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Liquid–liquid extraction in microchannels and conventional stage-wise extractors: A comparative study

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ABSTRACT

The objective of the study is to compare the performance of microchannels and conventional stage-wise extractors for liquid–liquid extraction by using a standard phase system. Three different microchannels – a T-junction microchannel, a serpentine microchannel and a split-and-recombine microchannel – have been used in the experiments. Conventional extractors are represented by a mixer-settler and an annular centrifugal extractor. The phase system used in the experiments is water (succinic acid) n-butanol system which is one of the standard phase systems recommended by the European Federation of Chemical Engineering. The extractors have been compared on the basis of percentage extraction, overall volumetric mass transfer coefficient and specific extraction rate. When compared on the basis of percentage extraction, performance of the microchannels and the conventional stage-wise extractors is found to be almost similar. Maximum values of overall volumetric mass transfer coefficient and specific extraction rates are found to be more in the microchannels than in the conventional stage-wise extractors. The ratio of maximum overall volumetric mass transfer coefficient in microchannels and conventional stage-wise extractors is found to range from 1 to 8.1. The ratio of maximum specific extraction rate in microchannels and conventional stage-wise extractors is found to range between 2.3 and 9.7.

1. Introduction

As evident by recent scientific literature, lot of interest is being shown in chemical processing in microchannels [1–3]. This is due to some unique advantages offered by microchannels. High surface to volume ratios make microchannels very useful for carrying out reactions in which fast heat transfer to avoid thermal degradation of the product is essential [4–7]. Low inventory of chemicals makes microchannels very attractive for carrying out reactions that involve hazardous conditions or substances [8–10]. Microchannels are very useful for carrying out two-phase reactions, gas–liquid and liquid–liquid mass transfer operations as the transfer paths are minimal and specific interfacial areas, due to physical constraint on the size of the dispersed phase, are very high. Consequently, a large number of studies on reactions, gas–liquid mass transfer, liquid–liquid mass transfer and other separation processes in microchannels have been reported [11–26]. Confident scale-up due to numbering up approach followed in scale-up is another distinct advantage offered by microchannels [27–30].

There are several advantages specific to liquid–liquid extraction in microchannels. One of these advantages is the control on the quality of dispersion in order to achieve the dual and conflicting objectives of fast mass transfer and quick phase disengagement [30]. The design of the microfluidic junction of the microchannel and flow conditions can be chosen to obtain almost monodispersed droplets [31,32]. Such control is not possible in any conventional liquid–liquid extractors because the way energy required to generate the dispersion is dissipated in conventional liquid–liquid extractors cannot be controlled. High mass transfer coefficients, ease of scale-up and reduction of solvent inventory are the other advantages if liquid–liquid extraction is carried out in microchannels. Possibility of reduction of solvent inventory is very attractive as it can make use of task-specific but expensive solvents commercially viable. Driven by the above advantages, there has been lot of research on liquid–liquid extraction in microchannels as evident by a large number of studies reported in recent literature [14,33–39].

Performance of a microchannel for liquid–liquid extraction depends on several factors which can be classified as the geometric parameters, operating parameters and physical properties. All these factors affect the performance by affecting the quality of dispersion (and hence specific interfacial area) and film coefficients. Among the geometric parameters, the type of junction at

Abbreviation: ACE, annular centrifugal extractor; EFCE, European federation of chemical engineering; LLE, liquid–liquid extraction; MS, mixer-settler.

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Nomenclature

K_La	Overall volumetric mass transfer coefficient (1/s)
C_{Ai}	Concentration of the aqueous phase at the inlet (mol/m^3)
C_{Ao}	Concentration of the aqueous phase at the outlet (mol/m^3)
C_{oi}	Inlet concentration of the organic phase (mol/m^3)
C_{oo}	Outlet concentration of the organic phase (mol/m^3)
C^*_{oi}	Concentration of the organic phase in equilibrium with the incoming aqueous phase (mol/m^3)
C^*_{oo}	Concentration of the organic phase in equilibrium with the outgoing aqueous phase (mol/m^3)
K_d	Distribution coefficient (−)
P_E	Percent extraction (−)
Q	Total flow rate (m^3/s)
Q_o	Flow rate of the organic phase (m^3/s)
S_{ER}	Specific extraction rate (mol/m^3/s)
v	Representative flow velocity (m/s)
V	Volume of the extractor (m^3)

Greek letters

Δ_{LMC}	Log mean concentration difference (mol/m^3)

which the immiscible liquids meet, layout of the channel after the junction, length of the channel and cross-stream dimension of the channel affect the performance for liquid–liquid extraction. Among the operating parameters, flow rates and flow rate ratio affect the quality of dispersion and hence the performance for liquid–liquid extraction. Among physical properties viscosities of the two liquid phases, interfacial tension and wettability affect the performance of a microchannel for liquid–liquid extraction.

There are several studies which highlight the effect of geometry of a microchannel on its performance for liquid–liquid extraction. In a recent study overall volumetric mass transfer coefficient (K_La) obtained in 5 different types of microchannels (T-junction microchannel with square cross-section, T-junction microchannel with trapezoidal cross-section, Y-junction microchannel with square cross-section, concentric microchannel and caterpillar microchannel) are reported [16]. For the same flow velocity, the ratio of K_La observed for the caterpillar microchannel and K_La observed for concentric microchannel was about 7.5. This clearly indicates the effect the geometry of the microchannel has on its performance for liquid–liquid extraction. Similarly, studies carried out on liquid–liquid extraction in microbore tubes also suggest that the geometric parameters such as microbore tube diameter and length affect the overall volumetric mass transfer coefficients and hence the performance of microbore tubes for liquid–liquid extraction [30,39–41].

There are studies in which the same microchannel has been used for carrying out liquid–liquid extraction experiments with different phase systems. Benz et al. carried out experiments in static micromixers using different phase systems and found that for a given total flow rate extraction efficiency was different for different systems [42]. Darekar et al. and Sen et al. used the same serpentine microchannel for conducting experiments with zinc-D2EHPA and TBP-nitric acid system, respectively [43,44]. The ranges of K_La for zinc-D2EHPA and TBP-Nitric acid system were reported to be 5.41×10^{-4} to $2.96 \times 10^{-2}\,s^{-1}$ and 1×10^{-3} to $4\,s^{-1}$, respectively. These studies clearly show that the performance of a microchannel is strongly dependent also on the physical properties of the phases involved in liquid–liquid extraction. There are several studies in which effects of flow rate and flow rate ratio on liquid–liquid extraction in microchannels are reported [34,45,46]. These studies highlight the effect of operating parameters on liquid–liquid extraction in microchannels.

Most of the reported studies on liquid–liquid extraction in microchannels end up by comparing the performance of microchannels and conventional extractors. The comparison is usually done by reporting the range of K_La values obtained for the

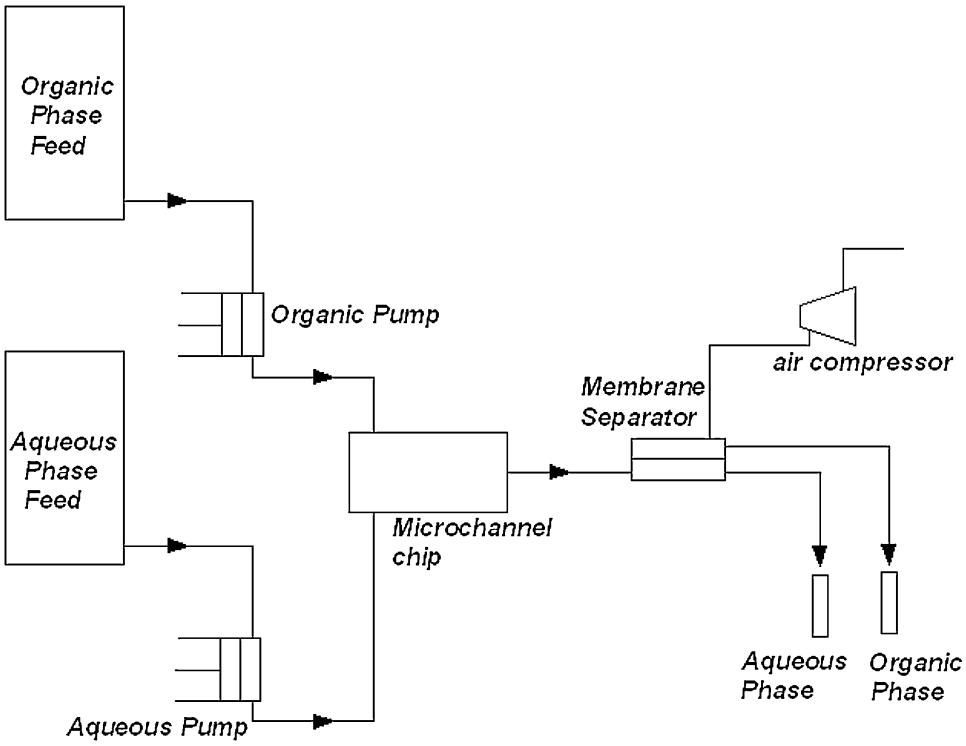

Fig. 1. Schematic diagram of the setup used in the experiments with the microchannels.