



Review

Micro-separation of fluid systems: A state-of-the-art review

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ABSTRACT

Micro-separation technology is based on the application of micro-structured equipment units. Such units contain structured elements with micro-scale dimensions. They are necessary for the implementation of classical downstream unit operations within the overall micro-scale production process. However, the development of micro-separation units for fluid mixtures faces substantial difficulties. This article gives an overview of current research activities in the field of micro-separation technology focusing on the unit operations extraction, absorption/desorption, distillation, as well as particle or droplets sorting. In addition, some examples are given for a combined application of different micro-separation operations. Both advantages and limitations of micro-separation operations are highlighted.

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1. Introduction

A characteristic feature of micro-process technology operations is that the contacting phases move through micro-structures. The prefix “micro” denotes structures with typical dimensions varying between sub-millimeters and sub-microns. Consequently, compared to conventional equipment, micro-structured units reveal extremely large specific surface-to-volume ratios. Moreover, at micro-scale, diffusion and heat conduction paths are shorter. Therefore, lower driving concentration and temperature differences are required for the transfer of a certain amount of mass or heat; alternatively, for fixed inlet and outlet conditions, shorter contact times and thus smaller unit volumes are necessary.

Up to now, major research activities dealing with micro-structured units have been focussed on reaction, mixing and heat-transfer technologies as well as on analytics [1–13]. Despite a very wide range of research initiatives [14] – not least due to the completely new aspects brought by the above-mentioned encouraging characteristics – pilot-scale or industrial applications are still hardly known [15–17].

On the contrary, the number of published research results in the field of fluid process engineering at micro-scale (micro-separation technology) is rather limited. This makes the development of micro-technological production processes difficult.

This article gives an overview of the essential developments in the field of micro-separation technology. The main focus is put on unit operations in fluid mixtures, namely distillation, liquid/liquid extraction as well as absorption and desorption. In addition, continuous size separation of particles or droplets is considered, because it is closely related to micro-fluidic operations. Finally, examples are given, in which the application of different micro-separation units is used within a micro-plant for the multi-step continuous-flow micro-chemical synthesis. Micro-contactors for carrying out two-phase or multiphase reactions are out of focus of this article. Comprehensive reviews on such units can be found in [18,19].

2. Liquid–liquid extraction

In liquid/liquid extraction processes, separation of liquid substances from a mixture is performed by means of a liquid solvent, while two steps – mixing (fluid contacting) and phase separation – are usually involved. Extraction requires that the liquid solvent (extraction agent) is only partly miscible or fully immiscible with the carrier liquid phase. Conventional extraction processes are usually performed in extraction columns or mixer-settler units, where one phase is dispersed in another phase. The relatively large dimensions of such units have a negative influence on the mixing quality and, consequently, on the separation efficiency. Therefore, miniaturisation seems to represent an appropriate way to improve the mass transfer between the two phases. In this context, diverse strategies are followed.

2.1. Extractors with membranes

2.1.1. Membranes stabilising phase interface

Similar to conventional separation processes, it is expected that operations at micro-scale can reach separation efficiency of several theoretical stages, and, therefore, a counter-current flow regime is usually preferred. However, it is difficult to realize stable counter-current flow in micro-channels, because of very high shear stresses. A possibility to stabilise the phase interface between two immiscible liquids is given by application of porous membranes, and, hence, polymer membranes with hydrophobic characteristics are often used. Consequently, the pores are filled by the organic

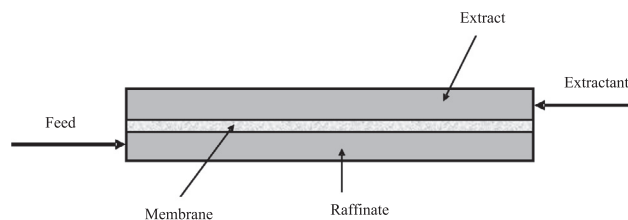


Fig. 1. Schematic set-up of a micro-extractor with separating membrane: feed and extraction phases are separated by a porous membrane in counter-current flow; mass transfer takes place through the phase interface immobilised at the pores.

phase and the phase interface is fixed at the pore edges. The stability of the interface is secured as long as the pressure drop over the pores does not exceed the capillary pressure. Fig. 1 illustrates the schematic set-up of such a micro-extractor.

An example of the application of micro-extractors with membranes is presented in [20]. Two different membranes were used in the two examined units, namely a 25 μm strong polyimide film (Kapton[®]) with a porosity of 26% and a pore size of 25 μm , and a 180 μm strong conventional PTFE film (Teflon[®]) with a porosity of 44% and a pore size of 3 μm . The first membrane was additionally coated with Teflon in order to further reduce the affinity towards water and hence to increase the breakthrough pressure. The channels at both sides of the membrane had the same dimensions; they were 100 mm long, 10 mm wide and had different depths of 200, 300, 400 and 500 μm .

Based on the test system water/cyclohexane/cyclohexanol, it could be shown that the channel depth reduction from 400 to 300 μm resulted in a remarkable increase of the extraction degree, whereas a further reduction to 200 μm brought nearly no change. This indicates that, for small channel depths, the mass transfer resistance is concentrated in the membrane pores. Both compared membranes showed similarly high separation efficiency.

Cai et al. [21] developed a microchip extractor composed of two 1.7 mm strong glass plates, each with an etched micro-channel, and a PTFE membrane placed between the two glass plates. The micro-channel for the aqueous phase on the top plate was 20 mm long, 500 μm wide and 65 μm deep. The micro-channel for the organic phase on the lower plate had the same width and depth; however it was 17 mm long. To regulate the flow rates, a reservoir with an adjustable height was installed at a support structure for each phase. The set-up and function principle of the microchip extractor are illustrated in Fig. 2.

With the microchip extractor developed in [21], the extraction of rhodamine B from water by isobutanol was studied and the concentration changes through the measurements of the fluorescence intensity were determined. In a first study, the flow rate of isobutanol was raised step by step from 3 to 13 $\mu\text{L}/\text{min}$, while the flow rate of the aqueous solution was kept at 35.7 $\mu\text{L}/\text{min}$. A reduction of the outlet concentration of rhodamine B in the aqueous phase by 55% could be observed. Finally, the flow rate of the aqueous phase was gradually reduced from 65 to 22 $\mu\text{L}/\text{min}$, with the flow rate of isobutanol being constant at 8.2 $\mu\text{L}/\text{min}$. On the overall, the reduction of the aqueous-phase flow rate caused a 63% reduction of the outlet concentration in the aqueous phase.

Supported liquid membrane (SLM) extraction is an excellent technique for selective removal of ionisable and polar compounds from aqueous samples [22]. It is a three-phase system, where the solutes are extracted from an aqueous solution into another aqueous solution through an organic extractant held in the pores of the membrane by capillary action. Wang et al. [23] designed and fabricated SLM micro-extractors for the enrichment of haloacetic acids in aqueous solutions. The supported liquid membrane was made by soaking a small piece of membrane in 5% trioctylphos-

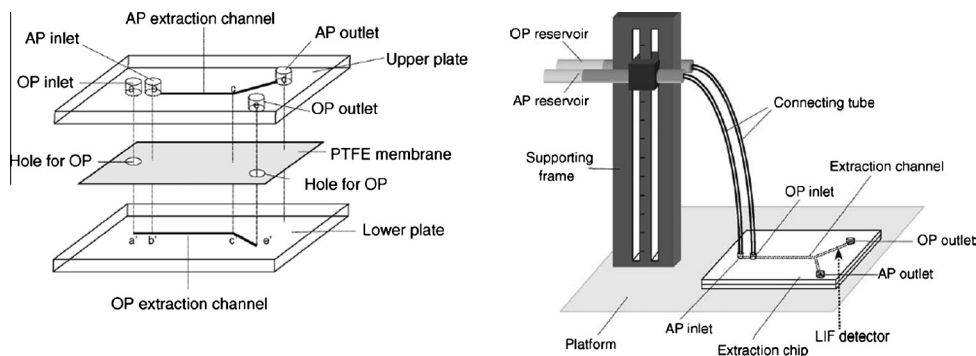


Fig. 2. Schematic set-up of a microchip extractor (left): the flows of the aqueous phase (AP) and the organic phase (OP) are regulated by height-adjustable reservoirs (right) [21].

phine oxide (TOPO) in di-hexyl ether (DHE) for 10 min, and then it was fixed between the polycarbonate blocks, forming the two micro-channels for two different aqueous phases. Highly concentrated solutes could be obtained, while the channel dimensions and the flow rates significantly influenced the extraction efficiency.

2.1.2. Membranes as dispersion medium

Membranes can be used for the creation of liquid–liquid dispersions in extraction processes. For instance, membrane dispersion micro-extractor with a micro-filtration membrane as the dispersion medium was developed in [24,25]. The continuous phase was pumped into the top side of the membrane (the mixing room), while the dispersed phase was pumped into the bottom and went through the stainless steel micro-filtration membrane (see Fig. 3) [25]. The membrane usually has very small average pores (e.g. 5 μm), and the mixing room also has a small scale (e.g., 2.5 cm \times 0.5 cm \times 2 cm). The two phases were mixed and the mass transfer occurred in the mixing room when micrometer-sized dispersed-phase droplets filtered through the membrane entered the cross-flow of the continuous phase. The performance of the membrane dispersion micro-extractor was tested with six extraction systems in [25], and the effects of flow rates on mixing and mass transfer characteristics as well as the relationship between the trans-membrane pressure and dispersed phase flow rate were studied. Similar to other micro-mixers, with an increase of volume flow rate, the size of droplet decreased and a higher extraction efficiency could be obtained in membrane dispersion micro-extractors due to the increase in specific interfacial area and decrease in diffusion paths. When the flow rates were high enough, the droplet diameter reached a minimum value (about 20 μm) and the extraction efficiency could achieve 100%, with a residence time less than 0.2 s. The capacity of this kind of micro-extractors reaches around 500 $\text{m}^3/(\text{m}^2\text{h})$.

2.2. Extractors with surface-treated channel walls

A further possibility to stabilise the phase interface between two continuous phases in micro-channels is given by the corresponding surface treatment of the channel walls. An organic and an aqueous phase may flow in a micro-channel either co-currently or counter-currently. The aqueous phase passes through the channel part, which is supplied with a hydrophilic coating, whereas the organic phase goes through the channel part with a hydrophobic coating. Thank to such an arrangement, it is possible to stabilise the phase interface in the middle part of the channel (“pinning”) and to ensure both co-current and counter-current flow of two continuous phases, as the capillary pressure balances the emerging pressure differences between the phases. This approach helps to obtain exactly defined phase interfaces and contact times between the two phases, and the interface is formed within just few seconds [26].

Oota et al. [27,28] used a horizontal glass channel, with its upper half treated with the caustic soda, in order to obtain a hydrophilic surface. The lower half of the channel was treated with octadecyltrichlorosilanes (OTS) in order to create a hydrophobic surface (see Fig. 4).

A mathematical model was developed to describe the fluid dynamics of two counter-currently flowing immiscible liquids [28]. This model was based on the Navier–Stokes equations supplied with the no-slip conditions at the walls and the continuity of velocities and shearing stresses at the phase interface. The model could be validated using fluorescence experiments with the test system water/butyl acetate. The same system was used to experimentally investigate the operating limits for the existence of a stable phase interface [27] (see Fig. 5).

In a further test series carried out in [27], extraction of cobalt tri(2-nitroso-5-dimethylamino phenolate) from toluene in water

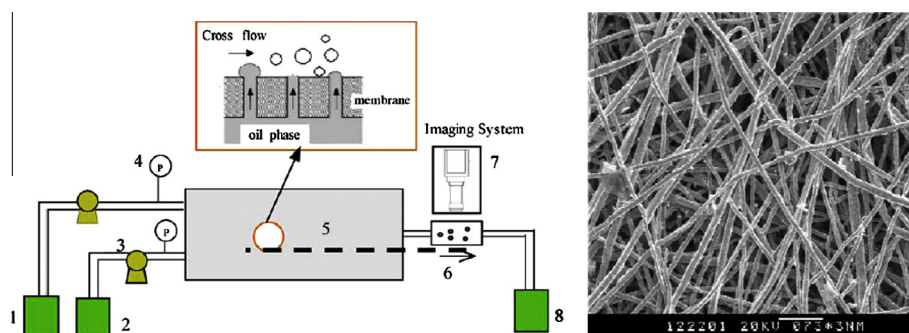


Fig. 3. Experimental set-up for extraction in membrane dispersion micro-mixer (left) and SEM image of the membrane surface (right) (adapted from [25]): (1) continuous phase tank, (2) dispersed phase tank, (3) pumps, (4) pressure meters, (5) mixing room, (6) watching room, (7) imaging system, and (8) mixed solution reservoir.

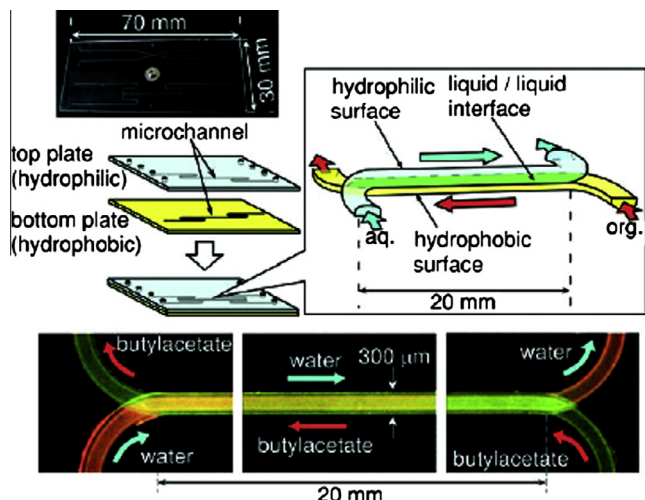


Fig. 4. Set-up of a micro-extractor [27]: the upper part is hydrophilic, whereas the lower part is hydrophobic; the phase interface between the two channel halves is “pinned” (above); fluorescence microscopic image of the counter-current flow in the operated micro-extractor (below).

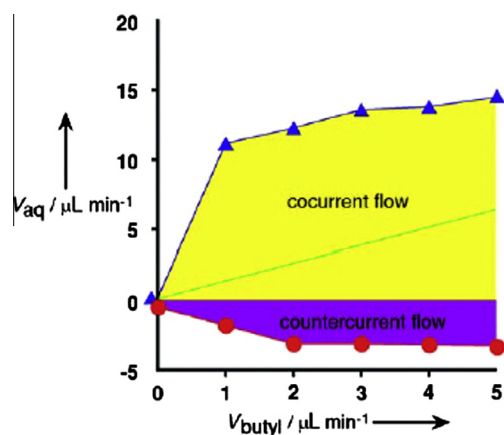


Fig. 5. Operating limits of the micro-extractor as function of volume flow rates of both phases [27]: the straight line denotes the operating line for untreated micro-channel walls; the triangles denote the operating limits for co-current mode and the circles denote the operating limits for counter-current mode.

was studied. The volumetric flow rates of both phases were equal and varied between 0.15 and 1.0 $\mu\text{L}/\text{min}$. In these experiments, the number of theoretical stages as function of volumetric flow rates could be determined.

Maruyama et al. [29] reported a parallel three-phase flow (water/*n*-heptane/water) in a micro-channel and used the organic phase (middle phase between the two aqueous phases) as a liquid membrane for separation of metal ions. They fabricated this micro-channel with photolithographic wet etching method. The confluent part of the three inlet channels was 3 cm long, 150 μm wide, and 25 μm deep, and the inlet and outlet channels were 50 μm wide and 25 μm deep, respectively. The surface modification of the middle outlet channel (for the organic phase) was realised using three-phase laminar flow in the device. Toluene solution containing 10 vol% OTS from the central outlet channel and pure toluene from the side outlet channels were fed in parallel. The flow rates of both solutions were kept at 0.5 mL/h for 2 h. The OTS solution flowed between the toluene phases along the confluent micro-channel, resulting in the chemical modification of the centre part of this channel. In [29], iridium ion could be selectively transported through the organic phase, and the continuous separation of the three

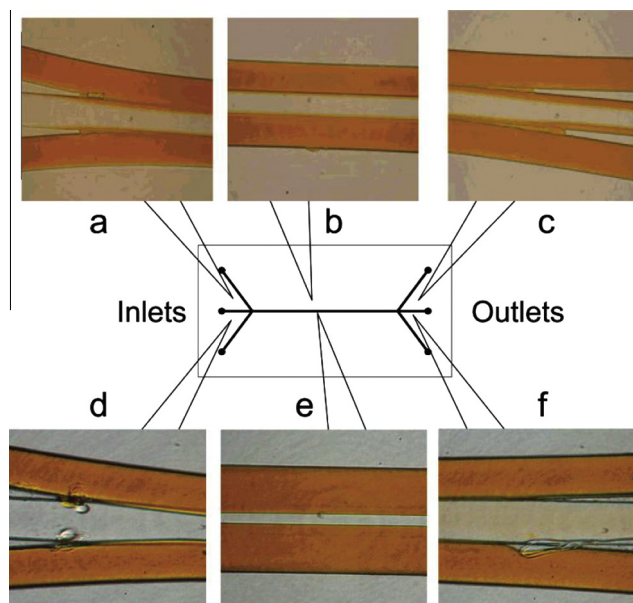


Fig. 6. Photographs of the three-phase flow in the micro-channel [29] without (a–c) and with (d–f) surface modification with octadecylsilane groups: (a and d) inlet junctions; (b and e) middle part of the micro-channel; (c and f) outlet junction; flow rates of the aqueous and organic phases were 0.4 and 0.7 mL/h for the case (a–c), and 0.4 mL/h for the case (d–f).

phases was achieved in the outlet channels due to the local surface modification (see Fig. 6).

2.3. Micro-mixer-settler units

Micro-mixer-settler units represent a further category of liquid/liquid extractors. Usually, creation of high liquid–liquid dispersions and a large specific interfacial area for the mass transfer are beneficial to extraction processes. For many extraction applications, it is necessary to quickly separate two immiscible liquid phases after mixing. The high dispersion (excellent mixing) and fast phase separation are difficult to realize in the same micro-device and within the same time period. Therefore, these two process steps are often treated separately using micro-mixers and micro-settlers. When studying the mixing performance and extraction efficiencies in micro-mixers, batch processes (e.g., separatory funnels) are usually used for the phase separation.

2.3.1. Micro-mixers

The diversity of micro-mixer concepts is large. Generally, micro-mixers can be classified as active or passive mixers according to the mixing principle applied. Passive micro-mixers that are easy to design and manufacture are widely used for laboratory tasks; they also have a high application potential in the field of micro-separation operations. In this section, we focus on the extraction applications of passive micro-mixers. Comprehensive reviews on active micro-mixers can be found elsewhere (see, e.g., [30,31]).

Compared to conventional mixers working in a turbulent flow regime, micro-mixers can achieve up to ten times better mixing efficiencies, i.e. they provide almost complete mixing at ten times shorter unit lengths than those typical for conventional mixers. For the laminar regime, the micro-mixers are even up to 40 times better [32]. Since the efficiency of mass transfer between the immiscible liquid phases is greatly enhanced by enlarged specific interfacial area, high dispersion of these phases is an indispensable prerequisite to achieve total phase saturation. The specific interfacial area itself is inversely related to the droplet size of the disperse

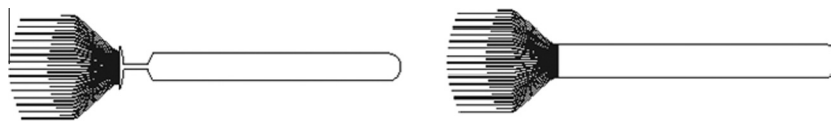


Fig. 7. Schematic representations of the applied glass chambers [36]: slit-shape mixing chambers (left), rectangular-shape mixing chambers (right); both chambers are 150 μm high and 3250 μm wide.

phase. Therefore, when designing micro-mixers, the main focus lays on the generation of possibly small droplets in order to increase the phase interface and to enhance mass transfer. In this regard, it is of particular interest to identify the way to influence both the average droplet size and the droplet size distribution by the micro-mixer structure and by different process parameters.

Passive micro-mixers can be differentiated according to their micro-structures realising the mixing process [30]. Typical micro-structure designs are T-flow (e.g., [33]) and Y-flow (also mentioned as T-shaped and Y-shaped) structures (e.g., [34,35]), interdigital structures as well as those working in accordance with the functional principle “split and recombine” (SAR). In what follows, the last two principles are discussed in details. Further, packed-bed micro-structured mixers are also reviewed.

Pennemann et al. [36] examined the droplet formation in micro-mixers based on an interdigital arrangement of corrugated inlet channels. They generated several lamellae moving in parallel to each other, yet separated from the continuous phase. This mixing principle was called multilamination. Two kinds of a micro-mixer made of glass were investigated, namely a slit-shape glass mixer and a rectangular-shape glass mixer, with an identical inlet channel structure (2×15 inlet channels, 60 μm wide, 150 μm high), but with different geometry of the mixing chambers. Both mixing chambers are illustrated in Fig. 7.

Experiments with the rectangular-shape glass mixer and a test system dodecan (disperse phase)/aqueous NaCl-solution (continuous phase) helped to discriminate two droplet formation modes. At total volumetric flow rates below 800 mL/h, the droplets are formed directly at the interdigital structure, and this results in a relatively large average droplets diameter ($>300 \mu\text{m}$). An increase in the total volumetric flow rate brings about significantly smaller droplets (average droplet diameter $<250 \mu\text{m}$). In this case, initially, lamellae are formed that subsequently decompose due to hydrodynamic instabilities (the so-called Rayleigh-Plateau instabilities). Higher continuous-to-disperse phase ratios also result into smaller droplets; however, this happens only at higher flow rates. This can be explained by the hydrodynamic focusing, according to which the dodecan lamellae narrow after leaving the channel thus tightening smaller droplets.

A comparison of slit-shape glass mixers with rectangular-shape glass mixers was performed based on the test system silicon oil (disperse phase)/water (continuous phase). It was found that the droplet diameter decreased much stronger with the total volumetric flow rate increase in slit-shape glass mixers than in rectangular-shape glass mixers. In a slit-shape glass mixer, the droplet formation can no longer be explained by hydrodynamic instabilities, rather it is mainly caused by the changed fluid dynamics resulting from the focused fluid flow through the slit geometry and its subsequent expansion. Vortices appear at this point, their intensity depending on the energy input, i.e. the flow rate of inflowing fluids. It can be expected that the formation of vortices induce additional shear forces.

Haverkamp et al. [37] and Löb et al. [38] investigated the so-called standard slit interdigital micro-mixer SSIMM developed at IMM (Institut für Mikrotechnik Mainz), which has a similar interdigital arrangement of inlet channels as the glass micro-mixers described above (see Fig. 8).

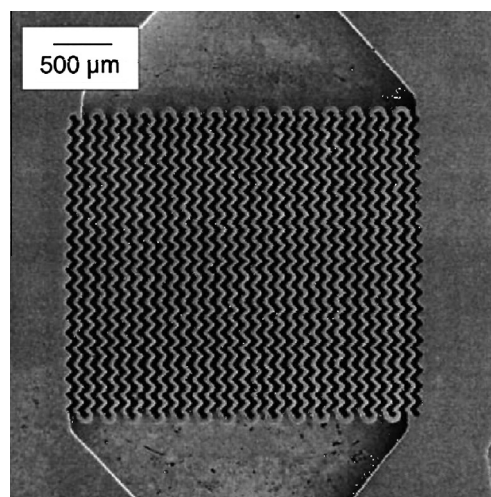


Fig. 8. Scanning electron microscope graph of the inlet channel of the SSIMM [37]: the structure consists of 2×15 interdigital corrugated channels.

A slit-shaped mixing chamber is connected to the inlet channel structure. The housing of this micro-mixer is made of stainless steel. In [37], the influence of the total volumetric flow rate on the droplet size distribution was experimentally investigated using the test system silicon oil/water. Whereas for low flow rates (300 and 400 mL/h), bimodal distribution of droplets – relatively narrow for small droplets and relatively wide for bigger ones – dominated, it became unimodal and more uniform when the total flow rate rose to 600 and, further, to 1200 mL/h. Within the course of these experiments, the average droplet diameter continuously decreased from 65 μm (300 mL/h) to 18 μm (1200 mL/h). In [38], the extraction efficiency of the SSIMM was experimentally determined by extracting the colouring agent Nile red from a continuous aqueous phase into a disperse *n*-heptane-phase. The increase of the total flow rate caused two opposite effects, which have a direct influence on the mass transfer between the two phases. On the one hand, the average diameter of droplets decreased, resulting in an increase in the mass transfer area. On the other hand, the residence time in the mixer was reduced. The interaction of these two effects brought about a minimum in the functional dependence of the extraction performance on the total flow rate (see Fig. 9).

Schönfeld et al. [39] studied the “caterpillar micro-mixer”, developed by IMM and based on SAR mixing principle, numerically, with the aid of computational fluid dynamics (CFD). This mixing principle is based on a multi-stage process. Each individual mixing stage comprises both unit operations separation and mixing, or, more exactly, a separation of a two-layer or multi-layer flow into partial flows perpendicular to the lamellae orientation and their recombination. Usually, this step is followed by a flow re-orientation. By halving the layer thickness, the diffusion path per mixing stage is reduced by 50%, too. Fig. 10 illustrates this multilamination principle as well as the schematic set-up of the studied micro-mixer. Based on the simulation results, micro-mixer optimisation strategies towards a more uniform configuration of the lamellae were proposed.

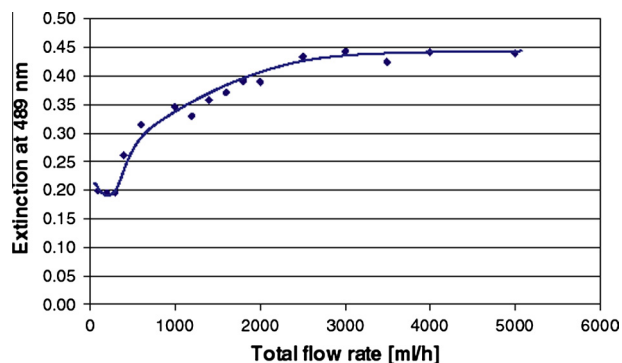


Fig. 9. UV absorption rate of extracted Nile red at 489 nm as function of the total volumetric flow rate [38]: here, the UV absorption rate is a measure for the concentration of Nile red in *n*-heptan and hence for the extraction performance.

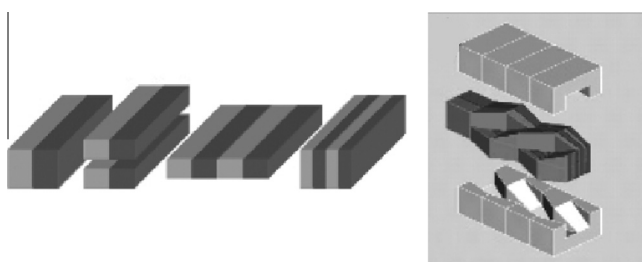


Fig. 10. SAR functional principle: Initial configuration, separation, reunion and reorientation of the two-phase flow (left); schematic set-up of two mixing stages in “caterpillar micro-mixer” (right); the dark and light layers display the different, non-miscible phases [39].

Mae et al. [40] developed two different designs of a micro-mixer, YM-1 and YM-2, which were also based on the SAR functional principle. The variant YM-1 consisted of altogether eleven different mixing stages; the first stage comprised eleven mixing elements. The number of mixing elements was gradually (one by one) reduced from stage to stage. In the variant YM-2, all eleven stages contained a constant number of 36 mixing elements. In each mixing element, two liquid flows were brought together and afterwards separated perpendicular to the cross-sectional area. For each mixing stage, the number of lamellae in both leaving streams was doubled. Both mixers were found to be suitable for industrial mass production applications.

In [40], the test system oil/water was used to examine the influence of the total volumetric flow rate and the phase ratio on the resulting droplet size distribution and on the average droplet size. It was found that, in case of increasing entire flow rate, the droplet size distribution became unified and the average droplet diameter reduced. This observation is in line with those for other micro-mixing units, such as the above-mentioned slit-shape glass mixer. Furthermore, in [40], the influence of the number of mixing stages was tested. It was discovered that the increase of the mixing stages caused a significant reduction of the average droplet size and unified the droplet distribution. However, already with five mixing stages, the unit showed a very similar distribution of droplets as with eleven stages.

In addition, the two mixing options of the IMM interdigital mixer SSIMM were compared with respect to the droplet distribution using the test system oil/water (phase ratio 1:4). Finally, the extraction of phenol from dodecan by water in YM-1 was investigated. It could be observed that in order to reach the equilibrium concentration, a total volumetric flow rate of 2.4 L/h was necessary at a phase ratio of 1:1, while the contact time was just 0.3 s.

In order to prevent the coalescence of dispersed droplets or to create larger specific interfacial areas for the mass transfer in extraction processes in micro-mixers, a placement of small constrictions or micro-particles was proposed [41–43]. Rothstock et al. [41] designed and fabricated a redispersion micro-mixer for liquid–liquid biphasic processes, in which the emulsification performance was investigated using the *n*-heptane/water system. It was demonstrated that a raw dispersion was refined or refreshed by repeated breakage of the droplets over the length of the reactor achieved with special micro-structured redispersion units. Two types of such units (foam and steel insets) resulted in different pressure drop and different dispersion performance in the micro-mixers. At a given flow rate, the steel insets delivered a smaller droplet mean diameter compared to the foam insets, which could be correlated to the higher specific energy input obtained in the former case.

Jovanović et al. [42] proposed an interdigital mixer-redispersion capillary assembly for preventing the liquid–liquid droplet coalescence. The redispersion capillary consisted of 1-mm-long constrictions with 0.25 mm inner-diameter, distanced 0.50 m from each other along the mixing channel. The application of these constrictions can prevent the droplet coalescence and results in finer droplets compared to those in mixing channels without constrictions, while the specific surface-to-volume ratio can be increased up to $230,700 \text{ m}^2 \text{ m}^{-3}$ by controlling the total flow rate and the ratio between aqueous and organic phases.

Su et al. [43] investigated the extraction processes in micro-channel mixers and packed-bed micro-channel mixers. It was found that a higher dispersion of two immiscible liquid phases could be obtained in the packed-bed micro-channels compared with non-packed micro-channels. The dispersion performance depended on the packing length of micro-particles and the flow velocity. The diameter of droplets produced in the packed-bed micro-channel was even less than $10 \mu\text{m}$ at high flow rates. The packing section made of micro-particles ensured better mixing performance and larger specific interfacial area, and clearly improved the mass transfer performance. The maximum extraction efficiency in the packed micro-channel reaches 96%, which approaches an equilibrium stage value and is much higher than the maximum extraction efficiency in the non-packed micro-channel (61%).

2.3.2. Micro-settler

Regarding the micro-mixers discussed above, it has to be said that the energy required for phase separation increases with decreasing droplet sizes. Thus, in order to benefit from a fast dispersion formation in a continuous extraction process, a prompt and efficient phase separation in a settler is required. In conventional settler types, the phase separation occurs in settler vessels due to the difference in density. At micro-scale, however, the gravity forces are much lower compared to the surface tension forces, and, hence, it is extremely difficult to reach a complete phase separation by using density differences.

Kralj et al. [44] described the liquid/liquid phase separation using capillary forces. A PTFE membrane was applied, with pores with diameters between 0.1 and $1 \mu\text{m}$. Owing to their surface properties, the pores of the membrane were filled selectively by organic liquids. If a dispersion consisting of an aqueous and an organic phase flows over the membrane (see Fig. 11), the organic phase penetrates through the pores, due to the wetting behaviour and the pressure difference at both sides of the membrane, whereas the aqueous phase retains. The phase separation works as long as the difference in pressure at both sides of the membrane is lower than the capillary pressure.

Okubo et al. [45] described a novel micro-coalescence unit, consisting of an upper glass plate, a PTFE bottom plate and side walls

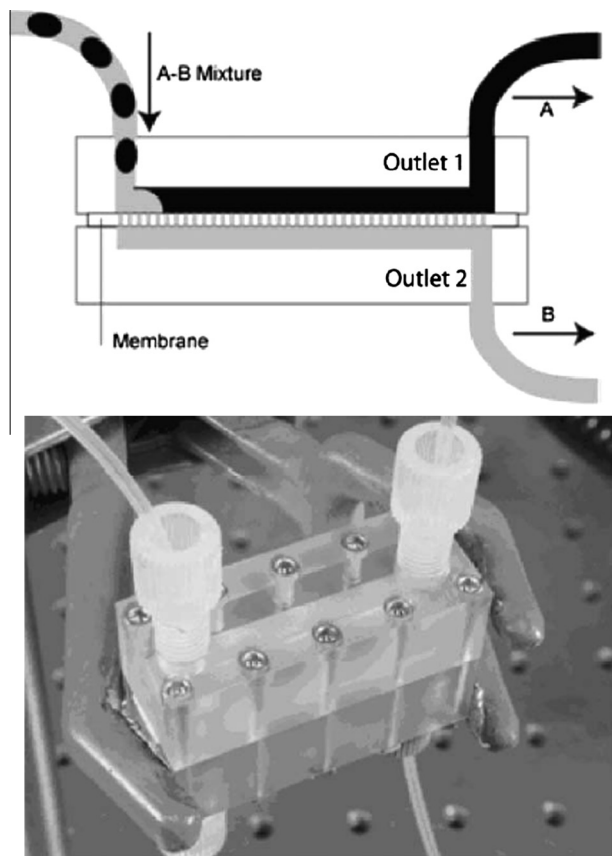


Fig. 11. Schematic representation (above) and photo (below) of a micro-membrane separator [44]: The representation above shows a disperse flow consisting of an aqueous phase (A) and an organic phase (B) separated by a hydrophobic membrane.

made of aluminium film. The distance between the glass and PTFE plates was 12–100 μm . Fig. 12 illustrates the schematic set-up of the micro-coalescence unit.

The dispersion comprising water (continuous phase) and dodecan (disperse phase) was fed into this micro-unit originated from the IMM mixer. The phase separation behaviour was investigated for different distances between the plates at a total flow rate of 3 mL/min (water/dodecan ratio 9:1). When the distance between the panels was 12 μm , intensive coalescence nearly resulting in a complete phase separation could be observed. Only a very insignificant amount of small dodecan droplets with diameters lower than 10 μm could be detected, while the contact time was just 0.01 s. An increase of the distance between the plates up to 100 μm changed the situation, namely, most of the droplets left the apparatus without any change and only few coalescence actions took place. This result can be explained by the fact that organic droplets cover the PTFE plate, whereas water is repelled by PTFE. These different wetting properties cause a velocity difference between the two

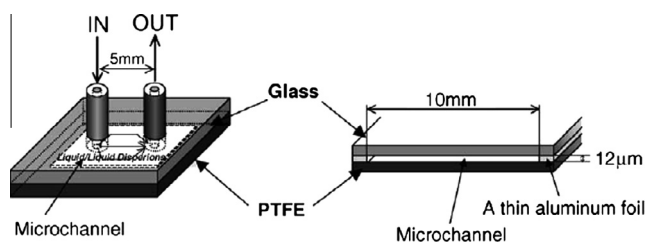


Fig. 12. Schematic set-up of a micro-coalescence unit [45].

phases, because larger organic droplets, whose diameter exceeds the channel height, are slowed down. Smaller droplets, which are not slowed down by the PTFE plates, catch up with the larger droplets and coalesce with them.

Kolehmainen and Turunen [46] performed experiments with an analogous arrangement and the test system water/Shellsol D60 (phase ratio 1:1; total volume flow rate 3 mL/min). In contrast to [45], they reported that a high phase separation efficiency was reached even in those cases, in which a large portion of the droplets in the dispersion was smaller than the channel height. In this context, the conclusion was made that, first, smaller droplets coalesce into bigger droplets, and afterwards, the latter are slowed down due to the influence of the PTFE plate.

Wengeler et al. [47] presented studies on a micro-hydro-cyclone developed by Ehrfeld Mikrotechnik BTS GmbH. The apparatus including the system periphery could be fixed as a modular system on a base plate. At the same time, it was possible to disassemble it completely to its component parts (cylinder, cone, tangential inlet, immersion tube, underflow), which made cleaning much easier. The diameter of the cyclone was 2.5 mm, the underflow was 0.25 mm and the immersion tube was 0.5 mm. Phase separation tests were carried out with the test system water/decanol. Contrary to other separators presented, a complete phase separation with one single cyclone was not possible. Only a concentration of emulsions as well as a classification could be reached.

Ookawara et al. [48] developed a micro-separator/classifier and examined its application in oil–water separation. The curved micro-channel with a slit (width 112 μm , curvature radius 10 mm, arc angle 30°) was fabricated on a SUS304 plate by the photoetching technology. A small amount of oil with density of 930 kg/m³ was dispersed and formed droplets in water in the feed container agitated by an impeller. The emulsion was fed into the curved micro-channel and was discharged from the inner and outer branches that formed bifurcations, and the lighter oil phase was collected from the outer branch (see Fig. 13). It was found that the pressure loss in this micro-separator was much smaller than that in existing hydrocyclones, and simultaneous separation of heavier and lighter phases could be achieved with the principle of lift-force induced separation.

If the throughput of micro-mixers is high enough, mini-settlers can be applied for the phase separation, while the density difference between the immiscible liquid phases remains the main driving force. In other words, separators with conventional dimensions can be combined with micro-mixers. Benz et al. [49] evaluated the extraction performance of a mixer-settler set-up using micro-mixers in combination with standard mini-plant settler systems for mini-plant production (see Fig. 14, above). Two types of passive micro-mixers developed by IMM GmbH were utilised for different

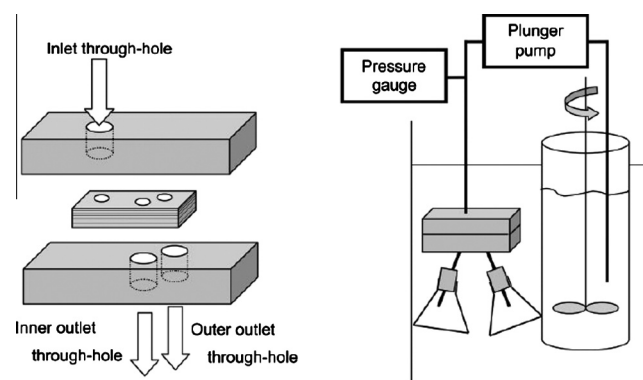


Fig. 13. Schematic diagrams of inter-connections in the micro-device (left) and of the experimental setup (right) [48].

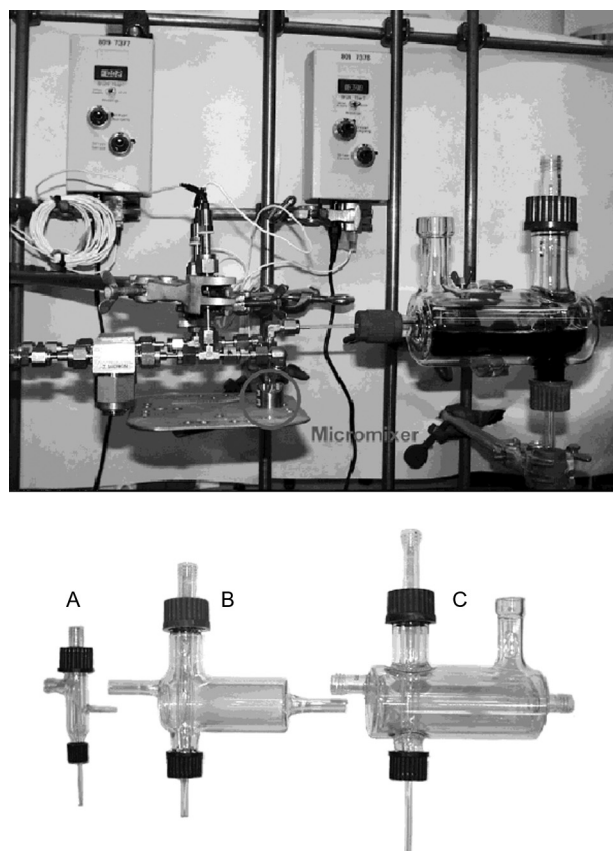


Fig. 14. Photograph of the experimental setup comprising feed lines, filters, pressure sensors, micro-mixer and mini-settler (above) and mini-settlers of 15 mL (A), 150 mL (B) volume and a mini-settler of 150 mL volume with heating jacket (C) (below) [49].

volume throughputs. For low and medium total volume flow rates of up to 1.6 L/h, a micro-mixer comprising 30 interdigital micro-channels with 40 μm width was used, and a micro-mixer array comprising 300 micro-channels arranged in 10 parallel segments of equal micro-structures was employed at higher total flow rates of up to 6.4 L/h. The mixing processes in these micro-mixers were based on the multilamination principle as discussed above. Two mini-settlers with different internal volumes (15 and 150 mL)

were used for the subsequent phase separation, depending on the flow rate (see Fig. 14, below). It was pointed out that a higher flow rate led to a higher dispersion of liquid phases in these interdigital micro-mixers, and the size of droplets was even smaller than 20 μm . Thus, the combination of mini-settlers could realise fast phase separation. The extraction efficiency was found to be a function of the volumetric flow, and one practical mixer-settler stage was found to reach one theoretical stage for different extraction systems at optimal flow conditions. In addition, the increase in the throughput of this mixer-settler set-up could be easily achieved by replacing a single micro-mixer with a micro-mixer array.

2.3.3. Slug flow in capillaries and micro-channels

The capillary reactors widely used in reaction engineering for kinetic studies represent a special form of the mixer-settler arrangements. Using a T-shaped splitter or a Y-shaped splitter, a slug-form dispersion is generated that flows along the capillary without any sign of coalescence. The continuous phase covers the walls of the capillary and is transported co-currently with the slugs. Inside the slugs, internal circulations emerge which enhance the convective mass transport [50–53].

Kashid et al. [54] carried out numerical and experimental investigations with a micro-capillary extractor and considered three different non-reactive extraction systems (water/kerosene/iodine, water/kerosene/acetic acid, water/*n*-butanol/succinic acid). Their respective capillary lengths were 100 and 300 mm, and the capillary diameters varied between 0.5 and 1 mm. It could be shown that high extraction degrees (>90%) were reached in contact times of just few seconds. The continuous phase separation at the capillary outlet was realised with a Y-shaped splitter, with its two parts made of different materials (steel and Teflon). The resulting different wetting properties of the two phases ensured a nearly complete phase separation. Furthermore, it was shown that the volumetric mass transfer coefficients reached in the micro-capillary were substantially higher than those in conventional liquid/liquid contactors.

Slug and bubbly flow operations in micro-channels (capillaries) can provide very high extraction efficiency advantageous for practical applications. On the contrary, parallel and annular flow operating windows are usually limited by the capillary length, due to relatively slow mass transfer rate resulting in significantly lower extraction efficiencies [55]. The comparison between the slug flow in a capillary and emulsification in the IMM micro-mixer was also

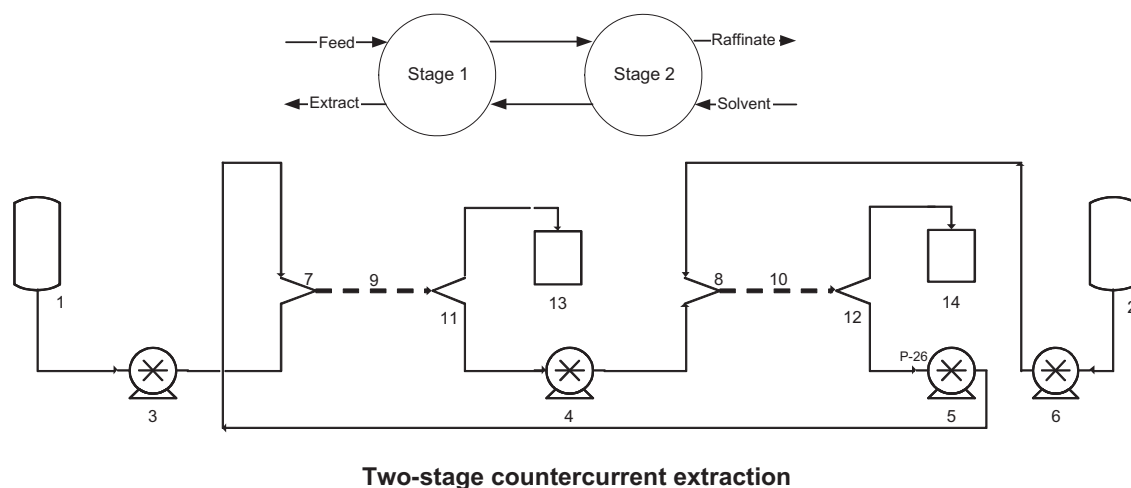


Fig. 15. Schematic representation of the counter-current arrangement of two micro-mixer-settler units [56]: (1 and 2) reservoirs; (3–6) pumps; (7 and 8) Y-shaped mixers; (9 and 10) capillaries; (11 and 12) Y-shaped phase splitters; (13 and 14) collecting containers.

carried out [52]. Regarding the industrial-scale throughput, the extraction using slug flow in a capillary might be suitable for the continuous operation of a process involving liquid–liquid extraction, since fast phase separation is expected to be possible. The extraction rate can be controlled precisely by adjusting operational parameters, e.g., the flow rate and the flow rate ratio. It is worth noting that emulsification extraction in the IMM micro-mixer requires substantially longer time for the phase separation than the extraction using slug flow in a capillary.

The mixer-settler arrangements discussed above represent only one equilibrium stage as a maximum. In order to reach several separation stages, these co-current units have to be combined to a counter-current arrangement. For the above-mentioned slug flow, this concept of classical mixer-settler cascades was realised as a combination of connected capillaries (see Fig. 15) [56].

3. Absorption/desorption

Absorption is a process of capturing and dissolving of gases and vapours by means of liquids. When a gas mixture and a solvent are brought into contact in absorbers, one or more gas components are separated in a possibly selective way. The solvent loaded with the gas components, the so-called absorbate, is usually regenerated in the process called desorption or stripping which is in essence inverse to absorption. For such a solvent regeneration, the absorber is followed by one or more desorbers, in which the previously absorbed gas is removed from the solvent. In general, all kinds of gas/liquid contactors can be used as absorbers. Most frequently, tray and packed columns as well as various hollow scrubbers are applied in conventional-scale applications.

To address the peculiarities of the micro-scale, different design concepts have been developed in the last years which provide an up to 1000 times larger effective mass transfer contact area compared to conventional units [32].

3.1. Absorbers/desorbers with membrane contactors

For the design of absorbers and desorbers at micro-scale, similar ideas concerning the realisation of a counter-current operation of two fluids apply as for extraction units. Consequently, similar principles for the stabilisation of the phase interface between two continuous fluids are used for micro-absorbers and micro-desorbers.

Cypes and Engstrom [57] compared mass transport characteristics of a conventional packed tower and a micro-fabricated stripping column. The latter consisted of a liquid and a gas channel, prepared from silicon wafer by standard etching techniques. The two wafers were linked by eutectic bonding. The bottom part of the liquid wafer contained 140 rows with three square boreholes,

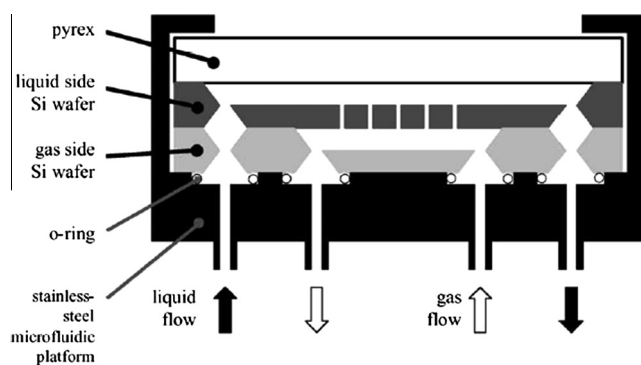


Fig. 16. Schematic set-up of the micro-desorber [57].

each with a side length of 50 μm , in order to realise mass transfer with the lower gas channel. Both micro-channels were 3.35 cm long, 920 μm (liquid side) respectively 450 μm (gas side) wide and 330 μm deep. Fig. 16 illustrates the set-up of the micro-desorber.

For the evaluation of the micro-fabricated stripping column, desorption of toluene from water into dry nitrogen was performed. For the sake of comparison, a stripping process in a packed column under the same operating conditions was studied, in which toluene was stripped out of water by dry air. This column had an internal diameter of 18.3 cm and a packing height of 114 cm. It was filled with 1.59 cm Pall rings. For both units, the volumetric liquid-phase mass transfer coefficients were determined experimentally, for varying liquid and gas loads (see Fig. 17), and it was found that these coefficients in the micro-unit were an order of magnitude higher than in the packed column, while keeping a similar effective mass transfer area. The better mass transfer conditions in the micro-desorption column can be explained by the thinner liquid film and, consequently, significantly reduced diffusion path in the liquid phase as compared to the packed column. Further, the gas volumetric flow rate is not limited by a flooding point as in the case of the packed column. Moreover, the micro-apparatus stands out for its low pressure drop characteristics. However, these benefits are counterbalanced by higher production costs, fouling phenomena in boreholes as well as by problems with scale up/numbering up.

Drost et al. [58] described a variant of a micro-membrane contactor for absorption/desorption processes. The membrane made of sintered stainless steel was 4 mm thick and had a porosity of 40%, while the micro-channels adjacent to the membrane were 100–300 μm high. The absorption of ammonia in water served as an example. In the course of the performed studies, the mass flow rates of ammonia varied between 0 and 4 g/min and of water between 0 and 33 g/min. In isothermal and adiabatic test runs, the temperatures ranged from 20 to 50 $^{\circ}\text{C}$, while the operating pressure was 1 to 2 bar. Under these conditions, absorption heat rates of 10–30 W/cm^3 were measured, which revealed that this micro-absorber could reach absorption rates an order of magnitude higher than those of conventional absorbers.

3.2. Absorbers/desorbers with surface-treated channel walls

Hibara et al. [59] developed a micro-channel arrangement consisting of a shallow and a deep micro-channel made of glass, both supplied with separate inlets and outlets, whose middle sections were connected (see Fig. 18).

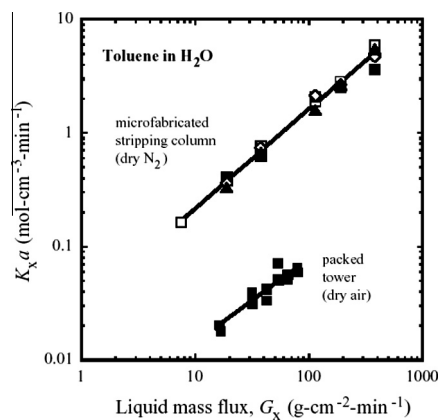


Fig. 17. Volumetric mass transfer coefficients against the liquid mass flow rate for a micro-desorption column and for a packed tower [57]. Different symbols represent different values of the gas mass flow rate (not specified exactly in [57]).

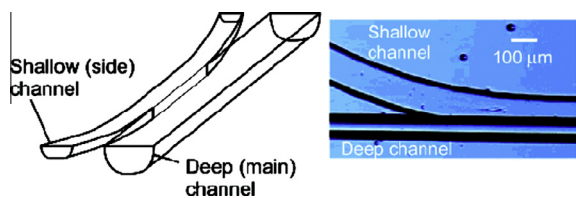


Fig. 18. Schematic representation (left) and photograph from above (right) of a micro-absorber with surface-treated channel walls [59].

Using an octadecyltrichlorosilan (ODS)/toluene solution, the surface of the shallow channel was made hydrophobic, whereas the deep channel surface remained hydrophilic.

The mass transfer performance of the unit was tested based on the desorption of oxygen from water into a stream of nitrogen. The inlet concentration of oxygen in water was 8.8 ppm. The liquid phase passed through the hydrophilic, deeper channel, whereas the gaseous phase went counter-currently through the hydrophobic, shallow channel. A stable two-phase flow could be established, and the amount of oxygen dissolved in water dropped by 90% after a contact time of just 19 s.

3.3. Gas–liquid dispersers

3.3.1. Dispersion in interdigital multi-channel mixers

IMM performed testing of the glass micro-mixers presented in Section 2.3.1 (slit-shape glass mixer, rectangular glass mixer) as well as the SSIMM with respect to their ability to generate gas/liquid dispersions with fine droplets and a narrow bubble-size distribution [60]. Using the test system nitrogen/aqueous glycerol solution, the influence of gas flow at a constant fluid load was studied. It was found that, with increasing gas flow, the gas bubble-size distribution became broader and the average bubble size grew. In this context, it is worth noting that the gas actually moves only through a part of the gas feeding channels (altogether 15 channels), while the rest is flooded by the liquid. This can be attributed to the minor deviations in the channel geometry and surface properties, which cause a difference in capillary forces. However, the number of “active” gas-inlet channels increases with rising gas flow rate. The wider gas bubble-size distribution at increased gas flow rates can be explained, first, by a higher steric hindrance of the neighbour bubbles during their formation, and second, by a growing bubble formation limitation by side walls and increased coalescence probability. Further, it was observed that an increase of the total flow rate, while keeping the phase ratio constant, led to more active gas-input channels and hence to a wider gas bubble-size distribution. The comparison between the glass micro-mixers showed that the slit-shape glass mixer yielded the smallest bubbles with a most narrow size distribution.

Similar test series with SSIMM demonstrated that the slit height represents an efficient parameter for the reduction of bubble sizes.

All in all, the studied interdigital multi-channel mixers, initially developed for the creation of liquid/liquid dispersions, cannot be considered suitable for the generation of gas/liquid dispersions with narrow distribution, unless further modifications are made.

3.3.2. Absorption in micro-channel mixers

Yue et al. [61] investigated two-phase gas/liquid flows generated in Y-shaped micro-mixers. Based on experimental studies with a test physical absorption system (absorption of CO₂ in water) as well as with a chemical absorption system (absorption of CO₂ in a NaHCO₃/Na₂CO₃ buffer solution) for different flow regimes, mass transfer characteristics as functions of both phase velocities were determined. Within these studies, different kinds of two-phase

flow could be observed (slug flow, transition between slug flow and annular flow as well as churn flow). The studied micro-mixer was found to provide mass transfer coefficients and mass transfer areas at least one to two orders of magnitude higher than those of conventional liquid/gas separation units.

A great potential of micro-channel mixers for CO₂ or H₂S absorption was demonstrated in [62–64]. Generally, a smaller micro-channel provides higher mass transfer rates, while the absorption efficiency increases with rising superficial liquid velocity and vice versa. An increase in the operational pressure results in an increase in mass transfer driving force, so that higher absorption efficiencies can be achieved. High pressure appears to be extremely beneficial for the absorption in the micro-channel mixers. Ye et al. [64] demonstrated that at 3 MPa, CO₂ absorption in micro-channel mixers could be almost completed (>99.94%) at a very short residence time (less than 2 ms) when the molar ratio of aqueous monoethanolamine (MEA) to CO₂ was kept at 2.2.

3.3.3. Absorption in other micro-structured absorbers

A kind of high-throughput micro-porous tube-in-tube micro-channel reactor (MTMCR) was designed and developed as a novel gas–liquid micro-contactor in [65]. MTMCR consists of two coaxial tubes, while numerous micro-pores in the wall are distributed circle-wise near the entrance of the inner tube (see Fig. 19). The section with micro-pores provides the dispersion means for the gas–liquid system; the mixing and mass transfer occur in the mixing chamber between the inner and outer tubes (see Fig. 20).

Chen et al. [65] and Gao et al. [66] thoroughly investigated the effects of structural parameters of MTMCR (e.g., mean pore diameter in inner tube and the width of mixing chamber), as well as the operating conditions on the mass transfer characteristics and removal efficiency of the CO₂ absorption. Their results showed that the measured liquid-side volumetric mass transfer coefficient in MTMCR was at least one or two orders of magnitude higher than that in the conventional gas–liquid contactors, and the specific interfacial area in MTMCR was as high as $2.2 \times 10^5 \text{ m}^2 \text{ m}^{-3}$, which was even much higher than that in micro-channels. A reduction of the micro-pore diameter and annular channel width of MTMCR can greatly intensify the gas–liquid mass transfer and increase the CO₂ removal efficiency. With a decrease in the superficial gas velocity or an increase in the superficial liquid velocity, the CO₂ removal efficiency improves, this phenomenon being similar to that in micro-channel mixers [62]. It was also found that the CO₂ removal efficiency could reach 90% or even higher at a high gas-phase throughput of 440 L/h, with an absorbent (MEA) concentration of 30 wt%.

The membrane dispersion micro-mixers providing high gas–liquid dispersions can also be used as absorbers [67,68]. Tan et al. [68] investigated the CO₂ capture process in a membrane dispersion micro-mixer, where a micro-filtration membrane with 5 μm diameter micro-pores was used as the dispersion medium in order to enhance mass transfer by realizing gas–liquid micro-flows. They studied the flow rate influence on the gas bubble size and mass transfer characteristics. It was shown that the membrane dispersion micro-mixer could provide enough specific interfacial area for the absorption (e.g. the bubble size could be smaller than 20 μm), and Murphee efficiency could reach nearly 100% even

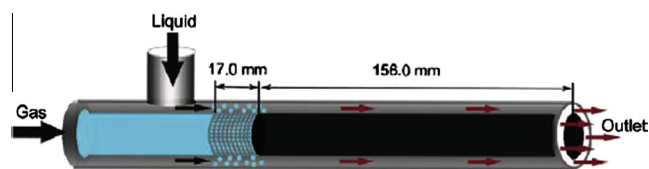


Fig. 19. Schematic diagram of micro-porous tube-in-tube micro-reactor [65].

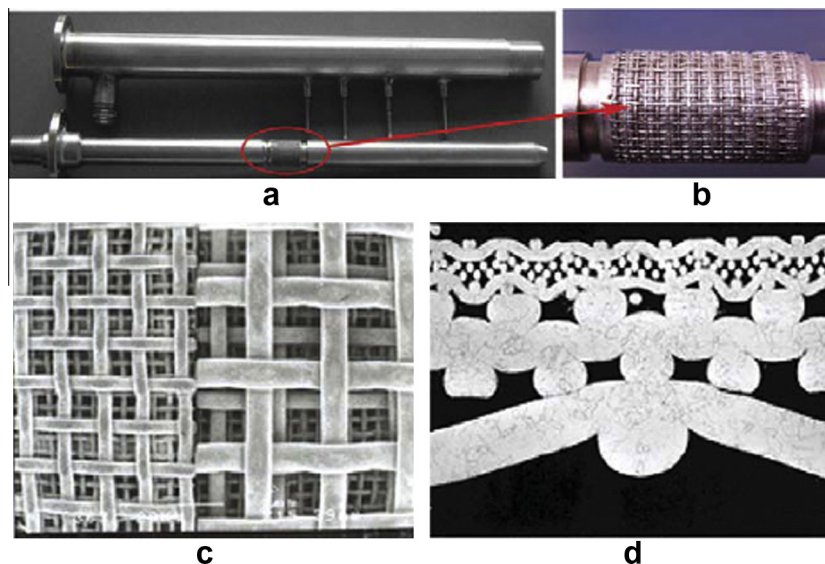


Fig. 20. Design of micro-porous tube-in-tube micro-reactor: a photograph of MTMCR (a), micro-porous section (b); SEM images of the front (c) and cross (d) sections of sintering metal wire mesh [65].

when the residence time was less than 2 s. Besides, these micro-absorbers show very good operation flexibility and low energy consumption. With the change of capacity from 160 mL/cm² s to 1000 mL/cm² s, such devices can maintain Murphee efficiency higher than 90%, and the transmembrane pressure is lower than 10 kPa. As claimed in [68], such micro-absorbers can realize absorption operations with broad applicability, high efficiency, low input energy and large capacity.

4. Distillation

Distillation is one of the most important thermal separation processes. It can be applied when the boiling points of the individual mixture components differ and these components do not suffer any thermal damage when boiling under process conditions. As a rule, components with lower boiling points accumulate in the vapour phase, whereas the liquid phase is enriched with high-boiling components. The continuous distillation, in which a vapour-phase flows in counter-current to a part of its condensate, is called rectification. Typical rectification units are tray columns as well as columns filled with random or structured packings.

Despite its importance in the process industries, distillation application at micro-scale is still very limited. Due to dominated surface forces, evaporation behaviour is hard to control, in particular for counter-current flow conditions. Furthermore, the large specific areas lead to considerable heat losses, which makes the temperature control in the micro-structure difficult.

Nevertheless, different micro-structured units have been developed comprising single-stage ones (e.g., a micro-flash separator) and units with counter-current flow. The latter are realised using diverse techniques to establish stable flow conditions. Single-stage units can be integrated in series, this helps to improve separation efficiency. A recent overview on separation units for micro-distillation with the focus on concurrent and counter-current flow arrangements is given in [69].

4.1. Micro-distillation column

Micro-distillation concepts have been developed with due consideration of specific micro-fluidic aspects. Already in 1985, Seok and Hwang [70] presented a distillation column with dimensions in the sub-millimeter range, operating in line with the heat pipe

principle (zero-gravity distillation). Fig. 21 illustrates the set-up of this unit.

The apparatus consists of common column components, such as an evaporator (1), a condenser (2) as well as an adiabatic separation zone (3) whose walls are covered with a porous layer. The mixture to be separated is fed through a valve (4) into the column, while the bottom and top streams are removed through the respective valves (5) and (6).

A binary mixture is evaporated and, driven by the pressure difference in the apparatus, moves to its cooler edge and condenses. The arising liquid phase flows due to capillary forces, in accordance with the wick principle, through the porous layer back to the evaporator. This provides a contact between the two counter-currently flowing phases in the separation zone, resulting in an accumulation of the volatile component in the vapour phase.

Studies with the test systems ethanol/water and methanol/water revealed that the tested micro-column exhibited a similar separation performance as a nine times longer conventional column. However, eight micro-columns had to be connected in parallel to reach the same throughput.

Tschernjaew et al. [71] presented a rigorous mathematical model based on the Stefan-Maxwell approach and describing multi-

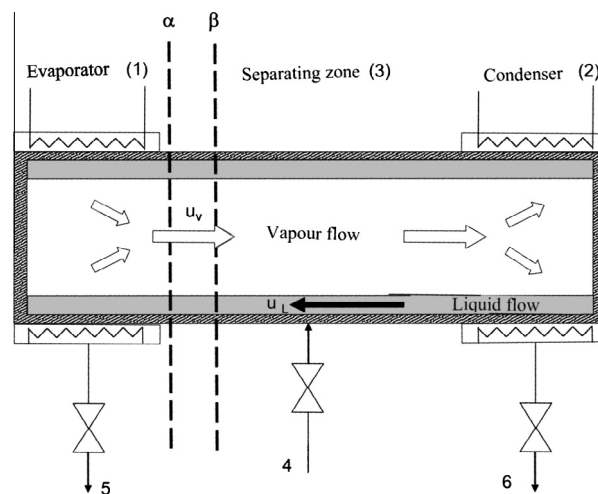


Fig. 21. Schematic representation of a micro-distillation unit based on the heat pipe principle (adapted from [70]).

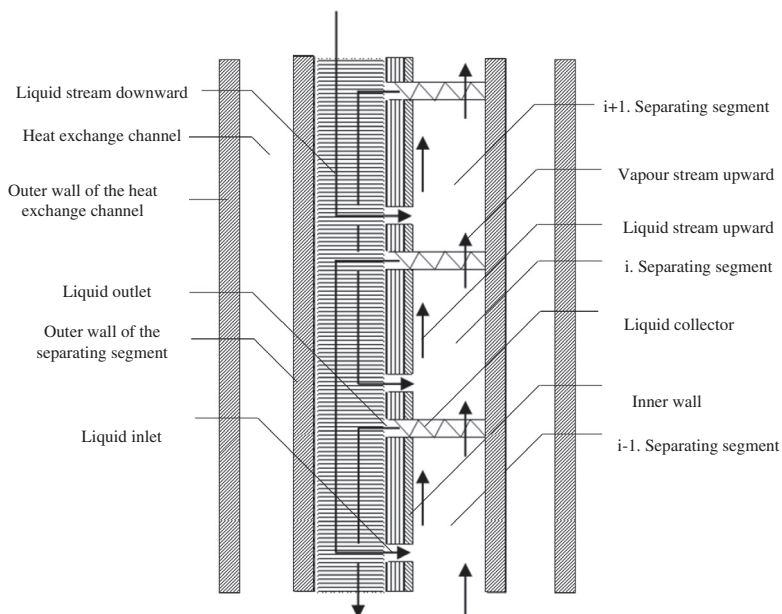


Fig. 22. Schematic set-up of a micro-distillation column (adapted from [77]).

component mass transport in micro-distillation columns with the zero-gravity principle. Using a test calculation for the ternary test system ethanol/isopropanol/water, they managed to confirm high separation performance of the micro-distillation columns.

Sundberg et al. [72] developed another flat micro-distillation column, also based on the zero-gravity principle. On the bottom of the column, they used a metal foam as a wick material. For a mixture of *n*-hexane and cyclohexane, separation efficiency comparable with that of Sulzer laboratory packing was achieved. In further works, the operation of the micro-distillation column was optimised by accurate control of reflux and boiling flow rates. By simultaneous heating of the separation unit, heat losses could be kept at a relative low level. Different test systems (methyl formate + methanol, *n*-hexane + cyclohexane and 2-methylbut-2-ene + ethanol + 2-ethoxy-2-methylbutane) were used to confirm the feasibility of using the developed micro-distillation column for process development [73,74].

Another configuration of the micro-distillation device based on the capillary effect was patented in [75] and was investigated in [76] for the distillation of desulfurised fuel. The device comprised 15 micro-channels with walls covered by wick material. The heated feed mixture was led into the wick of the channel, while low boiling components evaporated and flowed counter-currently to the feed mixture. At the end of the micro-channels, the vapour was condensed and a part of the condensate was returned to the wick. The device ran continuously for 100 hours.

Further developments are based on the realisation of a contact between a thin liquid film and a vapour phase. Tonkovich et al. [77] suggested a concept of a micro-distillation unit consisting of an arbitrary number of segments adjustable to a particular separation task. Fig. 22 illustrates the schematic set-up of such units.

After entering the *i*th separation segment, the liquid phase flows as a thin film along the inner wall of the relevant segment, due to capillary forces and/or the gas film drag. Inside the segments, the films get in contact with the gas and ensure interphase mass transfer. At the end of each segment, there is a liquid collector. Driven by capillary forces, the arriving liquid moves towards the segment outlet from which it is further transported by gravitation and/or by pumps to the (*i* - 1)th segment. At the same time, the vapour flow passes the liquid collector and flows in the next (*i* + 1)th separation segment. Using heating or cooling chan-

nels adjacent to both, liquid and gas, channels, the wall temperature can be adjusted quite precisely. Moreover, as a consequence of high heat transfer coefficients as well as high specific heat transfer areas, a fast start-up and shut-down of the column is possible. The achieved HETP values are below 5 cm, which is significantly lower than the values between 30 and 60 cm typical for conventional columns.

Based on the separation principle of conventional sieve tray columns, Ziogas et al. [78] developed an efficient micro-distillation apparatus for analytical and preparative separations (see Fig. 23). They placed micro-sieves (acting as a kind of micro-sieve trays here) inside of a flat micro-apparatus thus generating bubble layers

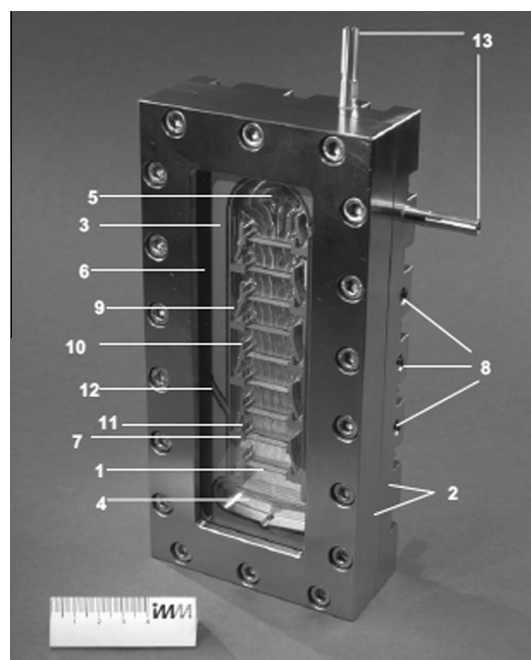


Fig. 23. Micro-distillation device (source IMM [78]): (1) plate; (2) housing; (3) plate inlay; (4) column bottom; (5) column top; (6) viewing window; (7) plate holder; (8) holes for heating cartridges; (9) downcomer; (10) outlet weir; (11) inlet weir; (12) feed; and (13) coolant inlet and outlet.

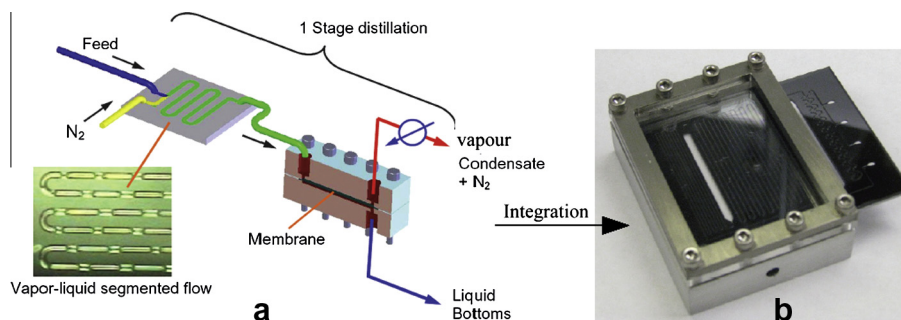


Fig. 24. Schematic diagram of micro-distillation based on a membrane micro-separator (a) the integrated device (b) [79].

with intensive gas–liquid interactions. The separation of different binary mixtures was performed, while the number of theoretical plates up to 12 could be attained.

4.2. Micro-distillation based on membranes

A single-stage micro-distillation can be realised in a micro-structured system with the help of carried (sweeping) gas and a membrane micro-separator [79]. The process takes place below the boiling points of the individual mixture components and is based on the difference between the partial vapour pressures of the relevant components in the liquid mixture. The liquid mixture and the carried gas are introduced into the micro-channel forming slug flow. The liquid components evaporate, and a rather long channel is required in order to approach the liquid–vapour equilibrium state.

A membrane micro-separator is used to separate enriched vapour from liquid based on capillary forces. With this separation step, the whole micro-distillation process is completed (see Fig. 24). In [79], this micro-distillation system was used to separate binary mixtures MeOH–toluene (50:50 mol%) and dichloromethane (DCM)–toluene (50:50 mol%) at 70 °C. It was found that a single-stage device yielded MeOH mole fractions of about 0.20 (liquid) and 0.80 (vapour). Similarly, DCM mole fractions were estimated to be about 0.16 (liquid) and 0.64 (vapour). As can be seen, this integrated micro-distillation system realises efficient separation of liquid mixtures, and multi-step micro-distillation is possible by integrating such kind of systems in series.

The carried gas does not always need to be in a direct contact with a liquid mixture. Instead, a membrane can be used for selectively transporting components between the liquid and gas phases [80]. With such an approach, just a following gas/vapour separation step is required, and the flow integrity is maintained through the control of surface properties of membrane and fluid flow dynamics. As shown in Fig. 25, this micro-distillation device consists of two horizontal plates, with a flat micro-porous membrane held in between. Two micro-channels above and under the membrane are used for the gas and liquid flows, respectively. The streams of the preheated liquid mixture and the cold carried gas can be arranged in co-current or counter-current mode. The volatile species evaporate at the hot liquid–vapour interfaces locating in the entrances of the micro-pores of the membrane, cross the membrane and then are swept by the carried gas. In [80], the performance of this micro-distillation device was studied with different membranes under different operational conditions. It was demonstrated that the separation of the liquid mixture by such micro-distillation devices was feasible and that the carried gas flow rate was a crucial factor influencing the separation performance. The selection of an appropriate membrane was found to be an important design factor for the reduction of temperature polarisation effects. Furthermore, it was possible to perform the

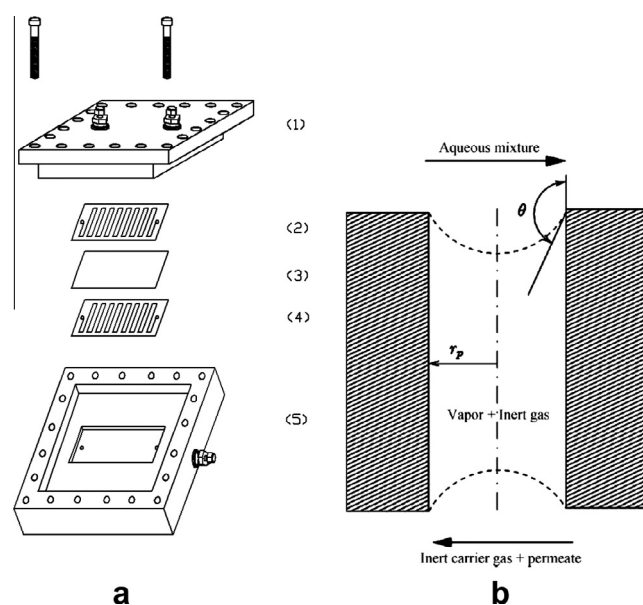


Fig. 25. (A) View of the membrane micro-separator [80], (1) cover plate for the permeate channel, (2) permeate channel, (3) membrane contactor, (4) feed channel, (5) cover plate for the feed channel; and (B) schematic diagram of mass transfer in liquid–vapour/gas membrane micro-separator.

separation process in a wide range of volumetric gas and liquid flow rates. This is due to the fact that the flows of both phases were separated by the membrane, and, therefore, there were no shear stresses between them.

In [81], a vacuum membrane distillation process was investigated using a microfluidic chip with two micro-channels, each for the liquid and the vapour phase (see Fig. 26). The channels were separated by a hydrophobic membrane. The chip was fixed on a hot plate and the vapour phase was kept under vacuum. In order to realise condensation and evaporation within the membrane distillation unit, a temperature gradient along the channels was imposed using cooled water pumped through an additional, adjacent channel. For the separation of a methanol–water solution at optimal operating conditions, the number of theoretical plates up to 1.8 could be attained.

4.3. Micro-distillation without using membranes

Introducing carried gas for the micro-distillation increases the operation complexity. Therefore, some other micro-distillation methods have been proposed. Capillaries combined with a micro-channel can be used for the liquid–vapour separation. In

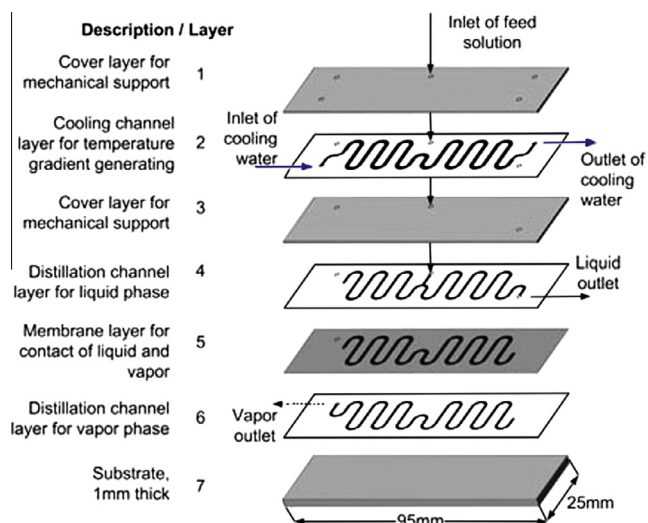


Fig. 26. Schematic diagram of the individual layers in the micro-distillation chip containing four microfluidic channel layers [81].

[82], the separation of mixtures acetonitrile–dimethylformamide (50:50 mol%) and dimethylformamide–toluene (50:50 mol%) was realised with a simple micro-distillation device, in which the separation efficiency was equivalent to 0.72 equilibrium stage.

In [83,84], several silicon-glass micro-distillation chips with different channel configurations were fabricated, and their performance was tested. A temperature gradient was established along the micro-channel by heating and cooling the two ends of the micro-channel, while the liquid mixture was introduced from the middle position of the micro-channel (see Fig. 27). The arrays of micro-pillars were incorporated along the side walls of the micro-channel. They forced the liquid to flow in the micro-pillars zones close to the micro-channel walls due to the effect of capillary forces thus avoiding flooding. As the space between the micro-pillars is sufficiently small, the capillary pressure can stabilise the liquid–vapor interface. The capillarity is the main driving force for the liquid flowing from the cooling region to the heating region, which can compensate liquid loss by vaporisation. Vapor pressure in the channel increases in the heating region due to liquid vaporisation, whereas pressure in the cooling region decreases due to the condensation. This pressure difference provides the driving force for the vapor flowing from the heating to the cooling region.

Lam et al. [83,84] carried out a thorough separation performance analysis of this kind of a micro-distillation chip using mixtures acetone–water and methanol–toluene. The relevant operating conditions, e.g. temperatures of the heating and cooling regions, the composition and flow rate of the liquid mixture, were studied. The feasible temperature profile along the micro-distillation chip limits the operational range. An increase in the heating temperature, a decrease in the cooling temperature and a zigzag-channel structure result in a better separation performance. The

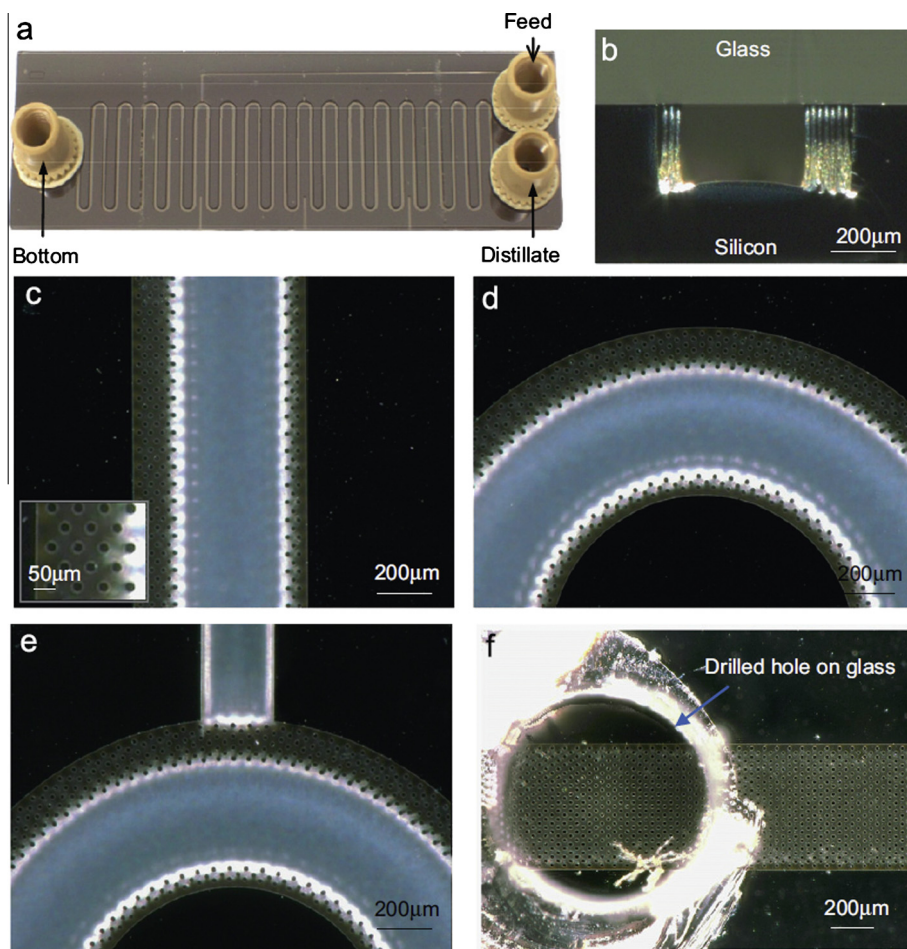


Fig. 27. Images of the micro-distillation chip [84]: (a) photo of the entire chip, (b) cross-section of the serpentine micro-channel, and (c–f) micro-pillars at various locations in the micro-channel.

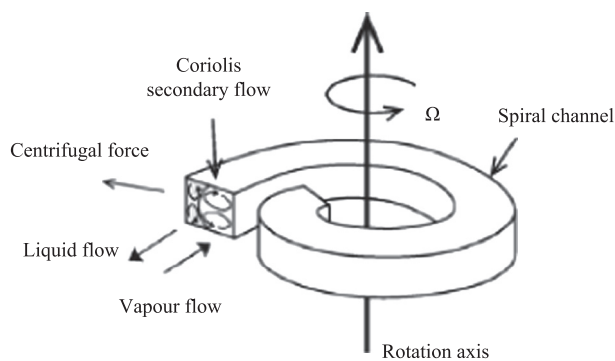


Fig. 28. Phase contacting in a rotating spiral micro-channel [88].

micro-distillation chip is particularly good for separating mixtures with high content of light component.

In a further work, the micro-distillation chip was used to perform an in situ study of the separation of a toluene/benzaldehyde mixture [85]. The structure of the micro-channel was serpentine. By an infrared imaging camera and in situ Raman spectroscopy, the temperature and the concentration along the channel were measured. Thereby, the length of the separation zone was identified in which a monotonic change of the toluene concentration was visible. The length of this zone was significantly shorter (ca. 2 cm) than the distance between the cooling and the heating end (6 cm).

Cypes et al. [86] patented a single-stage distillation device. It consists of a silicon plate on which a channel with a cross-section of $500 \times 280 \mu\text{m}^2$ and a length up to 100 cm is etched. In this channel, the feed is heated and partly evaporated. At the end of the channel, the resulting vapour–liquid mixture flows into an assembly of capillary channels ($10 \times 70 \mu\text{m}^2$), which is also etched on the plate. Here, the liquid phase is separated from the saturated vapour due to capillary forces. A binary mixture of pentane and octane was used as a test system, and at a feed flow rate of $0.5 \text{ cm}^3/\text{min}$, a separation efficiency equal to one ideal stage was achieved.

A device similar in design to that given in [86] was presented in [87] for a single-stage distillation of an ethanol–water mixture. The flat-glass device contains a meandering channel in which the ethanol/water mixture is evaporated. The vapour and liquid phase are subsequently separated in a flash chamber due to gravity. At feed flow rates of 0.02 and $0.1 \text{ cm}^3/\text{min}$, a stage efficiency of 80% and 65% was obtained.

Instead of capillary forces, MacInnes et al. [88] used the centrifugal force to drive the liquid phase (see Fig. 28). A prototype device containing a rotating spiral micro-channel was designed. In the spiral channel, the vapour and liquid phase flowed counter-currently, while the vapour phase was driven along the channel by a pressure gradient. The phase flow rates and the liquid film thickness were adjusted by changing the rotation rate and the pressure.

Furthermore, the Coriolis force caused a secondary movement of both phases, thus leading to an enhanced mass transfer. For a binary feed consisting of 2,2-dimethylbutane and 2-methyl-2-butene (50:50 mol%), the number of theoretical plates was 6.6. However, generation of the centrifugal force required a high technical effort.

5. Continuous size separation of particles or droplets

Accurate size separation and size measurement of various kinds of particles, including polymer beads, ceramics, cells, pharmaceutical emulsion droplets, etc., are important in the fields of industrial production, environmental assessment, and chemical

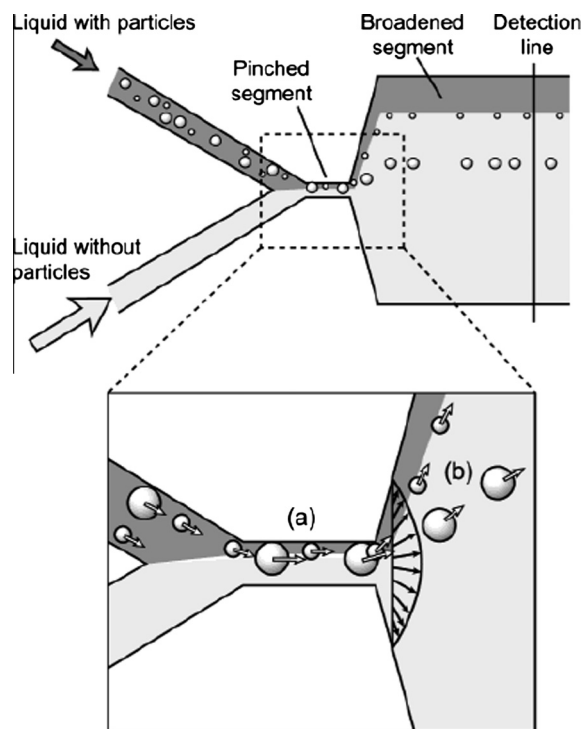


Fig. 29. Principle of pinched flow fractionation in micro-fluidic separators [90]. (a) In pinched segment, particles flow aligned to one sidewall by using another particle-free liquid stream; and (b) In enlarged channel, particles are separated according to their sizes by the spreading flow.

or biological research [89,90]. The particles or droplets with diameters from 1 nm to $100 \mu\text{m}$, can be separated by the conventional methods (e.g. field flow fractionation, hydrodynamic chromatography, split-flow thin fractionation), which are usually operated in a batch-wise mode or require external fields [91–98]. Moreover, the synthesis of nanoparticles or micro-particles and the production of emulsion in micro-mixers have attracted a growing worldwide interest of both academia and industry [99,100]. These particles produced in micro-mixers usually need to be further separated depending on their size distribution. Therefore, some continuous and simple micro-fluidic methods, which can be performed without the help of external fields, are required for the size separation of particles.

Yamada et al. [90] presented a novel concept of “pinched flow fractionation” for the particle sorting, based on laminar flow characteristics in the micro-fluidic devices. The structure of this device and the principle of pinched flow fractionation are shown in Fig. 29. A liquid phase including particles is continuously introduced into a pinched segment which is connected to an abruptly enlarged channel. The particles can flow aligned to one sidewall of the pinched segment by using another particle-free liquid stream. When leaving the pinched segment, the particles can be separated according to their sizes by the spreading flow in the enlarged channel. With such micro-fluidic separators, Yamada et al. [90] realised the separation of the mixture polystyrene/polydivinylbenzene beads, whose diameters were 15 and $30 \mu\text{m}$, respectively. It was found that the width of the liquid stream containing particles in the pinched segment should be lower than the diameter of the smallest particle in order to achieve efficient separation. These results were recently confirmed by simulations [101] that showed that the particles moved due to different lift forces because of the low pressure region between them and a sidewall of the pinched segment, and this forced the particles to flow toward the sidewall. This lift force effect can probably provide

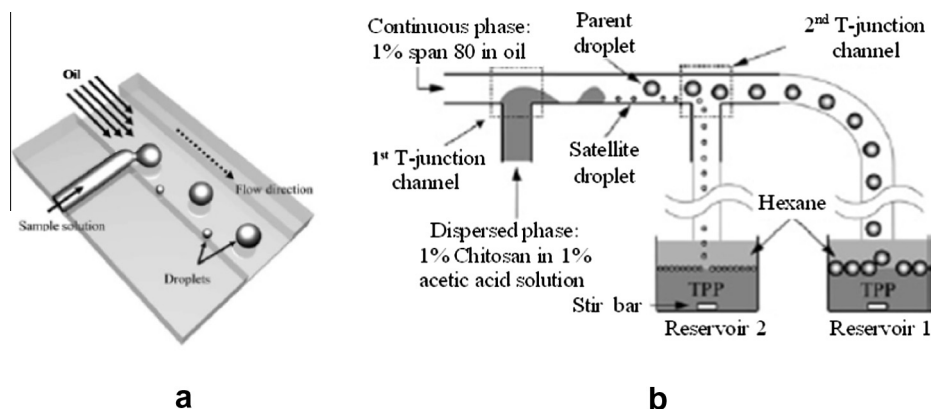


Fig. 30. Schematic illustrations of the working principle of a double T-junction micro-channel [105], (a) top view of the 1st T-junction channel, and (b) Illustration of microfluidic chip emulsification/separation (sorting) coupled with the ionic-crosslinking reaction process.

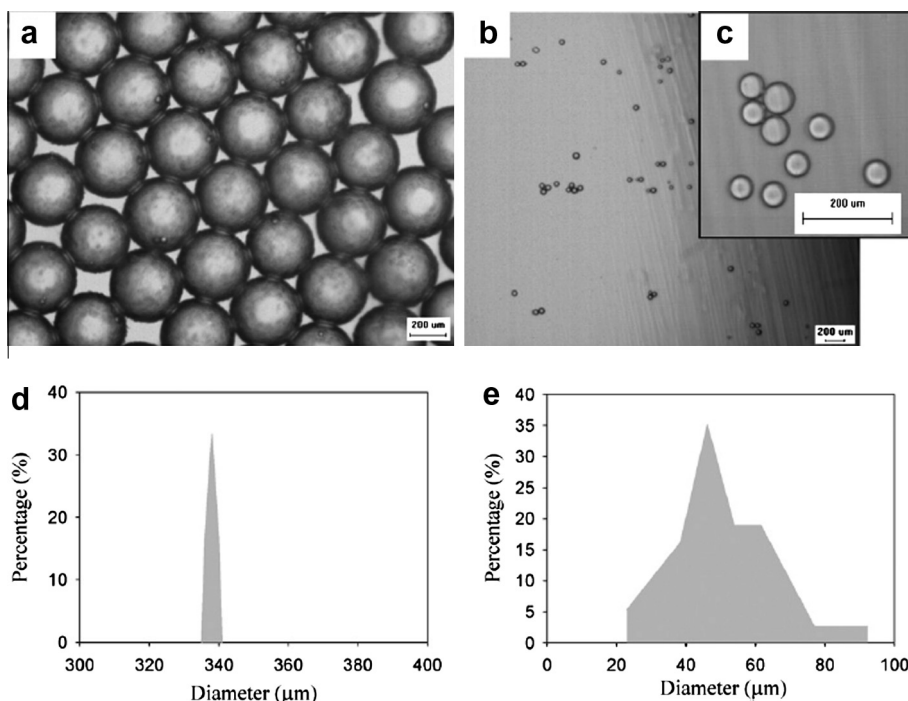


Fig. 31. Microscope images of chitosan micro-particles in [105] (a) in the Reservoir 1, and (b and c) in the Reservoir 2 (the scale bar is 200 μm). The size distribution of the micro-particles regarding (d) is corresponding to (a), and (e) is corresponding to (b).

an explanation for the experimental observation that a sharp expansion of the enlarged channel yields better separation performance than a gradual expansion.

This kind of a micro-fluidic separator can also be used to sort or select specific-sized droplets in polydisperse emulsion systems [102]. Moreover, with the technology of pinched flow fractionation, some special structures (e.g. a rotation structure and an asymmetric cavity) can be used as the enlarged channels, which can bring about obvious inertial force or centrifugal force for more efficient separation [103,104].

Continuous generation of droplets and size sorting can be combined in a simple micro-channel with a double T-junction design [105]. The first T-junction is used to produce droplets based on the shear effect of the continuous flow. The second T-junction is applied to separate the satellite droplets from their parent droplets in order to enhance the size uniformity. In [105], a narrow size dis-

tribution of emulsion micro-droplets was first obtained with aqueous solution including amino group (NH_3^+) of chitosan and $\text{P}_3\text{O}_{10}^{5-}$ anions and a continuous phase (organic phase, 1% span 80 in sheath fluid) at the first T-junction of the micro-channel (see Fig. 30). When the satellite micro-droplets travel to the second T-junction of the micro-channel, they are drawn to the side channel, while the parent micro-droplets keep travelling in the main channel, thereby enhancing the uniformity of the chitosan emulsion micro-droplets.

In [105], the separated satellite micro-droplets and parent micro-droplets were further converted to chitosan micro-particles through several processes, such as precipitation, reaction, and ionic-crosslinking. As shown in Fig. 31, the manipulation of size-controlled chitosan micro-particles with less variation than 2% in size could be successfully demonstrated with the double T-junction micro-channel system.

6. Combined application of micro-separation operations

Multiple separation operations are usually applied in chemical synthesis. Most of micro-chemical processes are limited either to a single reaction step or to multiple reaction steps without intermediate separation operations [106–114]. There are difficulties encountered when linking micro-unit operations together. So far, there are only few demonstrations dedicated to the integration of micro-reaction and micro-separation units for continuous-flow synthesis [115–117].

Sahoo et al. [115] demonstrated a combined application of different micro-separation units within a micro-plant for the multi-step continuous-flow micro-chemical synthesis (Fig. 32). The first micro-separator (μ S1) was used to realise the separation of two immiscible liquid phases after the first reaction step (phase-transfer reaction between aqueous azide and acid chloride) in a silicon-based micro-reactor (μ R1). This micro-separator was based on capillary forces and preferential wetting characteristics of a membrane. The formation of isocyanates from the organic azide in the second reaction step was conducted in a micro-reactor packed with solid acid catalyst (μ R2). Subsequently, the generated nitrogen was removed from the gas–liquid two-phase flow by the second micro-separator (μ S2). In the third step, carbamate was finally synthesised by contacting the generated isocyanate from μ R2 with alcohol in the third micro-reactor (μ R3). This integrated device comprising micro-reaction and micro-separation units can perform continuous multi-step synthesis for 6–7 days without any interruption and yield 96–99% of the carbamate. Moreover, such an arrangement can be beneficial for various micro-separation operations dealing with hazardous intermediate products.

Recently, a commercial micro-chemical module for the automated flow chemistry system has been developed by Syrris Ltd. [118]. This module mainly consists of a micro-reactor, a micro-separator, two optical sensors to monitor output stream purity and two back-pressure regulators to accurately control fluid pressure. The micro-extractor is connected following the micro-reaction stage, so that the output stream from the reaction chip is in contact with an immiscible wash stream. After contacting, the two streams are separated in the micro-extractor before being collected or passing into other processes. As claimed in [118], this combined module can remove unwanted compounds from the reaction mixture and continuously produce the desired product. However, many technical details, e.g. micro-extractor configuration, operational conditions, extraction efficiency and throughput are not given,

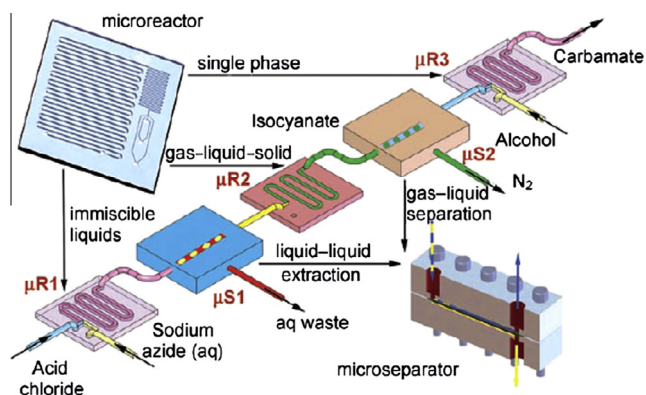


Fig. 32. The experimental setup for carbamate synthesis [115], μ R1, micro-reactor for conversion of acid chloride to organic azide; μ S1, quantitative separation of organic and aqueous streams; μ R2, micro-reactor loaded with solid acid catalyst for conversion of organic azide to isocyanate; μ S2, quantitative separation of gaseous N_2 from the liquid stream; μ R3, micro-reactor for reaction of isocyanate and alcohol to carbamate.

and, hence, it is difficult to judge on the application potential of this module for industrial production.

The combination of a micro-reactor and a micro-separator can be realised in different forms, including micro-reactor/micro-extractor [119], micro-reactor/liquid–vapour membrane micro-separator [120], micro-reactor/gas–gas membrane micro-separator [121,122] configurations. These combinations can be used for continuous operation promoting both reaction and product purification and enhancing safety when hazardous intermediates are involved in the multiple reaction steps.

7. Concluding remarks

This review provides a summary of existing trends and developments in the area of micro-separation technology. We largely focused on the description of units and methods, seldom giving any quality evaluation. The reason is that micro-separation technology is very young, and much more investigations are required for any reasonable quality assessment.

The literature survey shows that, both for liquid/liquid and for gas/liquid contacting phases, two basic ways towards setting-up separation units or modules in counter-current mode can be distinguished:

- A direct phase contact in co-current mode and an arrangement of the co-current flow modules towards the overall counter-current mode. The contact process can be intensified by introducing packings or membranes into the micro-structured devices as dispersion medium.
- A direct phase contact in counter-current mode and balancing the shearing forces at the phase interface with stabilising capillary forces. This can be achieved either with porous separating structures within which the phase interface is localised or with an appropriate modification of channel or unit inner surfaces/walls. Furthermore, centrifugal forces can be used to establish a stable counter-current flow of a gas–liquid system.

Generally, one can conclude that, till now, the contact methods described above have only been realised on a laboratory scale. There are just few exceptions, for instance, a concept suggested by Velocys, Inc. and based on the stabilisation of the phase interface by using porous structures [123] as well as the commercial micro-chemical module provided by Syrris Ltd. [118]. However, we have no information about any technical realisation.

We believe that an essential reason for missing technological breakthrough in the field of micro-separation technology has to do with insufficient design foundations, although some of the above-mentioned concepts already existed in the 1980ies. Consequently, there are several aspects that are not clear enough to provide a safe scale-up from the laboratory to the production scale, for instance:

- Fundamentals of fluid dynamics and mass transport:

Contrary to the micro-reaction technology, basic phenomena or sub-processes are described only insufficiently. Even the pressure profiles in the phases emerging along the flow direction are not discussed. Information about the flow pattern within the units is not always available. Mass transfer measurements are commonly based on macroscopic balancing or on phenomenological interpretations (see, e.g., [57]). All in all, there is a lack of multi-scale modelling concepts describing the complex flow conditions within the micro-structures as well as the coupling of the phases in terms of mass transport equations. Furthermore, there are currently no process models for modular arrangements, which would provide a

technical and economical evaluation of the concepts in comparison to equivalent conventional units.

- Experience with real systems on lab scale:

Especially the suitability of the micro-structures for process flows containing polluting particles is uncertain. Potential blockage of the channels or fouling on the large surfaces typical for micro-structures found no discussion in literature. Sometimes, fast sampling or on-line analysis in micro-structured equipment is difficult, depending on the throughput, material of micro-structures as well as on some other operational conditions. Moreover, sealing of micro-structures at stringent conditions, e.g. high pressure and high temperature, is still a challenge.

- Numbering-up of micro-separation units for production scale:

So far, no application examples of micro-separation technology for industrial production are reported. As well known, the traditional scale-up strategy through enlarging the equipment dimensions does not work in micro-reaction and micro-separation technologies. The strategy of numbering-up is the only means to increase the throughput of micro-separation units. The key issue for the successful numbering-up process is to realise the technical concepts of the phase distribution for the transformation of a single channel arrangement to a laboratory, pilot or a production module, while maintaining the fundamental principles.

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