing dispersed phase fraction requires recirculation of the emulsion. This, in turn, decreases the energy efficiency and prolongs industrial processes. Increasing the droplet phase throughput without losing the advantage of narrow droplet size distributions is the goal of recent developments: rotating membranes (Figure 20.9, top [53, 54]), droplet formation by jetting at microengineered membranes (Figure 20.8, right [30, 51, 59]) and premix emulsification (Figure 20.9, bottom [49, 51, 57]).

In premix membrane emulsification, emulsion premixes are pressed through the membrane pores. A phase inversion while passing the membrane is induced if the membrane surface is wetted by the droplet phase of the premix. Thus emulsions of high disperse phase fractions, even above 80%, can be produced at a throughput of up to several tons per square meter of membrane surface per hour. A narrow droplet size distribution requires a low number (2–3) of recirculations through the membrane. The mean droplet size is about twice the pore size [51].

If the disperse phase pore velocity is increased above a critical value in conventional membrane emulsification, jets emerge from the pore, which are stretched by the continuous phase. They become unstable (Rayleigh instability) and break into single droplets (“jetting”) [30, 51]. According to Cramer and coworkers [60, 61], the flow velocity of the continuous phase is of major importance for the formation of jets. A small pressure drop within the membrane (as e.g. in microengineered silicon membranes) is thus advantageous for jetting [51].

ROWE process (rotating membrane)



Premix-membrane emulsification

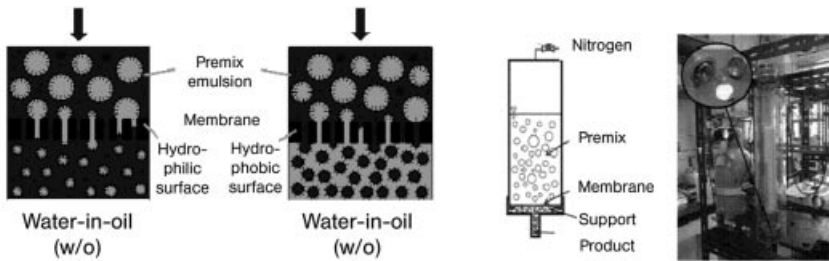


Figure 20.9 Processing applications of membrane emulsification: rotating membranes [53, 54, 56] and premix membrane emulsification [49, 51, 57].

Combining the advantages of microengineered membranes with increased shear at the membrane surfaces is the basis of rotating membranes (“ROME-process”) [53, 54, 62]. Mean droplet sizes are in the range of the membrane pore size.

By microchanneling (Figure 20.8, left), monodisperse emulsions may be produced in the absence of shear forces [63]. A strongly non-cylindrical geometry at the microchannel exit followed by a terrace is responsible for this effect [64, 65]. The droplet formation mechanism is limited to a critical velocity of the dispersed phase, above which the droplet sizes are widely distributed [51].

20.3.2.3 Microengineered Mixers (Micromixers)

Micromixers can also be used for emulsion forming, as they allow mixing of two phases within a short time and limited space and applying shear forces to the interfaces. As an example, two micromixer principles, one built at IMVT, Forschungszentrum Karlsruhe, and the other at IMM, Mainz, are depicted in Figure 20.10: V-Type MicroMixer (left), P-Type MicroMixer (middle) and Caterpillar Split–Recombine Microstructured Mixer (right). In the V-Type MicroMixer, the channels are cut straightforwardly in a metal foil (thickness <1 mm), clipped and stacked together. P-Type MicroMixer channels, in comparison, are cut round in the foil, whereby the outlet streams of both inlet streams meet in the same direction. In the Caterpillar Split–Recombine Microstructured Mixer, the two streams are combined vertically, split horizontally in half and combined again vertically, and so on.

In comparison with typical emulsification processes, shear stresses acting on the interfaces between continuous and dispersed phases are in a similar range to those

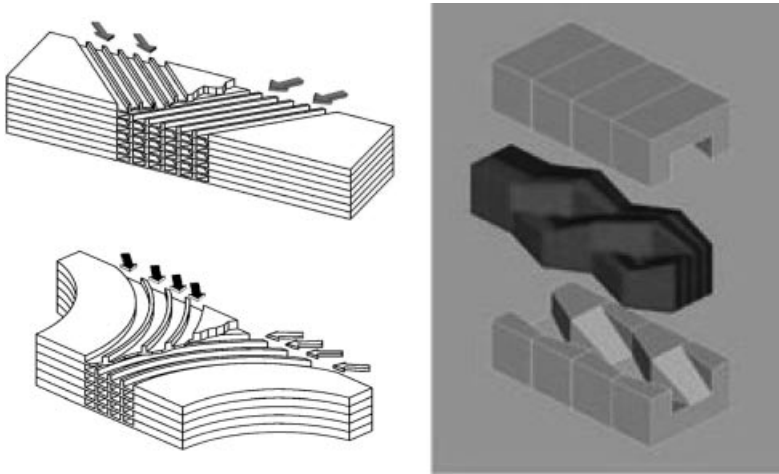


Figure 20.10 Schematic drawings of typical micromixers used for emulsification: V-Type MicroMixer (FZK, left), P-Type MicroMixer (FZK, middle) and Caterpillar Split-Recombine Microstructured Mixer [66] (IMM, right)

found in efficient “macro” mixers often used in the cosmetics and food industries. However, within the micromixers the flow conditions and thus resulting shear stresses are well defined whereas in typical mixing vessels shear stresses are widely distributed. Emulsification in stirred vessels (“macromixers”) thus implies a recirculation of the emulsions for up to several tens of minutes and usually results in very broad droplet size distributions (Figure 20.11, left). In contrast, well-defined shear stress profiles as applied in continuous micromixing result in narrow droplet size distributions (Figure 20.11, right).

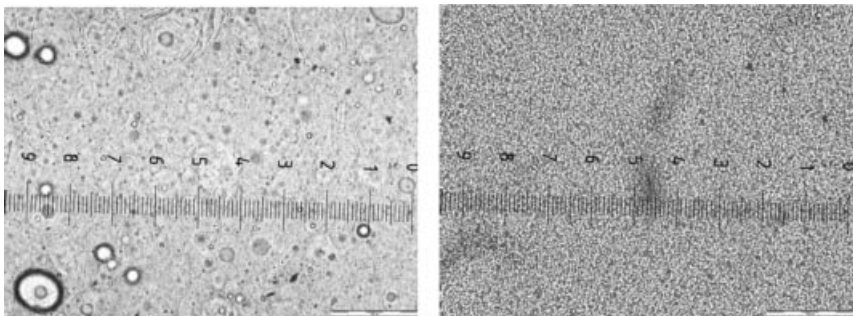


Figure 20.11 Photomicrographs of a fat-water emulsion. Left, produced by a rotor-stator system; right, produced by a micromixer. The body of the mixer applied consists of five foils stacked together, two foils for the aqueous phase and three for the fat phase, clamped between

cover plates. Each foil has a thickness of 200 μm and is structured with 10 channels. The channels have a width of 100 μm and a depth of 70 μm ; the channels are separated by walls with a thickness of 100 μm .

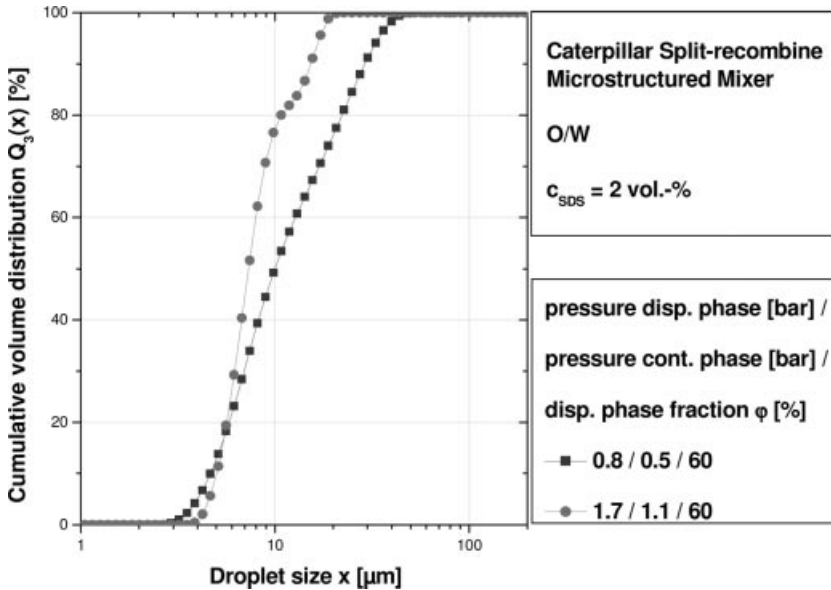


Figure 20.12 Influence of the pressure and pressure ratio on the droplet size of an oil-in-water emulsion produced by a Caterpillar Split–Recombine Microstructured Mixer.

Applying micromixers (such as the Caterpillar Split–Recombine Microstructured Mixer in the example shown) allows mixing of the phases and disruption of the droplets in one step. The micromixer is run with the dispersed phase on the first stream and the continuous phase on the second. Both streams are split and combined several times, producing small filaments of fluids, which disrupt in small droplets. The energy input applied is rather low. At an energy input of 0.8 and 0.5 bar (corresponding to $1.3 \times 10^5 \text{ J m}^{-3}$ in total), emulsions of a narrow droplet size distribution were produced (Figure 20.12). Increasing the energy input to 1.7 and 1.1 bar (total $2.8 \times 10^5 \text{ J m}^{-3}$) results in smaller droplets and narrower droplet size distributions. In the system depicted here, the interfacial tension without emulsifier was already below 2 mN m^{-3} , and with emulsifier added, even below 1 mN m^{-3} . With increasing interfacial tension, droplet sizes increase and, therefore, the energy input (or pressure) has to be increased significantly. If the energy input of the micromixed system cannot be adapted sufficiently, the droplet sizes are too high to achieve acceptable product qualities (in terms of, e.g., texture or stability).

20.3.2.4 Simultaneous Mixing and Homogenization (Microengineered SMH-Valve)

Combining high-pressure homogenization nozzles with micromixers helps in solving typical problems arising in emulsification. In droplet break-up, many small droplets result from a larger droplet and have to be stabilized by adsorbing emulsifier molecules. As the adsorption kinetics of some emulsifiers, such as food-grade emulsifiers, are fairly slow compared with droplet collision kinetics, droplet aggregation and coalescence are often observed in high-pressure homogenization.

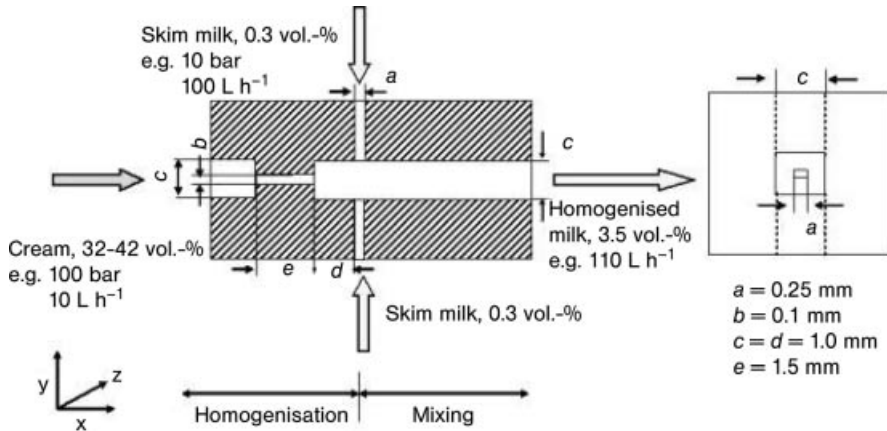


Figure 20.13 Principle design of the combined homogenization valve and T-shaped micromixer (SHM valve), developed at the University Karlsruhe (LVT) in cooperation with the Forschungszentrum Karlsruhe (IMVT). Example of application in the dairy industry.

Stabilizing them requires increasing the droplet distance by, e.g., diluting them directly after break-up. Microengineered devices combining the efficiency of a homogenization nozzle in droplet break-up with the possibility of mixing a second phase into the emulsion directly after their break-up are shown in Figure 20.13.

As an example, these microengineered nozzles could be successfully applied in solving typical production problems in the dairy industry. In milk homogenization, milk fat globules are disrupted and stabilized by casein micelles adsorbing not only on one but several globules at the same time. Hence high flocculation rates are found, preventing the dairy industry from increasing the fat content above 15–17 vol.%. However, if skim milk is injected into the droplet disruption zone, flocculation can be successfully suppressed. Applying a microengineered nozzle (SHM Simultaneous Homogenizing and Mixing Valve [67–69]), dairy cream with a fat content of up to 42 vol.% (as comes from the separation unit in industrial processes) can be homogenized and mixed directly with skim milk to the required final product fat content of 3.5% (full fat milk) or 1.5% (semi-skimmed milk) in one process step. This allows the dairy industry to reduce the volume to be homogenized at high pressures by up to 90% compared with full stream homogenization and thus results in energy savings of up to 60%.

Simultaneous Homogenizing and Mixing (SHM) valves allow for additional new applications. For example, inorganic nanoparticles, often of high abrasional character and destroying homogenization valves within minutes of production, can thus be added to emulsions, as recently proved for, e.g., pickering emulsions [67, 68, 70]. As the emulsion premix has to pass the homogenization valve at high pressure and the stabilizing nanoparticles are mixed to the emulsion by the T-shaped second stream at significantly reduced pressure, the durability of the valves is significantly increased without losing product quality.

20.3.3

Emulsification in Microengineered Devices

Emulsion product properties depend strongly on the droplet size distributions, and production costs depend on the energy to be applied for to achieve them. Thus, mean droplet sizes and droplet size distributions and the energy required are of interest in emulsion product and process design.

Different emulsification devices allow one to work in different ranges of specific energies and thus result in different droplet size distributions. Compared with conventional homogenization devices such as rotor–stator systems, homogenization nozzles optimized by microengineering allow for the energy use to be much more efficient (Figure 20.14). Membrane or microstructured fluidic devices (microchannels, microsieves and microporous membranes) decrease the specific energy required for target droplet sizes even more. Compared with macromixers (such as rotor–stator systems), micromixing results in lower mean droplet sizes at comparable specific energies as the flow conditions are well defined.

Increasing local turbulence by flow deflection, as shown in Figure 20.6 for the turn-around valve, results in the droplet size distributions being characterized by smaller droplets (Figure 20.15) at comparable pressures or specific energies applied [69, 71, 72].

Differences can be found not only in mean droplet sizes or specific energies required, but also in the width of droplet size distributions (Figure 20.16). High-pressure homogenization allows for the production of emulsions in the sub-micron range; however, the droplet size distributions are rather broad. In contrast, membrane emulsification results in droplet size distributions that are extremely narrow. Hence products with well-defined characteristics (e.g. release kinetics) can be produced, as required in, e.g., pharmaceutical applications.

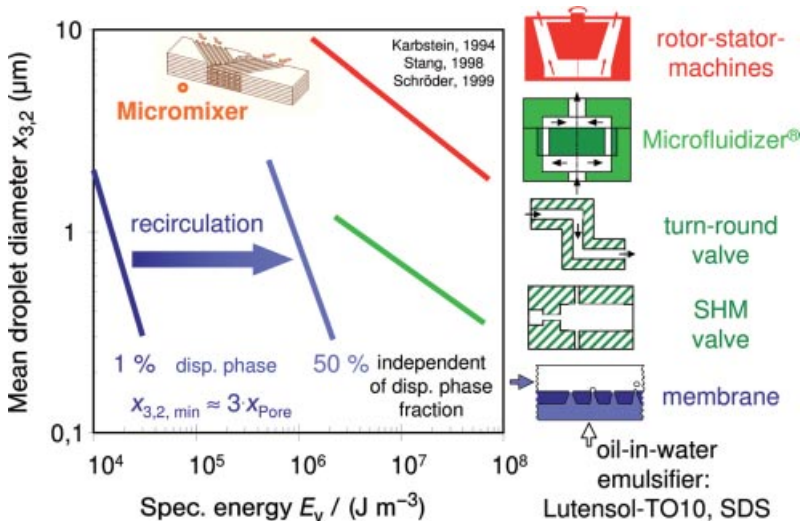


Figure 20.14 Droplet disruption and droplet formation in emulsification devices: different energy input, different efficiency.

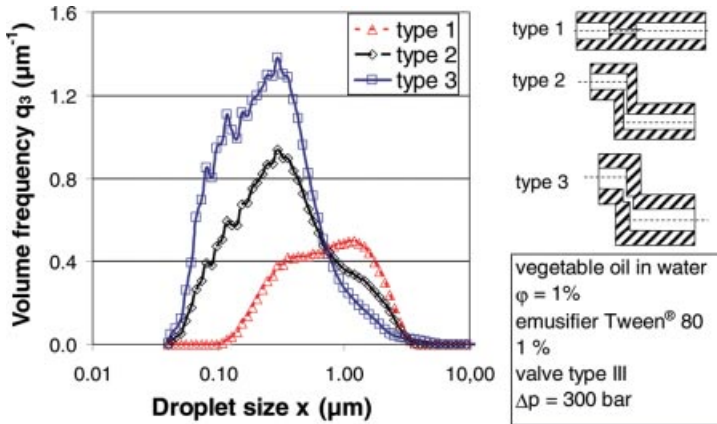


Figure 20.15 Influence of flow deflection in an orifice valve on the homogenization result at constant homogenization pressure or specific energy applied.

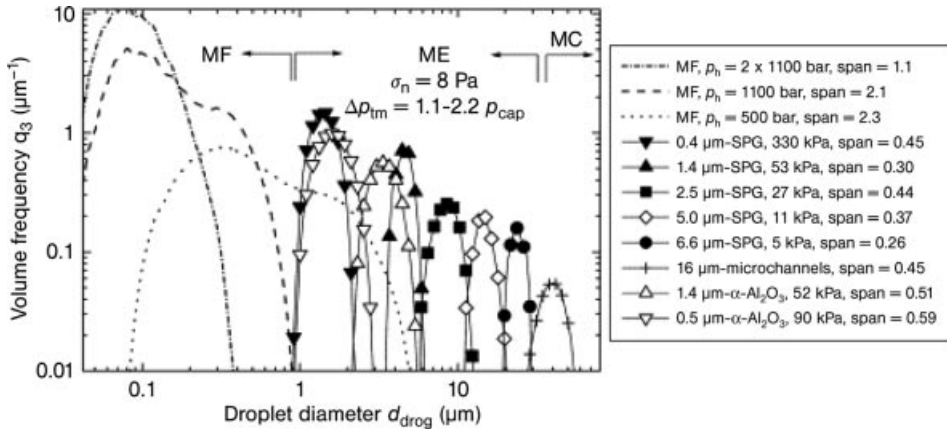


Figure 20.16 Influence of emulsification method on droplet size distribution (dispersed phase content ~1 vol.%) [73]. MF: high pressure homogenization (Microfluidizer) in comparison with SPG membrane, microchannel and α - Al_2O_3 membrane emulsification. The span value is a measure of the width of the droplet size distribution. It decreases when distributions become narrower.

20.4 Conclusion and Outlook

Emulsification techniques have been well investigated in recent decades, resulting in a broad knowledge of process and product design. Today they are applied not only in the production of liquid-liquid dispersions (emulsions themselves), but also in the

design of solid submicron-sized particles (nano-suspensions). Interesting results demonstrate that emulsification techniques open up new possibilities especially for solid particle design and active ingredient formulation. As submicron particles often enhance product quality, high-pressure dispersing and homogenization techniques are at the focus of future process developments. Microengineering allows for a target nozzle design. Whenever low shear is required (such as for formulations of shear-sensitive bioactive ingredients) or release characteristics have to be well defined, microengineered microfluidic devices (such as microchannel or microsieves) open up a new field of future production systems.

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