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Liquid–liquid extraction in twisted micromixers

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ABSTRACT

This paper reports a study on mixing performance and mass transfer enhancement between two immiscible liquid phases in proposed twisted micromixers. The experiments conducted for three different twisted micromixer and results were compared with a plain microchannel. Water (Cu) + D2EHPA + kerosene system, was chosen for evaluation of mass transport. The fluid flow patterns were compared in different studied twisted micromixers at the Reynolds number ranging from 76.7 to 460.3 at the same aqueous to organic flow rate. Moreover the effect of the twisted ratio on the overall volumetric mass transfer coefficient (K_La) and the extraction efficiency (E) was studied. Results show that creating more twist in micromixer is more effective for liquid–liquid mass transfer, but more energy is required to pump fluids to microchannel. Performance ratio was proposed to evaluate this matter from economic aspect. As far as the twisted ratio has direct effects on extraction efficiency and pressure drop, it was used as a design variable for determining the most appropriate channel geometry. The results show that the extraction efficiency as well as pressure drop increased with increase in twist ratio. Therefore, in order to reach the highest performance ratio an optimum value for twist ratio was proposed.

1. Introduction

In recent years, the application of micro reactors has gained increasing attention in the fields of chemical process industry. Due to several benefits such as shorter transport path in microchannels and high surface to volume ratio, the possibility of doing reactions involving toxic and dangerous chemicals and having a simple geometry, caused the use of microchannels in many fields such as heat and mass transfer [1–3]. The restrictions on use of microchannels are relatively high pressure drop, inability to transport a feed containing solid particles and possibility of blocking the channel. However, the use of microchannels is very benefit for doing liquid–liquid extraction. Solvent extraction is extensively used in many industries including the petroleum, hydrometallurgy, food and chemical industries and etc. Many researchers have tried to apply the microchannel in the field of liquid–liquid extraction. Zhao et al. [4] investigated the immiscible liquid–liquid mass transfer characteristics in two types of the opposing-flow and the cross-flow T-junction microchannels. Dessimoz et al. [5] carried out experiments to study the mass transfer performance of liquid–liquid two phases for Y- and T-junction microchannel in slug and parallel flow regimes. Assmann and von Rohr [6] used an inert gas to enhance the liquid–liquid extraction in microchannel.

Due to the application of rare earth metals and their compounds, in various industries including the electroplating, tanning, and metallurgical industries, extraction of these metals from aqueous solutions is very interesting. Solvent extraction in microchannels is one of the useful techniques for extraction, purification, separation and recovery of metal ions from aqueous solutions, has been popular among researchers in recent years. Darekar et al. [7] performed liquid–liquid two phase's extraction experiments with water (Zn) D2EHPA + dodecane system in the T-junction serpentine microchannel and the split and recombine microchannel. Yang et al. [8] carried out studies on the Cu^{2+} extraction from an aqueous to an organic phase under different operating conditions in a T-junction microchannel. Tamagawa and Muto [9] used a Y-junction microchannel to the solvent extraction of cesium. They investigated the effect of geometry and process parameters such as channel pattern, channel width and flow rate on the flow condition. Yin et al. [10] studied the La(III) extraction process with 2-ethylhexyl phosphoric acid-2-ethylhexyl ester as the extractant in a PMMA (polymethyl methacrylate) microreactor. Tsaousidis et al. [11] studied the extraction of uranium (VI) from aqueous nitric acid solutions into an organic phase containing tributyl phosphate (TBP) in a Teflon microchannel.

Microchannel geometry can play an important role in the mixing efficiency. So far, many researchers tried to determine the impact of the microchannel geometries on improving flow regime

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Nomenclature

A	Lateral surface area of main channel (m^2)
$C_{aq,in}$	Concentration of Cu(II) in the aqueous phase (mg/L)
$C_{aq,out}$	Concentration of Cu(II) in the outlet aqueous phase (mg/L)
C_{aq}^*	Equilibrium concentration of Cu(II) in the outlet aqueous phase (mg/L)
D_e	Hydraulic diameter of micromixer (m)
D_w	Channel width (m)
E	Extraction efficiency (−)
f	Friction factor (−)
g	Gravitational acceleration (m/s^2)
h_f	Friction loss head (m)
h_l	Local loss head (m)
K_La	Overall volumetric mass transfer coefficient (1/s)
k_l	Local loss coefficient (−)
L	Length of main channel (m)
L_i	Length of inlet channel (m)
L^*	length of one twist of channel (m)
ΔP	Pressure drop difference (Pa)
Q_{aq}	Aqueous phase volume flow rate (m^3/s)
Q_{oil}	Organic phase volume flow rate (m^3/s)
Re_m	Reynolds numbers of two phases (−)
t_M	Superficial residence time of mixture two phase (s)
U_M	Total superficial velocity of the liquid–liquid two phases (m/s)
U	The superficial velocity of the each phase (m/s)
V	Volume of micromixer (m^3)
Y	Twisted ratio

Greek letters

ε	Specific energy dissipation (Pa/s)
μ	Viscosity (Pa s)
μ_M	Viscosity of mixture two phases (Pa s)
μ_{aq}	Viscosity of aqueous phase (Pa s)
μ_{oil}	Viscosity of organic phase (Pa s)
ρ	Mass density of fluid (kg/m^3)
ρ_M	Mass density of mixture of two phases (kg/m^3)
ρ_{aq}	Mass density of aqueous phase (kg/m^3)
ρ_{oil}	Mass density of organic phase (kg/m^3)
σ	Surface tension (kg/s^2)
θ^*	Twist angle

Subscripts

aq	Aqueous phase
oil	Organic phase
in	Inlet
M	Mixture of the liquid–liquid two phases
out	Outlet

on micromixers and its performance [3,12–14].There are many interesting research in this field that among these, is mentioned in some of them. Hossain et al. [15] carried out the numerical analysis of mixing performance of the toluene-water system in three different geometries of micromixer, i.e., curved; zigzag and square-wave. Aoki et al. [16] examined the effects of channel bend and confluence geometries in various microchannels on mixing performance. The results showed that the bend geometry deforms the fluids and decreases the diffusion length between fluids, thus increases the performance of mixing.

For immiscible liquid–liquid two phase flow in micromixers, the flow patterns are depending on the inertia, interfacial tension and viscous forces [5]. The three forces compete together that may distort the interface of two immiscible phases [17]. Considering the dominance of each force on the others, different flow regimes were established in the microchannels. In addition, the effects of gravity on flow regimes is considered negligible at the micrometer scale [18]. At the micrometer scale, the Reynolds numbers are approximately small. Thus, inertia force effect is not significant compared with viscous and interfacial forces, if the total flow rate is not high enough [18,19]. The importance of inertia, interfacial tension and viscous forces on the flow pattern in main channel can be discussed by two important dimensionless, the numbers capillary number and the Weber number [17,20].

Since boosting the mixing efficiency is a key issue to improve the heat and mass transfer performance in microchannels, design of new geometry of micromixer could be interesting. Based on this motivation, in this work, it has been trying to explain the preference of twisted micromixer on mixing performance and liquid–liquid mass transfer compared to the simple micromixer.

2. Experiments

2.1. Experimental setup

The employed experimental setup is schematically shown in Fig. 1. The aqueous and oil phases are individually fed into the twisted micromixer at the same volumetric flow rate, by two high-precision syringe pumps. In addition, real images were recorded using a digital microscope to investigate the flow regime in the twisted micromixers. High precision pressure transducers (BD sensor, DMP 343, Germany) measured the pressure drop across channel. In order to study the effect of twisting the main channel on the mixing performance, a comparison between a simple T-shaped microchannel and twisted microchannels was carried out. In this work, three twisted microchannel with different twisted ratio ($Y = L/L^*$) of 3, 8 and 16 were applied. In this ratio, L is the total length of main channel and the L^* is the length of main channel that contains a complete twist. In order to create one twist, first of twist was kept fixed and end of the twist was rotated 360° around the center axis of the main channel. For all microchannels, transparent PVC tubes with an internal diameter of 800 μm were used to make the inlet tubes and the main channel. For all micromixers, angle between inlet channels was 180° and the lengths of inlet channels (L_i) and the main channel (L) were 30 and 200 mm, respectively. Twist angle (θ^*) for three examined channel were 20°, 30° and 45°. In addition, the channel width (D_w) for all micromixers is 800 μm. The detailed channel geometry information has been shown in Fig. 2.

2.2. Material and apparatus

The materials used in this work were prepared from following suppliers: Copper sulphate pentahydrate (Merck, ≥99.6% purity), D2EHPA (Merck, ≥99% purity), and sodium acetate trihydrate (sigma, ≥99% purity). In addition, the deionized water was used in preparation of all aqueous solution. The kerosene was provided from Tehran Refinery Company, Iran. The copper ions have been extracted from the aqueous phase based on reactive extraction using D2EHPA as solvent. Many studies on the mechanism of solvent extraction of Cu(II) by D2EHPA have been reported in literature [21–23]. The aqueous phase was prepared using dissolving copper sulphate pentahydrate in acetate buffer media. The 0.2 M acetate buffer solution was made by using dissolving sodium acetate tri-hydrate in deionized water.

All experiments were carried out at room temperature with the 1000 ppm initial concentration of the Cu(II) in aqueous solution, 1:1 organic to aqueous phase ratio and initial pH of aqueous phase