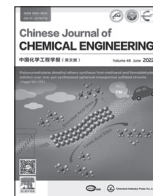




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Full Length Article

Solvent extraction with a three-dimensional reticulated hollow-strut SiC foam microchannel reactor

Ye Zhang^{1,2}, Yong Gao², Peng Wang^{1,2}, Duo Na², Zhenming Yang², Jinsong Zhang^{2,*}¹ School of Materials Science and Engineering, Northeastern University, Shenyang 110819, China² Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

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ABSTRACT

Recently, there has been considerable interest in the use of microchannel reactors for hydrometallurgy of rare earths (REs). Here, a novel integrated microchannel reactor based on the hollow-strut SiC foam material is presented and demonstrated to extract Ce³⁺ and Pr³⁺ using 2-ethylhexyl phosphoric acid mono-2-ethylhexyl ester (P507) as the extractant. The typical three-dimensional reticulated structure of the hollow-strut SiC foam was characterized by scanning electron microscopy and X-ray micro computed tomography. Since the reactor's structure plays a key role in fluid mixing and mass diffusion during the extraction process, the structure-performance relationship of the foam was studied by extraction experiments combined with numerical simulations. Using the foam with the optimal structure, the influence of the flow rate Q_0 of the two liquid phases on the extraction efficiency η and overall volume mass transfer coefficient K_La was discussed. For both RE ions, with increasing Q_0 , η decreases while K_La increases. For the total flow rate of the two phases of 4 ml·min⁻¹, the η values of Pr³⁺ and Ce³⁺ reached 98.7% and 97.0%, respectively. For the total flow rate of 36 ml·min⁻¹ which was much higher than that of many other microchannel reactors reported in the literatures, the η values of Pr³⁺ and Ce³⁺ still reached 92.2% and 86.9%, respectively, and the K_La values of Pr³⁺ and Ce³⁺ were 0.198 and 0.161 s⁻¹, respectively, similar to the high values reported for other microchannel reactors studied in previous work. These findings indicate that the hollow-strut SiC foam microchannel reactor is suitable for use in REs extraction.

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1. Introduction

Microchannel reactors (or microfluidic devices) are generally defined as reactors containing channels or similar fluid paths with a size below one millimeter [1,2]. Based on the reaction modes, microchannel reactors can be divided into two types: (i) microfluidic mixing reactors in which the reactions are carried out through fast and uniform mixing of the samples within the delicate mixing channel; (ii) ordinary reactors in which the reactions are carried out by injecting the sample solution into a microchannel or adjusting the external reaction conditions (e.g., temperature) to induce the reaction within the microchannel or chamber [3]. The past two decades have seen far-reaching progress in the development of microchannel reactors for applications in the chemical and biological fields due to their small footprint, rapid reactions, safe operation, high selectivity, and low energy consumption [4].

Rare earths (REs) are strategic resources that have received increasing attention worldwide because of their essential role in nuclear energy, permanent magnets, catalysts, high temperature superconductors, lamp phosphors, and rechargeable batteries [5,6]. Solvent extraction plays a key role in the processes of REs production and purification. Microchannel reactors offer excellent mass and heat transfer performance for solvent extraction and multiphase reactions [7,8], so that many studies within the field of REs hydrometallurgy have focused on the development of novel microchannel reactors and investigations of their extraction performance in recent years [8–12].

The extraction performance of a variety of reactors depends mainly on the mixing process between the organic and aqueous phases. However, mixing in the microchannel reactors is challenging due to laminar flows in the microchannels arising due to the low Reynolds number determined by the channel's hydraulic diameter, solution's kinetic viscosity, and flow rate [4,13]. Ward and Fan [13] provided an excellent review of the studies of mixing in microfluidic devices and of the mixing enhancement methods

* Corresponding author.

E-mail address: jszhang@imr.ac.cn (J. Zhang).

that highlights the importance of the mixing process enhancement by altering the geometric structure or spatial configuration of the fluid channels.

Microchannel reactors are generally fabricated using a range of materials, including ceramics, polymers, stainless steel, and silicon [8]. Because of integration and miniaturization, microchannel reactors suffer from high manufacturing costs, particularly when the channel structure is complex. The use of microchannel reactors for industrial production requires the arrangement of a large number of channels in a parallel network to enable operation at the macro-scale flow rates [4,14]. Ceramic foams are a class of important inorganic materials composed of a three-dimensional (3-D) network of ceramic struts that commonly exhibit cellular microstructure, low density, high specific surface area, high mechanical strength, and excellent chemical resistance [15–17]. If the foam skeleton is replaced with fluid channels and the channel size is controlled to be below 1 mm, the foam may be used as a microchannel reactor for solvent extraction, and its complex network structure will be conducive to enhanced fluid mixing. Therefore, we propose to hollow out the dense skeleton of an ordinary SiC foam to prepare a novel ceramic reactor with 3-D reticulated microchannels. Compared with many other microchannel structures (e.g., T-junction, Y-junction, serpentine microchannel) reported in the literatures [9,18–20], this 3-D network structure is essentially the integration of a large number of short microchannels in various directions in space. Fluids will be constantly split and recombined as they flow through the foam, and the mixing process is therefore strengthened. In recent years, some excellent studies have been reported on the ultra-light SiC foams containing hollow struts with a diameter of approximately two microns and these foams are mainly used for microwave absorption [21–24]. The hollow-strut SiC foam with the microchannel diameter of several hundred microns is very novel and interesting, and to the best of our knowledge to date no studies have used this foam to prepare microchannel reactors for solvent extraction.

This study proposes a novel 3-D reticulated microchannel reactor based on the hollow-strut SiC foam material prepared by our research group and explores its application in REs extraction. In addition, numerical simulations were used to explain the experimentally obtained relationships between the different microchannel reactor properties and to optimize the foam structure.

2. Materials and Methods

2.1. Materials and reagents

The hollow-strut SiC foam materials were prepared by our research group. The aqueous phase was prepared by dissolving $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ and $\text{Pr}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ into deionized water, and the concentrations of Ce^{3+} and Pr^{3+} were both $0.55 \text{ g} \cdot \text{L}^{-1}$ (total REs concentration was $7.8 \text{ mol} \cdot \text{m}^{-3}$). $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ and $\text{Pr}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (purity > 99.9%) were purchased from Aladdin Biochemical Technology Co., Ltd. (Shanghai, China). Using a pH meter (Alalis Instrument Technology (Shanghai) Co., Ltd., China), the initial pH of the aqueous phase was adjusted to 3.5 prior to extraction by HNO_3 . Analytical grade HNO_3 and NaOH were supplied by Sinopharm Chemical Reagent Co., Ltd. (Shenyang, China). The organic phase consisted of 2-ethylhexyl phosphoric acid mono-2-ethylhexyl ester (P507) as the extractant and sulfonated kerosene the diluent that were both purchased from Hecheng New Material Technology Co., Ltd. (Zhengzhou, China). P507 was saponified by NaOH (saponification rate was 40%) and its concentration in the organic phase was $0.10 \text{ mol} \cdot \text{L}^{-1}$.

2.2. Experimental set-up

As shown in the flow chart of the extraction experiment presented in Fig. 1, the aqueous phase and the organic phase with the same volume simultaneously flow into the hollow-strut SiC foam microchannel reactor at the same flow rate Q_0 driven by two peristaltic pumps (BT100-1F, Longer Precision Pump Co., Ltd., Baoding, China). The complex microchannel of the hollow-strut SiC foam facilitates the mixing of two liquid phases, and the RE ions in the aqueous phase react with the saponified P507 in the organic phase; thus, the extraction process is achieved. After mixing and extraction in the microchannel reactor, the two phases are driven into a funnel to complete the phase separation. Based on the same chemical conditions, hollow-strut SiC foams with different structural parameters were used in the extraction experiment in order to study their structure-performance relationships. Then, the mass transfer performance of the hollow-strut SiC foam with the optimal structure was also studied at different flow rates.

2.3. Data processing

The concentrations of Pr^{3+} and Ce^{3+} in the aqueous phase before and after extraction were measured using an inductively-coupled plasma spectrometer (ICP, iCAP6300, ThermoFisher, USA), while the concentrations in the organic phase were calculated by the law of mass conservation. According to these data, the extraction efficiency η of REs ions can be obtained by Eq. (1):

$$\eta = \frac{c_{\text{aq,in}} - c_{\text{aq,out}}}{c_{\text{aq,in}}} \times 100\% \quad (1)$$

where $c_{\text{aq,in}}$ and $c_{\text{aq,out}}$ are the concentrations in the aqueous phase before and after extraction, respectively.

The partition coefficient K of the RE ions in the two phases after extraction is calculated by Eq. (2):

$$K = \frac{c_{\text{org,out}}}{c_{\text{aq,out}}} \quad (2)$$

where $c_{\text{org,out}}$ is the concentration in the organic phase after extraction.

The separation factor β between Pr^{3+} and Ce^{3+} is calculated by Eq. (3):

$$\beta = \frac{K_{\text{Pr}}}{K_{\text{Ce}}} \quad (3)$$

The residence time of the two phases in the hollow-strut SiC foam microchannel reactor is defined as τ , and can be calculated by Eq. (4):

$$\tau = \frac{V}{2Q_0} \quad (4)$$

where V is the total volume of the microchannel.

The overall volumetric mass transfer coefficient $K_L a$ is obtained by Eq. (5):

$$K_L a = \frac{1}{\tau} \frac{c_{\text{aq,in}} - c_{\text{aq,out}}}{\Delta c_{\text{in}}} \quad (5)$$

where Δc_{in} represents the mass transfer force between the two phases, and is calculated by Eq. (6):

$$\Delta c_{\text{in}} = \frac{(c_{\text{aq,in}} - c_{\text{aq,in}}^*) - (c_{\text{aq,out}} - c_{\text{aq,out}}^*)}{\ln \left[(c_{\text{aq,in}} - c_{\text{aq,in}}^*) / (c_{\text{aq,out}} - c_{\text{aq,out}}^*) \right]} \quad (6)$$

where $c_{\text{aq,in}}^*$ and $c_{\text{aq,out}}^*$ are the equilibrium concentrations in the aqueous phase before and after the extraction, respectively.

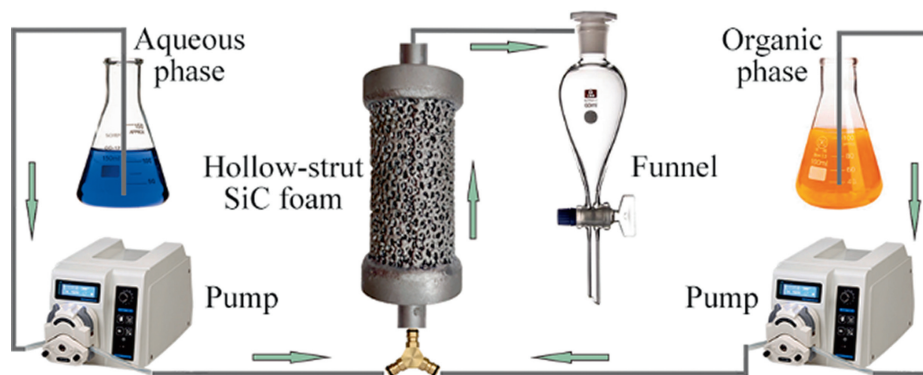


Fig. 1. Flow chart of the extraction experiment.

3. Results and Discussion

3.1. Structural characterization of materials

As shown in Fig. 2, the macro-morphology and micro-structure of the hollow-strut SiC foam were characterized. Fig. 2(a) shows a typical integrated microchannel reactor used in this study that consists of three parts: (i) 3-D reticulated hollow-strut SiC foam as the functional area in the middle; (ii) sealing layers on both sides; (iii) connecting tubes at both ends. The foam is prepared into a cylinder with the diameter Φ of 40 mm and the length H of 80 mm. Fig. 2(b) shows the foam skeleton observed by scanning electron microscopy (SEM, Inspect F50, FEI, USA). It is observed that the 3-D interconnected foam skeleton is hollow, and can be used as a fluid channel. The section shape of this inner channel is similar to a circular shape with a diameter of approximately 600 μm , conforming to the definition of the microchannel. For more comprehensive structural information, a typical cubic sample cut from the SiC foam was scanned by X-ray micro computed tomography (Micro-CT, YXCT Modular, YXLON, Germany). Micro-CT employs computer-processed X-rays to produce tomographic images or slices of specific regions of the object under investigation, and is ideally suited for imaging opaque and intricate porous media [25]. As presented in Fig. 2(c) and (d), the red part of the image represents the tube wall of the SiC foam, and the green part represents the inner microchannel. Both the foam skeleton and the microchannel show regular cellular structure, and the foam cells are well-connected. Fig. 2(e) shows the Micro-CT image of a hollow strut of the foam for which the inner diameter and wall thickness are observed to be approximately 600 and 200 μm , respectively. The above structural characterization indicates that the microchannels of the hollow-strut SiC foam are uniform and 3-D interconnected, making them suitable for continuous flow of fluids. Furthermore, it is observed from Fig. 2(d) and (e) that the inner surface of the tube wall is not smooth and there are many small bulges that can enhance the mixing process and mass transfer of fluids.

3.2. Numerical simulation

Because the SiC foam material is opaque, it is difficult to observe the flow in the microchannels. Numerical simulations based on computational fluid dynamics (CFD) have been proven to be reliable for both qualitative and quantitative analysis of flow structures, species concentration and mixing performance [25–29]. Fig. 3 shows the CFD modeling and simulation of extraction in the hollow-strut SiC foam microchannel reactor. As shown in Fig. 3(a), the real foam microchannel structure is simplified into the Kelvin open cell model [30,31] that is composed of six square

and eight regular-hexagonal faces. The minimum length of the lattice surrounding this tetrakaidecahedron model represents the cell size L , and the inner diameter of the foam microchannel is expressed as D . Considering the rapid reaction process of the saponified P507-sulfonated kerosene- $\text{Ce}^{3+}/\text{Pr}^{3+}$ system [6,32], extraction between the two liquid phases in the hollow-strut SiC foam microchannel reactor can be simplified as the coupling of fluid mixing and mass diffusion in a single phase flow. In this study, numerical simulations were performed using the COMSOL Multiphysics 5.5 software, which is widely used in the study of micromixers [33]. Two main modules of fluid flow and chemical species transport were coupled to solve for the velocity and concentration fields. “Water, liquid” was added as the fluid material. The Laminar Flow interface is used in 3-D and solves the Navier–Stokes equations:

$$\rho(\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] \quad (7)$$

$$\rho(\nabla \cdot \mathbf{u}) = 0 \quad (8)$$

where μ is the dynamic viscosity, $\mathbf{u}$ is the velocity, ρ is the fluid density, and p is the pressure. The free tetrahedral mesh was selected. At the inlet, a step change in the concentration was applied using an inlet node. The inlet flow is laminar with an average velocity that is calculated according to the experimental conditions. At the outlet, the model specifies a constant reference pressure of 0 Pa.

Taking into account the processing ability of the computer, four foam cells in series were selected as the computational domain. In the simulations performed in this study, the concentration of RE ions in each region is expressed by color, and the colorimetric scale is given. Fig. 3(b) shows the concentration settings at the cell inlet: the blue part on the left represents the organic phase (initial RE concentration is 0), and the red part on the right represents the aqueous phase (initial RE concentration is 7.8 $\text{mol} \cdot \text{m}^{-3}$). Fig. 3(c) shows the results of the simulation for the RE concentration at the cell outlet. As observed from the color change, the RE concentration in the organic phase increases while the RE concentration in the aqueous phase decreases, and the RE concentration in the middle region of the cell outlet tends to be 3.9 $\text{mol} \cdot \text{m}^{-3}$. The overall concentration streamline of the two phases in the four cells in series is presented in Fig. 3(d). It is observed from the color change of the streamline that the RE concentrations of the two phases change continuously during the flow. As the fluids flow through the microchannel, they continuously separate and mix, and two steps occur in the mixing process of the foam cells: heterogeneous mixing created by convection, and homogeneous mixing at the molecular level caused by the diffusion between adjacent domains [34]. The streamline of the overall model is shown in Fig. 3(e). It is

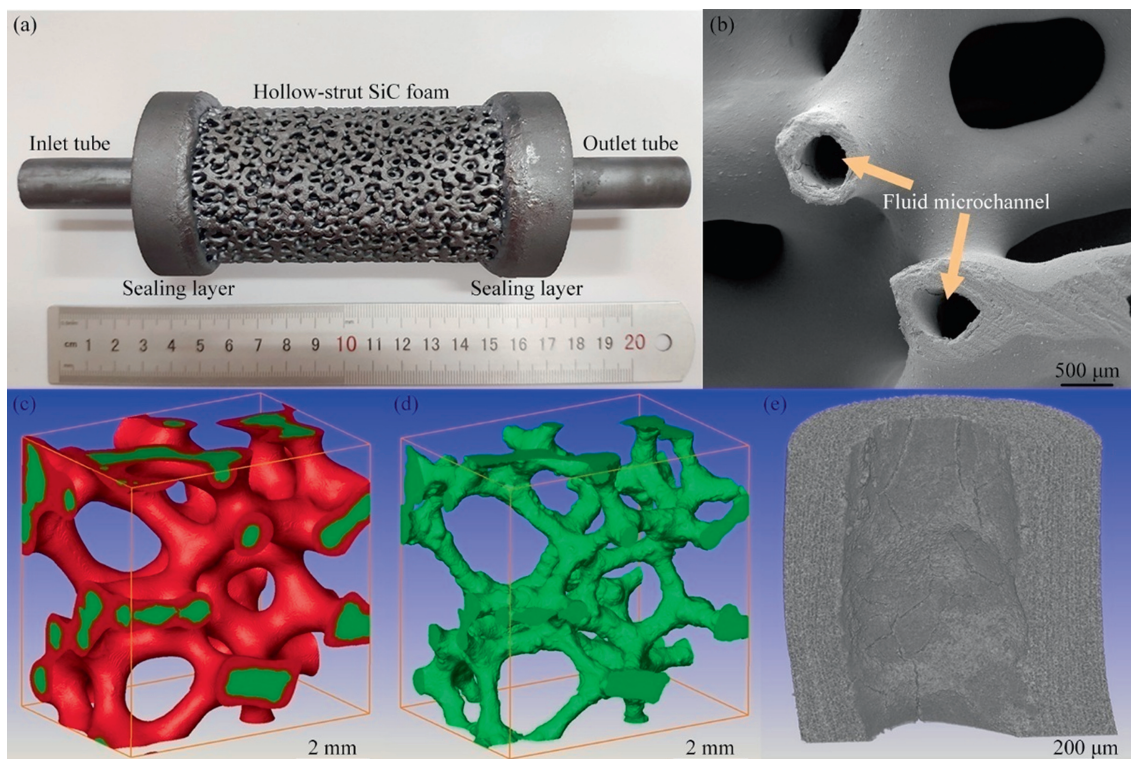


Fig. 2. Structural characterization of materials: (a) macro-morphology of the hollow-strut SiC foam reactor; (b) SEM image of the foam skeleton; Micro-CT images of the (c) skeleton, (d) microchannel, (e) strut.

observed that the direction and magnitude of the fluid velocity are constantly changing. The foam structure splits the inlet streams of the fluids to be mixed into several substreams and then puts them in contact in various ways, generating the contact between many thin fluid lamellae. This increases the contact area between the fluids and reduces the required diffusion length [35]. Thus, in addition to the short mass transfer path in the small contact space of the microchannels, the disturbance of the fluids by the 3-D reticulated foam structure also enhances the extraction of the two phases.

3.3. Structure-performance relationship

The structure-performance relationship of the hollow-strut SiC foam was studied experimentally and by numerical simulations to select the foam with the optimal structure for solvent extraction. The D of all of the foam samples in this study was 0.5 mm. Prior to the extraction experiments using hollow-strut SiC foam microchannel reactors, extraction equilibrium data (η of Pr^{3+} : 98.9%, η of Ce^{3+} : 97.6%, β between Ce^{3+} and Pr^{3+} : 2.28) based on the same chemical conditions were obtained by shaking the conical flask with a shaker at $180 \text{ r} \cdot \text{min}^{-1}$ for 2 h.

3.3.1. Effect of SiC foam length

Hollow-strut SiC foams ($L = 4 \text{ mm}$, $\Phi = 20 \text{ mm}$) with different lengths ($H = 20, 30, 50, 70, 90$, and 110 mm) were prepared and used for extraction experiments. The flow rates of the two phases were controlled as $Q_0 = 10 \text{ ml} \cdot \text{min}^{-1}$. Fig. 4 reveals the gradual growth in the extraction efficiency (η of Pr^{3+} increases from 73.3% to 87.4%, and η of Ce^{3+} increases from 65.2% to 79.6%) as H increases from 20 to 110 mm. This trend can be explained as due to the better mixing of the two phases with the increasing length of the foam reactor. However, a longer SiC foam also means a larger pressure drop, leading to greater energy consumption. Therefore,

$H = 50 \text{ mm}$ was selected as the optimal foam length for subsequent experiments.

3.3.2. Effect of SiC foam diameter

Hollow-strut SiC foams ($L = 4 \text{ mm}$, $H = 50 \text{ mm}$) with different diameters ($\Phi = 20, 30, 40, 50$, and 60 mm) were prepared and used for extraction experiments. The flow rates of the two phases were set to $Q_0 = 10 \text{ ml} \cdot \text{min}^{-1}$. It is observed from Fig. 5 that the η of Pr^{3+} (Ce^{3+}) first increased from 78.1% to 84.8% (from 69.4% to 76.0%) as Φ increases from 20 to 30 mm and then decreased to 71.8% (63.1%) as Φ increases further to 60 mm. The results indicate that Φ has a non-monotonic effect on the extraction performance. For the foams with the same L and H , a smaller Φ means fewer foam cells act as the mixing elements for the two phases, and the total cross-section area of the microchannel at the inlet will be smaller. For a constant flow rate, the average velocity of the inlet flow will be higher for a smaller cross-section area, so that the residence time of the two phases in the microchannel reactor will be shorter. Therefore, when Φ is small, the number of cells in the hollow-strut SiC foam microchannel reactor is not large enough, and the mixing time of the two phases in the microchannel reactor is too short, leading to a poor mixing performance. Conversely, when Φ is very large, the fluids will be highly dispersed in the foam so that the extraction performance will also be reduced due to the poor contact between the two phases. Therefore, $\Phi = 30 \text{ mm}$ was selected as the optimal foam diameter for subsequent experiments.

3.3.3. Effect of SiC foam cell size

Hollow-strut SiC foams with two cell sizes ($L = 4 \text{ mm}$, 6 mm) were used in the experiments in order to compare their extraction performance at different flow rates. The flow rates of the aqueous and organic phases were set to Q_0 that ranged from 2 to $16 \text{ ml} \cdot \text{min}^{-1}$.

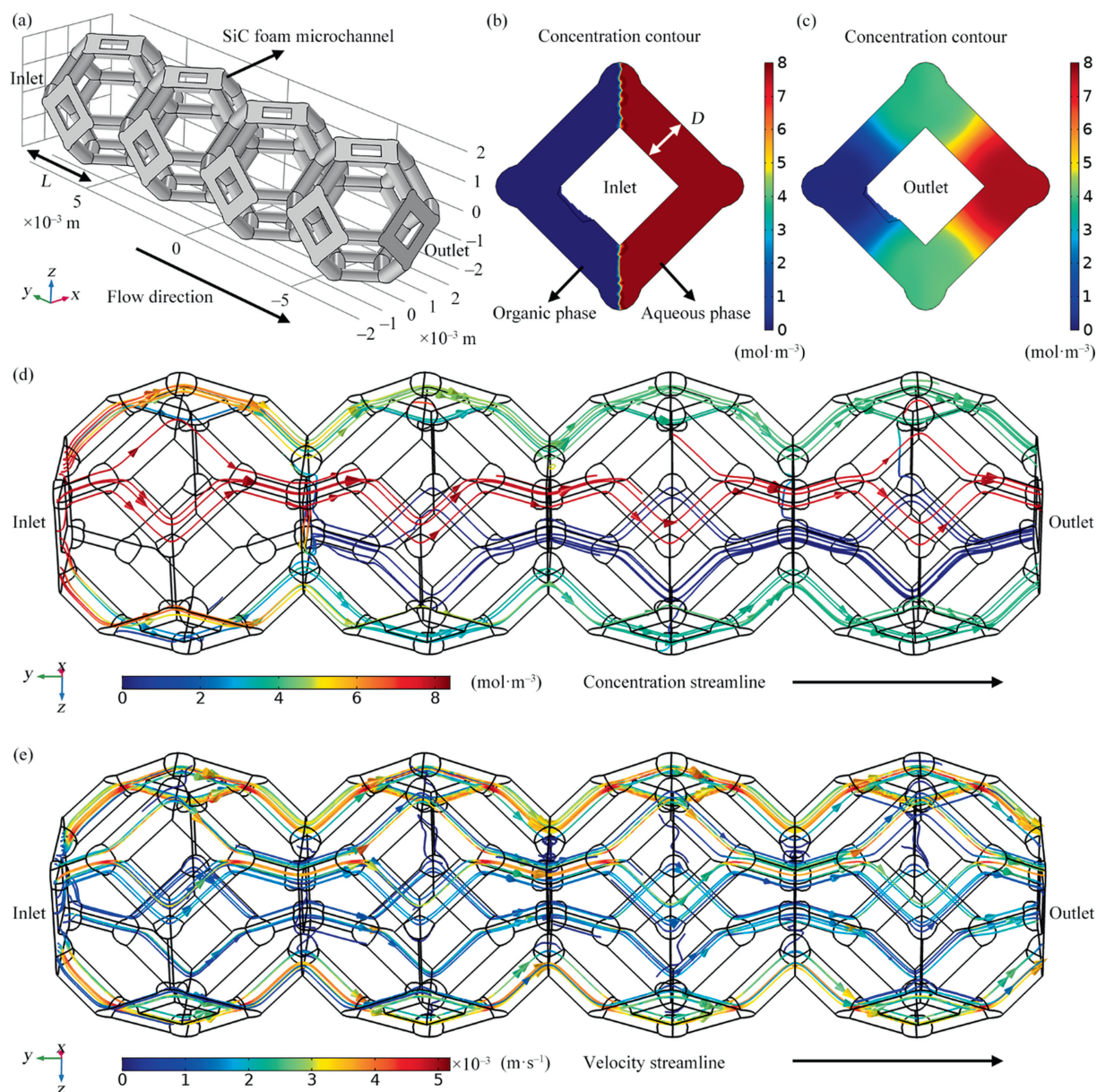


Fig. 3. Simulation of extraction in the hollow-strut SiC foam microchannel reactor: (a) CFD modeling; concentration contours of (b) the inlet and (c) the outlet; (d) concentration streamline; (e) velocity streamline.

As shown in Fig. 6, for $L = 4$ mm, the η of Pr^{3+} (Ce^{3+}) decreases significantly from 98.3% to 72.1% (from 96.2% to 61.5%) as Q_0 increases from 2 to 16 $\text{ml}\cdot\text{min}^{-1}$; while for $L = 6$ mm, the η of Pr^{3+} (Ce^{3+}) decreases significantly from 93.1% to 65.4% (from 86.4% to 55.0%) as Q_0 increases from 2 to 16 $\text{ml}\cdot\text{min}^{-1}$. In addition, the η of RE ions for $L = 4$ mm is always larger than that for $L = 6$ mm.

To explain the experimental results, numerical simulations were carried out. Fig. 7 shows the simulation results for the concentration distribution of the outlet obtained using the same microchannel diameter ($D = 0.5$ mm) and different cell sizes ($L = 4, 6$ mm). We note that to objectively compare the simulation results obtained for different cell sizes, the outlet concentration contours shown in Fig. 7 are all 12 mm long along the flowing direction, that is, $=4$ mm, the fluids flow through three cells, and for $L = 6$ mm, the fluids flow through two cells. Comparison of the color changes of the two images presented in Fig. 7 shows that the concentration distribution becomes more uniform with the smaller cell size of the foam microchannel. This is because for

the constant macro volume and microchannel diameter of the hollow-strut SiC foam, a smaller L means a larger number of cells that leads to a more pronounced enhancement effect of the 3-D reticulated structure on the mixing process of the two phases.

In addition, to explain the influence of the flow rate on the extraction efficiency, numerical simulations were carried out based on the SiC foam with $D = 0.5$ mm and $L = 4$ mm. As observed from the simulation results for the outlet concentration shown in Fig. 8, the concentration distribution becomes more uniform with decreasing Q_0 . For the same hollow-strut SiC foam microchannel reactor, the residence time τ of the two phases in the reactor will be longer at lower flow rates, so that a better mixing effect and more satisfactory mass diffusion will be obtained.

3.4. Pressure drop

The pressure drop is closely related to the energy consumption and process economy, and thus it is highly important to obtain the optimal reactor design with the lowest possible pressure drop and

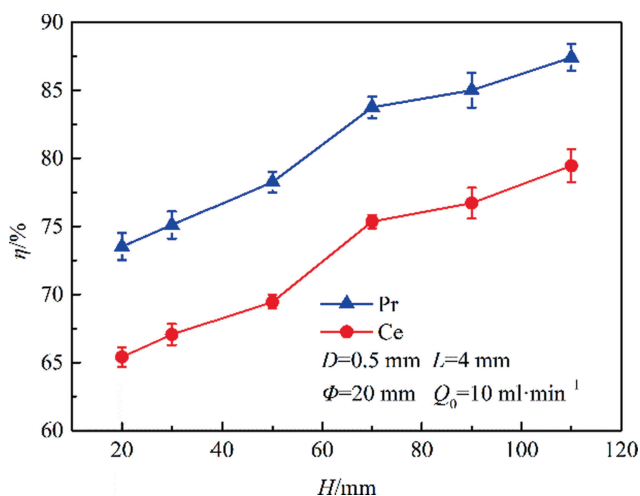


Fig. 4. Effect of foam length on the extraction efficiency.

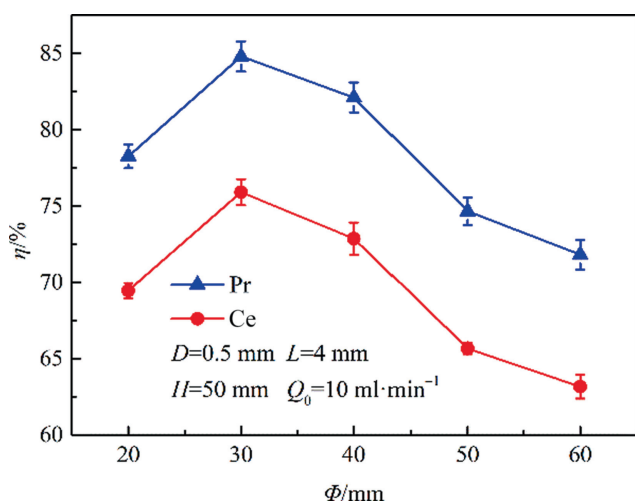


Fig. 5. Effect of foam diameter on the extraction efficiency.

optimal flow rate for carrying out a given chemical reaction at any required reactor performance [36,37]. As an important parameter for the estimation of the pressure drop Δp of the microchannel

reactor, pressure drop per unit length is defined as δ and can be calculated by Eq. (9):

$$\delta = \frac{\Delta p}{\Delta L} \quad (9)$$

In our previous report [38] on the pressure drop of the hollow-strut SiC foam microchannel reactor, the influence of D and L on δ was investigated by numerical simulations, and the results showed that δ is minimized when the ratio of D to L is controlled at approximately 0.1. This result was taken into account in the preparation of the SiC foam materials in this work. Furthermore, the pressure field of the microchannel reactor was simulated to verify the stability and reliability of the hollow-strut SiC foam microchannel reactor. As shown in Fig. 9(a), the central cross-section of four foam cells ($D = 0.5$ mm, $L = 4$ mm) in series was selected to study the pressure drop. “Water, liquid” was added as the fluid material. The total average velocity v of the two phases at the inlet was calculated and set according to the experimental conditions, and the pressure at the outlet was set to 0 Pa. As observed from the pressure contour shown in Fig. 9(b), the Δp and δ of the foam cells are proportional to Q_0 for a given foam structure. For the total flow rate of the two phases of $16 \text{ ml}\cdot\text{min}^{-1}$ ($Q_0 = 8 \text{ ml}\cdot\text{min}^{-1}$), the δ of the hollow-strut SiC foam microchannel reactor is $2.8 \text{ kPa}\cdot\text{m}^{-1}$, which is lower than that of many other microchannel reactors reported in previous studies [36,37,39,40].

3.5. Mass transfer performance

Considering the extraction performance and pressure drop, the hollow-strut SiC foam with the optimal structural parameters ($H = 80$ mm, $\Phi = 30$ mm, $D = 0.5$ mm, $L = 4$ mm) was prepared and used in the experiment to investigate its extraction efficiency and mass transfer performance. The flow rates of both aqueous and organic phases were set to Q_0 that ranged from 2 to $18 \text{ ml}\cdot\text{min}^{-1}$.

As shown in Fig. 10(a), the η of Pr^{3+} (Ce^{3+}) was found to decrease slightly from 98.7% to 92.2% (from 97.0% to 86.9%) as Q_0 increases from 2 to $18 \text{ ml}\cdot\text{min}^{-1}$. The β between Ce^{3+} and Pr^{3+} was found to decrease from 2.27 to 1.79 as Q_0 increases from 2 to $18 \text{ ml}\cdot\text{min}^{-1}$, as displayed in Fig. 10(b). As an important parameter to estimate the practicability and productivity of the microchannel reactor, the total flow rate of the two phases in the present work ranges from 4 to $36 \text{ ml}\cdot\text{min}^{-1}$, which is much higher than that of many other microchannel reactors in the literatures [9,19,20,41–43] in recent years. Both the extraction efficiency and separation factor reach the high values reported in previous studies [6,10,11,44].

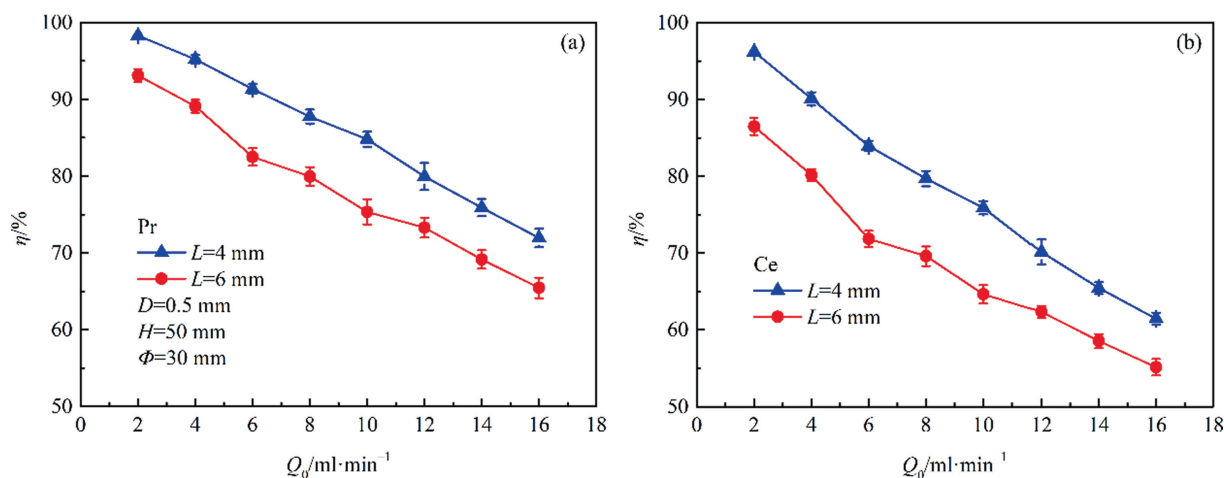


Fig. 6. Effects of cell size and flow rate on the extraction efficiency of (a) Pr^{3+} and (b) Ce^{3+} .

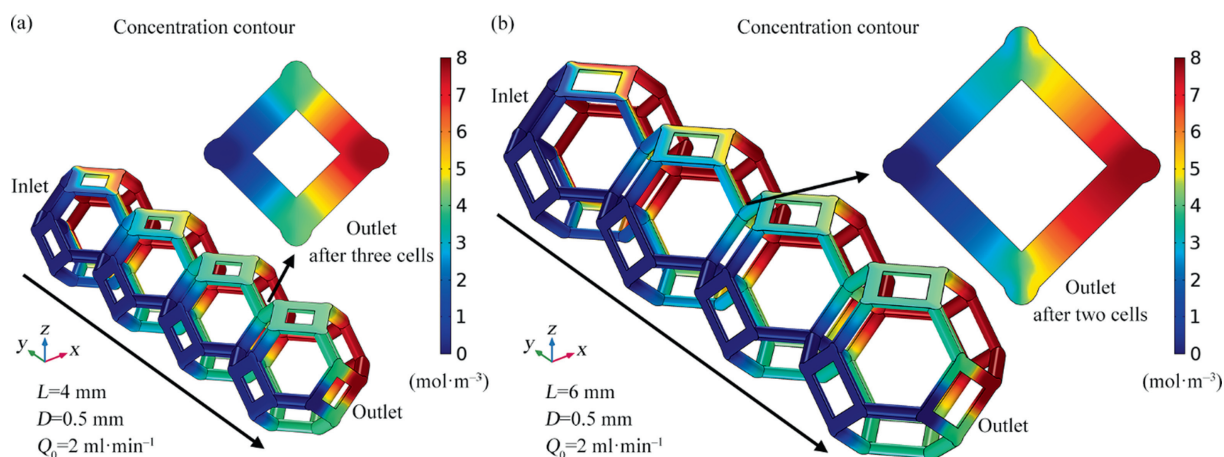


Fig. 7. Simulation results of the outlet concentration contours with different cell sizes: (a) $L = 4$ mm; (b) $L = 6$ mm.

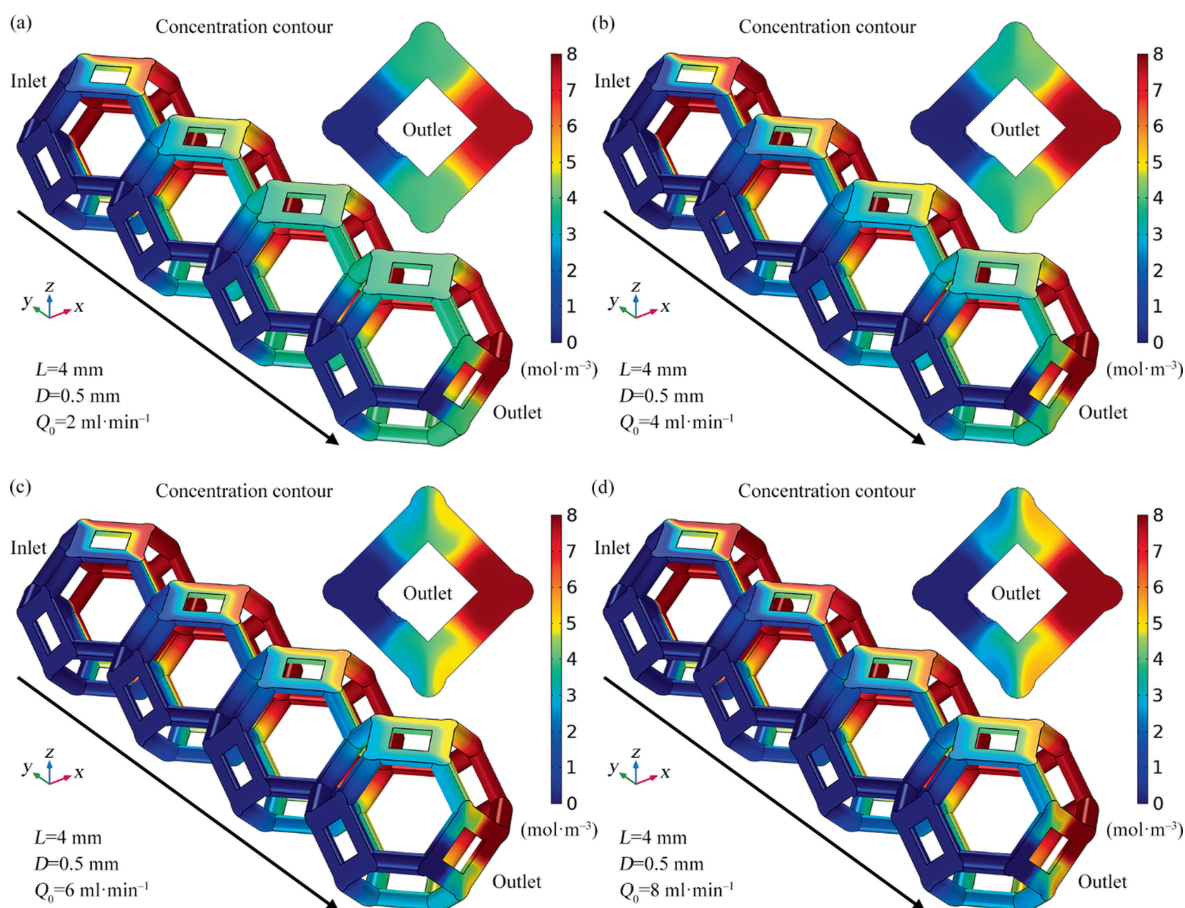


Fig. 8. Simulation results for the outlet concentration contours at different flow rates: (a) $Q_0 = 2$ ml·min⁻¹; (b) $Q_0 = 4$ ml·min⁻¹; (c) $Q_0 = 6$ ml·min⁻¹; (d) $Q_0 = 8$ ml·min⁻¹.

Therefore, the hollow-strut SiC foam microchannel reactor is considered to be suitable for application in REs extraction.

Furthermore, the overall volumetric mass transfer coefficient $K_L a$ was calculated using the above experimental data. The total cavity volume of this hollow-strut SiC foam microchannel reactor measured by the drainage method was 8.1 ml, so that the residence time τ of the fluids in the reactor ranges from 13.5 to 121.5 s. Fig. 11 shows the influence of τ on $K_L a$. It is observed that $K_L a$ of Pr^{3+} (Ce^{3+}) continuously decreases from 0.198 to 0.049 s⁻¹ (from 0.161 to 0.042 s⁻¹) with the increase of τ from 13.5 to

121.5 s. This result can be explained as follows: a shorter τ means that the flow rate is larger, and there will be a subtle increase in the interfacial mass transfer area between the two phases due to the intensified local turbulence when the fluid flows through the reactor, giving rise to enhanced mass transfer [29,31]. $K_L a$ of Pr^{3+} is always larger than that of Ce^{3+} due to the difference between their distribution coefficients of the two phases [45]. In addition, as described in Section 3.3.1 the largest $K_L a$ value obtained in this study was 1.26 s⁻¹ for $L = 4$ mm, $\Phi = 20$ mm, $H = 20$ mm, and $Q_0 = 10$ ml·min⁻¹, similar to the high values reported previously

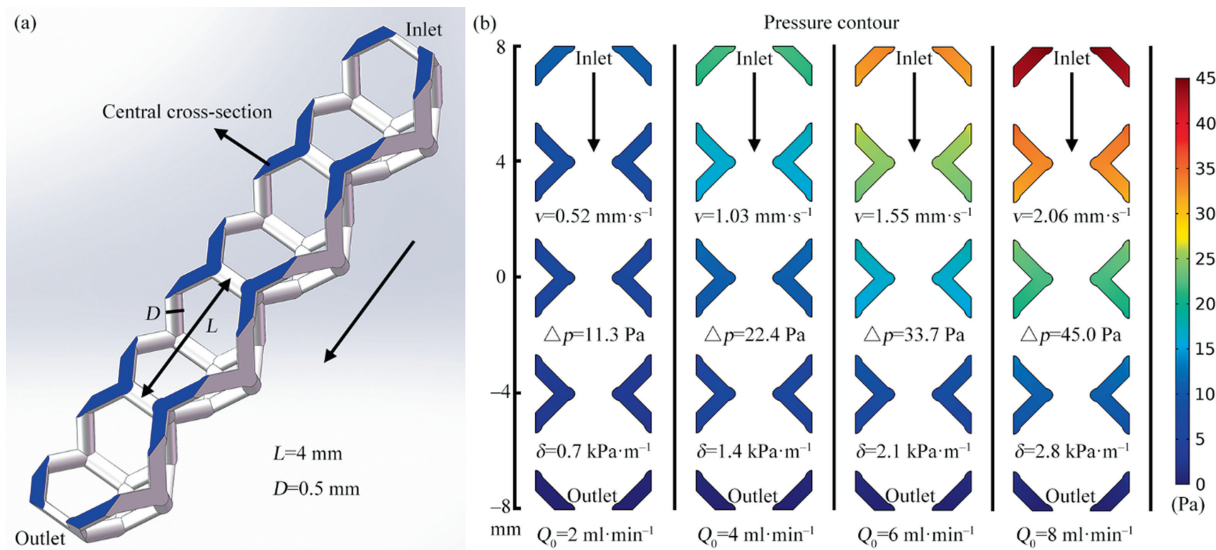


Fig. 9. (a) Central cross-section, (b) simulation results for the pressure contours at different flow rates.

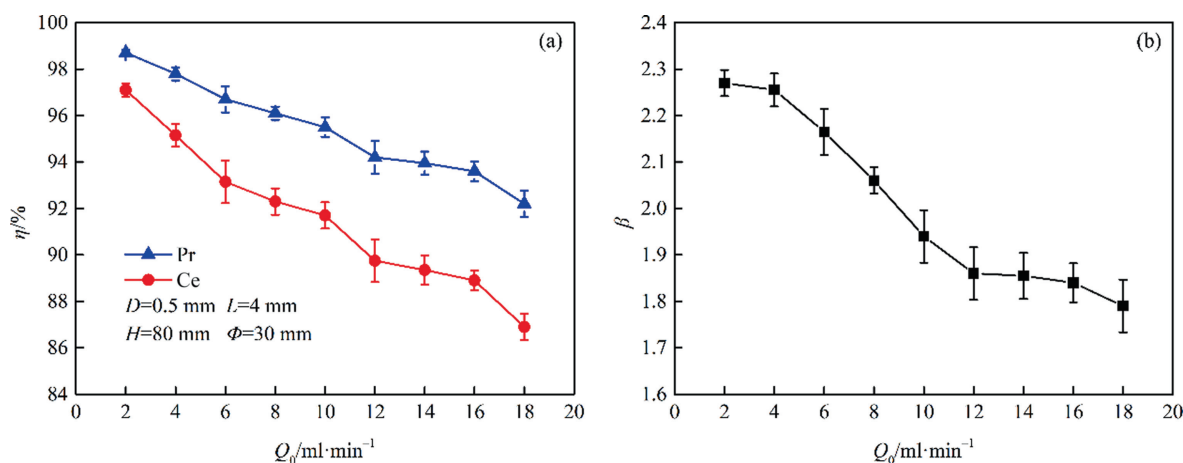


Fig. 10. Effects of the flow rate on the (a) extraction efficiency and (b) separation factor.

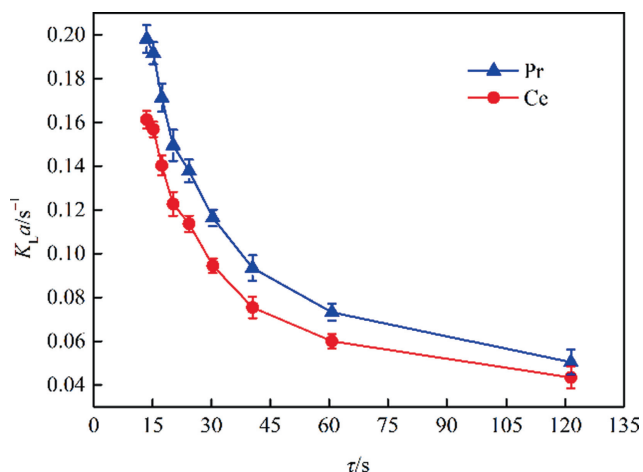


Fig. 11. Effect of residence time on the mass transfer coefficient.

for other excellent microchannel reactors [11,44,46] based on similar extraction systems.

4. Conclusions

The present study proposed a novel hollow-strut SiC foam microchannel reactor and explored its application in RE extraction. The SEM and Micro-CT scanning results suggest that the hollow-strut SiC foam has a regular cellular structure and contains 3-D reticulated microchannels that can be used for fluid flow. The numerical simulation results show that the microchannel reactor offers excellent mixing effect within a low pressure drop. Based on the saponified P507-sulfonated kerosene- $\text{Ce}^{3+}/\text{Pr}^{3+}$ system, extraction experiments were carried out to investigate the structure-performance relationship of the hollow-strut SiC foam. The experimental data are in good agreement with the results of numerical simulations. Optimal foam structures ($H = 80 \text{ mm}$, $\Phi = 30 \text{ mm}$, $D = 0.5 \text{ mm}$, $L = 4 \text{ mm}$) were selected and used in the experiment to study the influence of the flow rate Q_0 on η

and $K_L a$. As Q_0 increases, η decreases while $K_L a$ increases. At the total flow rate of $36 \text{ ml} \cdot \text{min}^{-1}$ which is much higher than that of many other microchannel reactors reported in the literatures, the η values of Pr^{3+} and Ce^{3+} still reach 92.2% and 86.9%, respectively, and $K_L a$ values of Pr^{3+} and Ce^{3+} reach 0.198 and 0.161 s^{-1} , respectively. Both the extraction efficiency and the mass transfer performance of the hollow-strut SiC foam microchannel reactor reach the high values reported previously for other microchannel reactors. Therefore, the hollow-strut SiC foam is an ideal material for the development of microchannel reactors for REs extraction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

c	concentration of RE ions, $\text{mol} \cdot \text{m}^{-3}$
c^*	equilibrium concentration of RE ions, $\text{mol} \cdot \text{m}^{-3}$
Δc_{in}	mass transfer force, $\text{mol} \cdot \text{m}^{-3}$
D	inner diameter of the foam microchannel, m
H	length of the foam, m
K	partition coefficient
$K_L a$	overall volumetric mass transfer coefficient, s^{-1}
L	cell size of the foam, m
p	fluid pressure, Pa
Δp	pressure drop, Pa
Q	total flow rate of the two phases, $\text{ml} \cdot \text{min}^{-1}$
Q_0	flow rate of the single phase, $\text{ml} \cdot \text{min}^{-1}$
u	fluid velocity, $\text{m} \cdot \text{s}^{-1}$
V	total volume of the microchannel, m^3
v	total average velocity at the inlet, $\text{m} \cdot \text{s}^{-1}$
β	separation factor
δ	pressure drop per unit length, $\text{kPa} \cdot \text{m}^{-1}$
η	extraction efficiency, %
μ	dynamic viscosity, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
ρ	fluid density, $\text{kg} \cdot \text{m}^{-3}$
τ	residence time, s
Φ	diameter of the foam, m

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