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# Liquid–liquid two-phase mass transfer in T-type micromixers with different junctions and cylindrical pits

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ABSTRACT

This paper reports an experimental investigation of flow pattern and liquid–liquid two-phase mass transfer in different T-type micromixers with novel shapes. These micromixers were rectangular with a dimension of 0.5 mm width, 1 mm depth and 100 mm long. New configurations of T-micromixers were fabricated with change in their junction shapes and designing pits on the mixing channel to achieve the efficient mixing and mass transfer. Mixing and mass transfer in micro-mixers with one pit on T-junction and array of pits, in collinear and non-collinear orientation, on mixing channel was examined. Water–propionic acid–1-octanol was chosen for mass transfer analyzing. Results show that various type of two-phase flow pattern established at examined geometries. Results also depict that diameter of pit at the junction and designing of pit on mixing channel and its diameter has significant effect on mass transfer coefficient and extraction efficiency. The highest enhancement in the extraction efficiency of micromixer with pitted junction-non collinear channels was 28.7% compared with micromixer with Plain junction. In addition, extraction efficiencies in the micromixers with pitted mixing channel-collinear channels and pitted mixing channel-non collinear channels increased up to 55.7% and 78.7% compared with that of plain junction, respectively.

## 1. Introduction

Recently, progress on the development of micro-reactor and micromixers with the sub-millimeter scales provides high mass transfer rate because of their large surface-to-volume ratio and the short transport path [1–3]. Owing to vast application field of microfluidic systems, it is important that mixing performance and mass transfer characterizes of these devices have been evaluated as these issues are essential part of chemical processes [4]. The mass transfer of two immiscible liquids in microscale mixers is commonly encountered in chemical processes, such as multiphase reactions, liquid–liquid extraction, and emulsification [5,6]. Micromixers were proposed to enhance the mass transfer characteristics of the two-phase flow because of characteristic dimension of micron scale and thereby increasing the specific interfacial areas of two phases [7]. Liquid-liquid extraction is one of the most focusing two-phase mass transfer processes that can be intensified in microchannels owing to short transport distance and high specific interfacial areas of two phases [8,9]. Flowing two immiscible fluids in a microchannel causes stretching, deforming and folding the interfacial area of two phases that causes more effective interphase mass transfer. Under this condition, mass transfer rate and the overall volumetric mass transfer coefficient can be improved [6]. Micromixers depending on the style of the fluid agitation can be classified into active and passive mixers [10–12]. Active micromixers use the disturbance generated by an external driving force for the mixing process such as using mechanical stirrers and valves, magnetic energy [13], piezoelectric and vibrating [14,15]. Owing to applying the integrated components and the external force, the structure of active micromixers is complicated [16]. Passive mixers have simple structures and use the energy of flow for increasing the interfacial contact area between the fluids and they are not applying any external energy [17]. In passive mixers, mass transfer and mixing in micro fluidic devices is generally driven by molecular diffusion of the laminar flow regime [18,19]. The geometrical structure of the micromixer has a direct influence on the condition of the fluid streams collision and flow distribution [20]. There are some basic designs of the passive micromixer, which split liquid flows into small laminar flow patterns or cause chaotic advection. The simple principle in this case is basically as the description of T-shaped channel performance. In this simple shape of the micromixer, two separate fluid streams collide at the confluence and are in contact within the mixing channel. Then, the

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**Nomenclature**

| | |
|---|---|
| A | Cross-sectional area of the microchannel (m$^2$). |
| a | Interfacial area (m$^2$). |
| C | Concentration of propionic acid (mol/L). |
| d | Pit diameter (m). |
| $D_H$ | Hydraulic diameter of the microchannel (m). |
| E | Extraction efficiency (−). |
| h | Channel depth (m). |
| $K_La$ | Volumetric mass transfer coefficient (1/s). |
| $L_{0avg}$ | Average slug size in PJ (m). |
| $L_{davg}$ | Average drop size (m). |
| $L_{in}$ | Inlet channel length (m). |
| $L_m$ | Mixing channel length (m). |
| $L_{savg}$ | Average slug size (m). |
| PJ | Plain junction. |
| PJC | Pitted junction-collinear channels. |
| PJN | Pitted junction-non collinear channels. |
| PMC | Pitted mixing channel- collinear channels. |
| PMN | Pitted mixing channel-non collinear channels. |
| Q | Volumetric flow rate (m$^3$/s). |
| $Re_m$ | Reynolds numbers of two phases (−). |
| T | Temperature (K). |
| $t_m$ | Residence time of two-phase mixture (s). |
| $U_m$ | Total superficial velocity of the two immiscible liquid–liquid phases (m/s). |
| V | Total volume of mixing channel (m$^3$). |
| W | Channel width (m). |
| x | Volume fraction of each phase (m$^3$/s). |

Greek letter

| | |
|---|---|
| $\mu_m$ | Mixture viscosity (Pa s). |
| $\rho_m$ | Mixture density (kg/m$^3$). |
| $\Upsilon$ | The relative extraction efficiency ratio (−). |

Subscripts

| | |
|---|---|
| aq | Aqueous phase |
| avg | Average |
| d | Drop |
| org | Organic phase |
| in | Inlet |
| m | Mixture of the liquid–liquid two phases |
| out | Outlet |
| s | Slug |
| * | Equilibrium |

flow gets out from the mixing channel while does not significantly contribute to mixing and mass transfer. The behavior and distribution flow pattern in the mixing channel will be affected the mass transfer rate in microchannels. There are many techniques to achieve efficient shape of T-mixers including changes in the size, cross sectional shape, junction contraction and confluence and creating pits on the mixing channel. Successfully and efficiently design of micro-scale mixers for detailed characteristics of multiphase flow mass transfer and the underlying physics of the transport processes is needed. Up to now, many studies have been reported in literature where researchers have tried to study the effect of micromixer geometries on the flow regimes and mixing performance [21–27]. One of the main strategies that can be adopted to achieve efficient mixing in T-or Y-mixers within a shorter distance is design concept of these mixers based on chaotic advection that results in splitting, stretching, folding and breaking of the flow and consequently better mixing performance [28]. Chaotic advection can be generated by the modification of the mixing channel shape such as designing wavy-wall and convergent–divergent mixing channel, creating grooves and embedding many cylinder obstacles along or herringbone structures on the floor of the mixing channel [28].

Ansari and Kim [29] analyzed and optimized a staggered herringbone groove micromixer in which mixing of two fluids have been performed. The main purpose of this design was investigation the effect of the ratio of the groove depth to channel height ratio and the angle of the groove on mixing index. Their optimization results show that the mixing is very sensitive to the shape and angle of the groove which can be used in controlling the mixing in micro devices.

At the work of Chen and Cho [30] mixing characteristics for an electrokinetically driven flow through microchannels with a wavy surface have been analyzed. The wavy shape of mixing channel increases the mixing performance by increasing the interfacial contact area between two fluid streams in comparison with a simple mixing channel.

Hossain et al. [24] investigated mixing and flow structures in T-mixers with different shape of mixing channel including zig-zag; square-wave; and curved channel. The square-wave mixing channel shows the best mixing performance, and the curved and zig-zag ones depict nearly the same performance.

Afzal and Kim [21] compared the mixing performance of convergent–divergent T-micromixer by straight, square-wave, zig-zag, and sinusoidal microchannels for a fixed mixing length. The convergent–divergent mixer shows at least a 19% higher overall mixing index compared with the other designs.

Wang et al. [27] designed three simple novel Y-mixers with different sizes of cylindrical grooves adjoining to the mixing channel and both simulated and experimental results showed that mixing has been enhanced because of introducing grooves along the main channel. Alam and Kim [31] analyzed mixing in a curved T-micromixer with rectangular grooves. Their results show that grooved mixer produce better mixing performance than smooth ones at low Reynolds numbers. All mentioned works were attributed single phase applications while most of the chemical processes and available micro-reactors are rely on multi-phase systems.

With this motivation, taking a liquid–liquid two-phase system as an important case study encouraged authors to investigate the effects of junction shapes as well as designing cylindrical pits on the mixing channel of T-mixers on the mass transfer enhancement. Because of the direct link between the flow patterns and mass transfer rate [22,23,32–35], in this study the hydrodynamics of liquid–liquid two-phase flow and mass transfer characteristics in these micromixers have been investigated. The idea is that the flow of two immiscible flows at the junction and in the mixing channel diverted into cylindrical pits is stretched, folded or rotated, thus leading to a good mixing and higher mass transfer. The purpose of the experiments undertaken in this work was extraction of propionic acid dissolved in water as aqueous phase and transferring it to 1-octanol as organic phase. The extraction efficiency (E) and mass transfer coefficient ($K_La$) was determined as a means to investigate liquid–liquid two-phase mass transfer.

## 2. Experimental

### 2.1. Materials

The materials used in this two-phase mass transfer system containing distilled water, 1-octanol, propionic acid and phenolphthalein solution and NaOH powder. Propionic acid and 1-octanol with purity more than 99% were provided from Merck Company. Distilled water was used for preparing the aqueous phase and in all