Microgels for the Intensification of Liquid-Liquid Extraction Processes – Feasibility and Advantages

Miriam Faulde, Josia Tonn, Andreas Jupke

Microgels are cross-linked polymers with a high application potential in liquid-liquid systems due to their surface activity and switchable stabilization properties. A process concept utilizing microgels in extraction processes is presented. The microgels are located at the drop surface and prevent coalescence, enabling monodisperse operation. At the column top, the stabilization is switched off by temperature shift. The switchable stabilization and the absence of additional mass transfer resistance are crucial requirements for the concept and tested experimentally. The results provide the basis for the model-based evaluation of the process performance, revealing a broader operating window, capacity increase at equal height equivalent of theoretical stage (HETS) for high loads, and reduced HETS for small loads.

Keywords: Liquid-liquid extraction, Mass transfer, Microgels, Process intensification

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1 Introduction

Microgels are cross-linked polymers which gain increasing attention due to their outstanding properties. They are commonly obtained by precipitation polymerization of a monomer and a cross-linker, forming porous networks typically with a spherical shape and diameter of less than 1 μm [1]. The cross-linking gives the microgels their soft and deformable character. One of their most prominent features is their responsiveness to external triggers, e.g., temperature shifts, changing their structure and properties. The trigger depends on the utilized monomer; the most prominent example is the temperature responsiveness of poly(N-isopropylacrylamide) (P(nIPAM)) microgels. Above the so-called volume phase transition temperature (VPTT) the microgel collapses, drastically reducing the size and the softness of the microgel which leads to a radical change of its features [1].

The microgels are very lyophilic and at water-oil interfaces, they deform and flatten, penetrating only marginally into the oil phase [2]. The switchability combined with their surface-active properties [2] makes them promising candidates for the application in liquid-liquid systems. In this study, a new process concept to intensify liquid-liquid extraction processes by utilization of microgels is introduced.

The performance of liquid-liquid extraction processes is determined by the apparatus height required for the separation task and strongly depends on fluid dynamics such as coalescence and breakage of drops [3, 4]. Coalescence reduces the interfacial area for mass transfer, and the often resulting broad drop size distribution leads to a broad residence time distribution and thus a flat concentration profile along the apparatus. Furthermore, entrainment of small drops by the continuous phase reduces the performance. Microgels can counteract these drawbacks by stabilization of the drops leading to monodisperse drops.

The process concept for microgel application in a counter-current extraction column is illustrated in Fig. 1. Microgels are introduced at the disperser generating monodisperse drops at the bottom of the column. The microgels at the interface prevent coalescence during drop rise and mass transfer. At the top of the column coalescence is required for phase separation. Here, a temperature shift triggers the structural change of the microgels, thus enabling phase separation. The microgel-rich aqueous phase from the settler can be recycled by filtration [5] while the organic phase containing the target product proceeds to the next process step.

To realize this concept, two major microgel-related requirements need to be fulfilled: an efficient switchable stabilization and destabilization of microgel-covered drops, and microgels should not impede the mass transfer in the dispersed system. These two requirements are tested experimentally in this study by batch settling experiments and mass transfer experiments in a stirred two-phase cell. Subsequently, potential advantages of the proposed process concept are evaluated by process simulation utilizing a population balance simulation tool based on representative drops [6–8]. The evaluation in this study considers the potential impact of microgels on mass transfer and fluid dynamics.

Miriam Faulde, Josia Tonn, Prof. Dr.-Ing. Andreas Jupke

andreas.jupke@avt.rwth-aachen.de

RWTH Aachen University, Fluid Process Engineering (AVT.FVT), Forckenbeckstrasse 51, 52074 Aachen, Germany.
1.1 Microgel-Stabilized Systems

Disperse liquid-liquid systems stabilized by solid particles or surfactants are well established and understood [9, 10]. Droplet stabilization by solid particles strongly depends on their wettability and size since coalescence is predominantly prevented by steric effects [9, 11]. For amphiphilic surfactants, the reduction of interfacial tension is the most prominent stabilization feature [10]. Microgels also lower the interfacial tension drastically [12]. However, the interfacial activity of microgels appears more complex due to their softness and deformability [1, 13, 14].

The deformation at the interface and the penetration to the oil phase of the microgel is visualized by various techniques [2, 13], revealing a flattened "fried egg"-like structure when the initially spherical microgels adsorb to the liquid-liquid interface [13]. The extent of deformation strongly depends on the microgel structure. The degree of cross-linking of pure P(nIPAM) microgels predominantly affect the deformation. The less cross-linked the microgels are, the more they spread at the interface leading to more stable emulsions [1]. P(nIPAM) microgels preferably stabilize oil-in-water emulsions. For effective stabilization, a certain size and cross-linking specific concentration is required [12]. The switching of the stabilization by exposure to the external trigger of the microgel was also demonstrated [15]. However, the mechanisms are not yet fully understood and still in the focus of current research.

1.2 Mass Transfer in Disperse Systems Containing Surface-Active Species

Mass transfer in extraction processes is a complex process with overlapping and relating phenomena involved. The presence of surface-active species increase complexity since they affect the hydrodynamic regime of the drops, mass transfer-induced turbulences, and Marangoni convection inside the drops, respectively [7, 16]. These phenomena strongly affect the mass transfer kinetics because they promote mixing and thus the decay of radial concentration gradients. These effects can cause a mass transfer enhancement by factor 10 compared to pure diffusion [7]. Another important aspect is the interfacial area provided for mass transfer.

Regarding mass transfer in disperse systems in the presence of surfactants, two main aspects are considered: (i) the additional mass transfer resistance of the adsorbed interfacial surfactant layer and (ii) their effect on the interfacial mobility and the resulting hydrodynamic behavior of the covered drops [16]. The ratio of impact of these effects strongly depends on the solvent system and surfactant type and concentration. Moreover, micelles can incorporate hydrophobic solutes in the aqueous phase and thus change the distribution coefficient [16, 17].

The effects of microgels on the stability of disperse systems have been investigated in detail [1, 13, 14], also mass transport through microgels has been studied [18, 19]. However, the effects of interfacial microgel layers on mass transfer in disperse systems and the underlying phenomena are little understood so far. In an earlier study, the effect of microgels on interfacial mobility of a single drop is demonstrated in single-drop experiments [20]. Less cross-linked microgels lead to less internal circulation in the drop, as the microgels spread more at the interface forming an interpenetrated film and thus a higher resistance to momentum transfer [20]. Since this effect can reduce the mass transfer, it will be considered in the process performance evaluation by a case study.

Monteillet et al. [21] qualitatively investigated extraction in an ionic liquid-water system stabilized by P(nIPAM) microgels. In their emulsion experiments, they qualitatively demonstrate the permeability of the microgel-covered drop interface using visible transfer agents [21]. Furthermore, the permeability of immobilized microgel layers is investigated for membrane applications. In these processes, the permeability of high-molecular-weight compounds is significantly reduced for swollen microgels [22]. The transfer of smaller molecules such as solvents inside the gels is investigated by simulation and experimentally, whereby the porous structure of the microgels enables fast mass transfer [18, 19]. The latter findings regard single, suspended microgels. As the microgels deform at the interface, a transfer of the described results to interfacial microgel layers should be made cautiously.

2 Materials and Methods

Toluene (disperse)/water (continuous)/acetone (c→d) is used as standard test system for liquid-liquid extraction [23]. The system has a high interfacial tension (36 mN m⁻¹ at 20 °C [23]); hence, the phase separation behavior is dominated by coalescence. For the aqueous phase bidistilled water is utilized. The microgels are introduced to the aqueous phase. Toluene and acetone are purchased from Merck in ENSURE® quality. All experiments are repeated twice at minimum.

2.1 Utilized Microgels

Two different microgels are utilized. Both are P(nIPAM) microgels, containing different amounts of the cross-linker...
between 0.05 and 0.1 g L–1. Both phases are stirred at 800 rpm and microgel concentration and ionic strength. The ionic strength is adjusted with NaCl to 50 mmol L–1 [26]. Next, the microgels are added to the aqueous phase, their concentration is varied between 0.05 and 0.1 g L–1. Both phases are stirred at 800 rpm for 120 s in the cell. After the stirrer is stopped, the phase separation is recorded by a video camera [25].

2.2 Experiments on Switchable Stabilization of the Dispersed System

Setting experiments are conducted in a batch settling cell [25]. Prior to each experiment, toluene and water are mutually saturated for 2 h. The phase ratio between organic (toluene) and aqueous phase is 1:2 in all experiments, to obtain an oil-in-water dispersion. The aqueous phase is modified regarding microgel concentration and ionic strength. The ionic strength is adjusted with NaCl to 50 mmol L–1 [26]. Next, the microgels are added to the aqueous phase, their concentration is varied between 0.05 and 0.1 g L–1. Both phases are stirred at 800 rpm for 120 s in the cell. After the stirrer is stopped, the phase separation is recorded by a video camera [25].

2.3 Mass Transfer Experiments

Partition coefficients are determined in equilibrium experiments in 20-mL flasks. The samples are mixed for 24 h by rotation at 25 °C. The samples containing microgels with a concentration of 1 g L–1 in the aqueous phase are separated at 25 °C by centrifugation. The acetone concentration in the organic phase is determined by gas chromatography using methylethylketone as internal standard (Agilent 6890N with polar FS-CW 20 M-CB-1 column; CS Chromatographie, Langerwehe Germany).

For the investigation of time-resolved mass transfer through a microgel-covered interface, a stirred two-phase cell is utilized [27]. The total volume of the cell is 500 mL. Before the experiments, toluene and water are mutually saturated as described above. The system is filled into the cell and paused for 120 min allowing the microgels to cover the interface. The time required to cover the interface is tested in preliminary experiments as described in the Supporting Information, Sect. S1.3. At the beginning of the mass transfer measurement, acetone is injected into the aqueous phase. The mass transfer is tracked by sampling the organic phase and analyzed by gas chromatography as described above.

2.4 Simulation Settings

For the evaluation of the process performance, a population balance simulation tool based on representative drops is used. The tool calculates drop velocity, coalescence, breakage, and mass transfer for each drop class [6]. As a reference scenario, data from experiments in a DN80 pulsed sieve tray extraction column without microgels is employed [28]. The data contains four stationary operating points with different loads and one flooding point. The VPTT of the microgels is about 34 °C.

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For the evaluation of the microgel-stabilized system, the simulation parameters are modified. To account for the stabilizing effect of the microgels, the probability of coalescence and breakage of the drops is set to zero. The potential impact on mass transfer is regarded by a parameter study.

For the evaluation of the fluid-dynamic operating window, the load and the phase ratio are varied, starting at a volume flow of 4 L h–1 for the continuous phase and the volume flow is increased until flooding occurs. This is repeated for 12 phase ratios \( V_d/V_c \) between 1.8 and 8.1. For the evaluation of fluid dynamics, the flow though the column is simulated for 900 s, while for mass transfer 3600 s are simulated to ensure steady-state conditions.

3 Results and Discussion

3.1 Temperature-Responsive Phase Separation

For the evaluation of the switchable phase separation, settling cell experiments were performed with a toluene/water system and microgels with 2.5 and 5 mol % BIS at different concentrations in the aqueous phase, at temperatures below and above the VPTT. The resulting settling times are displayed in Fig. 2. The long settling times in the experiments performed at temperatures below the VPTT reveal an extremely good stabilization of the disperse system by the microgels in their swollen state. At 25 °C the settling time of the pure system is

![Figure 2. Settling time of the toluene-water system without microgels and different concentrations of microgels in the aqueous phase. Microgels with cross-linking contents of 2.5 and 5 mol % are investigated. Experiments were carried out at 25 and 40 °C, corresponding to swollen and collapsed state of the microgels, respectively.](image-url)

1) List of symbols at the end of the paper.
24.3 ± 1.6 s. The settling time increases with higher microgel concentration, indicating improved stabilization of the droplets by the microgels. For the less cross-linked microgels with 2.5 mol % BIS, an effective stabilization is reached at lower concentrations than for the higher cross-linked microgels with 5 mol % BIS. This result is in good agreement with findings from Destribats et al. [14] since the ability to deform at the interface increases with reduced cross-linking, consequently less microgel is required to cover the interface.

For the proposed process concept the phase separation via temperature shift is required; therefore, the settling behavior at 40 ºC where the microgels are collapsed is also tested. At 40 ºC complete separation is reached in all experiments. The settling process of microgel-containing systems takes about three times longer than for the pure solvent system at this temperature. This increases the required settler length in the future process [25]. Regarding the cross-linker content of the microgels, no trend can be determined in the settling time. These results demonstrate that the required switchable phase separation is feasible in pilot scale. Since the collapse time of microgels is in the scale of milliseconds [19], the crucial factor for the settler design will be to realize a rapid heat transfer. Subsequent to the phase separation, the microgels in the aqueous phase can be recycled by filtration [5].

3.2 Mass Transfer through Microgel-Covered Interface

As basis for the evaluation of the mass transfer, first a possible impact of the microgels on liquid-liquid equilibrium is tested. The partition coefficient is determined to be 0.635 ± 0.010 wt %\textsubscript{mg} wt %\textsubscript{aq}⁻¹ for the pure system and 0.648 ± 0.013 wt %\textsubscript{mg} wt %\textsubscript{aq}⁻¹ with microgels at 25 ºC. In the conducted experiments, the microgels do not affect the liquid-liquid equilibrium. This can be explained by their undissolved presence in the aqueous phase; thus, they do not contribute to the molar composition of the phase and consequently the partition of the components.

Besides the partition coefficient, the dynamics of the mass transfer are of interest for the design of extraction processes. The dynamics of mass transfer through the microgel-covered liquid-liquid interface are investigated in a stirred two-phase cell. The transfer of acetone from the aqueous to the organic phase, through the flat interface of the undispersed system, is observed. The resulting time-dependent concentration profiles for the organic phase is illustrated in Fig. 3.

The trend of the accumulation of acetone in the organic phase is very similar for the pure and the microgel-containing system. From the concentration profile the mass transfer coefficient is calculated (details in the Supporting Information, Sect. S1.3). For the calculation it is assumed that the microgels are uniformly distributed and permeable. Consequently, the mass transfer area equals the cross-sectional area of the cell (Fig. 3). Due to the small deviation of the mass transfer coefficients within the range of errors, no significant impact of the microgel layer can be determined. Therefore, the utilized microgels do not significantly impede the mass transfer for the selected test system. Nevertheless, it should be noted that acetone is a very small molecule compared to the microgel and its porous structure. Consequently, it is assumed that no additional mass transfer resistance of the interfacial layer has to be considered in the simulation. Only hydrodynamic effects on the mixing inside the drop will be taken into account for the model-based performance evaluation of the process.

3.3 Model-Based Evaluation of Intensification Potential

The evaluation of the intensification potential considers two aspects of the process performance: the fluid-dynamic operating window and the separation performance.

3.3.1 Model-Based Evaluation of Fluid-Dynamic Operating Window

The fluid-dynamic operating window is evaluated by simulating operating points with different volume flows and phase ratios. The resulting operating window is shown as area of feasible operating points for the polydisperse reference and the monodisperse microgel-stabilized system in Fig. 4. The operating window is limited by the holdup, with increasing load the drop velocity in the countercurrent flow decreases, leading to local accumulation of drops and thus an increasing holdup [8]. The upper limit of the operating window is the flooding point which is defined by a local holdup of 50 %, since greater holdups could lead to phase inversion during the process. The lower limit was set to a holdup of 3 %.

Regarding the operating windows for different monodisperse drops in Fig. 4, the flooding limit is shifted to higher loads with increasing drop diameter. Comparing the different monodisperse drops to the polydisperse reference case, the operating window is broadened especially for phase ratios smaller than 1. For these ratios, the advantages of the monodisperse drops are particularly strong. In liquid-liquid extraction these ratios are favorable since they aim to reduce the amount of solvent.
3.3.2 Model-Based Evaluation of Separation Performance

Besides the operating window of the apparatus, the separation performance depending on the monodisperse drop diameter is evaluated. Therefore, the separation performance of the microgel-intensified monodisperse scenario is compared to the polydisperse reference at constant phase ratio of $V_d/V_c = 1.2$ as in the polydisperse experiments. The microgels covering the drop surface can reduce the interfacial mobility of the drops [20].

To account for the possible hydrodynamic effects on the mass transfer, the impact of the instability parameter $C_{IP}$ on the separation performance is investigated. It affects the effective diffusion coefficient $D_{eff}$ in Eq. (1) [7], which further depends on the quiescent diffusion coefficient for the dispersed phase $D_d$, the terminal drop rise velocity $v_\infty$, and the drop diameter $d$ as well as ratio of viscosities $\eta_d/\eta_c$.

$$D_{eff} = D_d + \frac{v_\infty d}{C_{IP} \left( 1 + 2\eta_\infty/\eta_c \right)}$$ (1)

The value of $C_{IP}$ for the reference system is 5527 [7]. To account for a reduced mixing due to the repulsion of internal circulation by the microgels, the parameter $C_{IP}$ is varied in multiples of the references value, up to the fivefold value, 27 635. The contribution of the enhancement becomes stronger with larger drop diameter, as the size of the formed eddies increases and ensures better mixing [6]. In case of the 2-mm drop, the resulting mass transfer coefficient of the dispersed phase for the less turbulent system is reduced by half. More details can be found in the Supporting Information, Sect. S2.2.

The reduction of the mass transfer coefficient propagates to the process separation performance as illustrated in Fig. 5, as height equivalent of theoretical stage (HETS) for different loads at constant volume flow ratio. Comparing the separation performance, it can be seen that for bigger drops the capacity of the apparatus can be increased by up to 55 % for 4-mm drops at equal separation performance, presuming that the effect of the microgels on mass transfer is minor ($2C_{IP}$).

Furthermore, at lower loads, an increase in separation efficiency and hence a reduction of HETS of about 20 % can be achieved by application of small drops (Fig. 5, white arrow). For small drops, the effect of turbulences is less pronounced; hence, the effect of the instability parameter on the HETS is minor. For lower loads, the provided interfacial area is the dominant effect for mass transfer. In this case, the smaller monodisperse drops are favorable since for big drops the resulting holdup is insufficient to provide the separation performance.

4 Conclusion

This study indicates that microgels have the potential to intensify the separation performance and operating window of liquid-liquid extraction processes. The feasibility was demonstrated with regard to the switchable phase separation behavior and mass transfer. The monodisperse drops can significantly increase the feasible operation window of the apparatus.

Regarding the separation performance, the results revealed that microgel-stabilized monodisperse drops can enable a capacity increase of about 55 % at equal separation performance, assuming that the mass transfer is not reduced due to fluid dynamics. Therefore, single-drop mass transfer and coalescence experiments are required in future to determine the optimal interfacial microgel coverage to efficiently prevent coalescence while not reducing mass transfer. For small drops, possible fluid-dynamic effects are minor and the separation performance is increased by enlarging the interfacial area provided by the microgel-covered drops.
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Symbols used

- $c$: concentration [g L$^{-1}$]
- $C_{ip}$: instability parameter [-]
- $d$: drop diameter [m]
- $D$: diffusion coefficient [$m^2 s^{-1}$]
- $v_t$: terminal drop velocity [$m s^{-1}$]
- $V$: volume flow [$m^3 h^{-1}$]
- $w$: mass fraction [wt %]

Greek letter

- $\eta$: viscosity [Pa s]

Subscripts

- $c$: continuous phase
- $d$: dispersed phase
- $eff$: effective
- MG: microgel

Abbreviations

- BIS: N,N$'${-methylenebis(acrylamide)}
- HETS: height equivalent of theoretical stage
- P(nIPAM): poly(N-isopropylacrylamide)
- VPTT: volume phase transition temperature

References

[1] W. Richtering, Langmuir 2012, 28 (50), 17218–17229. DOI: https://doi.org/10.1021/la302331s
[2] K. Geisel, K. Henzler, P. Guttmann, W. Richtering, Langmuir 2015, 31 (1), 83–89. DOI: https://doi.org/10.1021/la503959n
[3] C. Korb, H.-J. Bart, Hydrometallurgy 2017, 173, 71–79. DOI: https://doi.org/10.1016/j.hydromet.2017.08.009
[4] F. Buchbender, M. Schmidt, T. Steinmetz, A. Pfennig, Chem. Ing. Tech. 2012, 84 (4), 540–546. DOI: https://doi.org/10.1002/cite.201100174
[5] O. Nir, T. Trieu, S. Bannwarth, M. Wessling, Soft Matter 2016, 12 (31), 6512–6517. DOI: https://doi.org/10.1039/c6sm01345g
[6] M. Henschke, Auslegung pulsierter Siebboden-Extraktionskolonnen, Berichte aus der Verfahrenstechnik, Shaker, Aachen 2004.
[7] M. Henschke, A. Pfennig, AIChE J. 1999, 45 (10), 2079–2086. DOI: https://doi.org/10.1002/aic.690451006
[8] B. Weber, C. Meyer, A. Jupke, Chem. Ing. Tech. 2019, 54 (3), 167. DOI: https://doi.org/10.1002/cite.201900057
[9] B. P. Binks, Curr. Opin. Colloid Interface Sci. 2002, 7 (1–2), 21–41. DOI: https://doi.org/10.1016/S1359-0294(02)00008-0
[10] V. B. Fainerman, R. Miller, in Surfaceants: Interfacial Properties, Applications (Eds: V. B. Fainerman, D. Möbius, R. Miller), Studies in Interface Science, Vol. 13, Elsevier, Amsterdam 2001.
[11] B. P. Binks, C. P. Whithy, Langmuir 2004, 20 (4), 1130–1137. DOI: https://doi.org/10.1021/la0303557
[12] B. Brugger, W. Richtering, Langmuir 2008, 24 (15), 7769–7777. DOI: https://doi.org/10.1021/la800522h
[13] M. Destrabets, V. Lapeyre, M. Wolfs, E. Sellier, F. Leal-Calderon, V. Ravaine, V. Schmitt, Soft Matter 2011, 7 (17), 7689. DOI: https://doi.org/10.1039/c1sm05240c
[14] M. Destrabets, M. Eyharts, V. Lapeyre, E. Sellier, I. Varga, V. Ravaine, V. Schmitt, Langmuir 2014, 30 (7), 1768–1777. DOI: https://doi.org/10.1021/la4044396
[15] B. Brugger, B. A. Rosen, W. Richtering, Langmuir 2008, 24 (21), 12202–12208. DOI: https://doi.org/10.1021/la8015854
[16] N. Paul, M. Kraume, S. Schön, R. von Klitzing, AIChE J. 2015, 61 (3), 1092–1104. DOI: https://doi.org/10.1002/aic.14699
[17] N. Paul, P. Schrader, S. Enders, M. Kraume, Chem. Eng. Sci. 2014, 115, 148–156. DOI: https://doi.org/10.1016/j.ces.2013.02.018
[18] J. Riest, Ph.D. Thesis, Heinrich-Heine-Universität Düsseldorf 2016.
[19] R. Keidel, A. Ghavami, D. M. Lugo, G. Lotze, O. Virtanen, P. Beumers, J. S. Pedersen, A. Barдов, R. W. Winkler, W. Richtering, Sci. Adv. 2018, 4 (4), 905–913. DOI: https://doi.org/10.1126/sciadv.aao7086
[20] M. Faulde, E. Siemes, D. Woll, A. Jupke, Polymers 2018, 10 (8), 809. DOI: https://doi.org/10.3390/polym10080809
[21] H. Montellet, M. Workamp, X. Li, B. Schuur, J. M. Kleijn, F. A. M. Leermakers, J. Sprakel, Soft Matter 2014, 50 (81), 12197–12200. DOI: https://doi.org/10.1039/c4sm04990j
[22] M. Barth, M. Wiese, W. Ogieglo, D. Go, A. J. C. Kuehne, M. Wessling, J. Membr. Sci. 2018, 555, 473–482. DOI: https://doi.org/10.1016/j.memsci.2018.03.037
[23] Standard Test Systems for Liquid Extraction (Eds: T. Mišek, R. Berger, J. Schröter), 2nd ed., Institution of Chemical Engineers, Rugby 1985.
[24] A. Pich, W. Richtering, in Chemical Design of Responsive Microgels (Eds: A. Pich, W. Richtering), Springer, Berlin 2011.
[25] M. Henschke, Ph.D. Thesis, RWTH Aachen University 1995.
[26] M. Soika, A. Pfennig, Chem. Ing. Tech. 2005, 77 (7), 905–911. DOI: https://doi.org/10.1002/cite.2005003229
[27] W. Nitsch, M. Raab, R. Wiedholz, Chem. Ing. Tech. 1973, 45 (16), 1026–1032. DOI: https://doi.org/10.1021/002330451606
[28] D. Garthe, Ph.D. Thesis, TU Munich 2006.
Research Article: An innovative process concept utilizing switchable microgels in extraction processes is presented. The microgels prevent coalescence facilitating monodisperse drops. At the column top, the microgels are switched by a temperature shift enabling phase separation. The requirements for the concept are tested experimentally. A model-based evaluation of the process assesses the advantages of the concept.

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