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The Transport of Copper(II) through Hollow Fiber Renewal Liquid Membrane and Hollow Fiber Supported Liquid Membrane

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Abstract: In this paper, hollow fiber renewal liquid membrane (HFRLM) and hollow fiber supported liquid membrane (HFSLM) were used to simultaneously remove and recover copper(II) from aqueous solutions, and the transport performance of these two techniques were compared under the similar conditions for the system of $CuSO_4$ +D2EHPA in kerosene +HCl. The results showed that the HFRLM process was more stable than the HFSLM process. The HFRLM process had a higher overall mass transfer coefficient than that of HFSLM process in single-pass experiments. These were because the renewal effect of the liquid membrane layer could reduce the mass transfer resistance of the lumen side and replenish the loss of the membrane liquid in the HFRLM process. The transport results were better in the HFRLM process than that in the HFSLM process with recycling experiments. Therefore, HFRLM technique is a promising method for simultaneous removal and recovery of heavy metal from aqueous solutions.

Keywords: Copper(II), hollow fiber renewal liquid membrane (HFRLM), hollow fiber supported liquid membrane (HFSLM), stability, transport performance

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INTRODUCTION

The development of industries generates large amounts of industrial effluents containing heavy metal ions, such as copper(II), Cr(VI), etc. It is necessary to remove and recover this highly toxic and nonbiodegradable heavy metal for environmental protection and reuse of heavy metal resources (1–3). However, the inherent disadvantages, i.e. poor selectivity, inefficient, high investment, and/or operation costs, etc. obstruct the application of traditional methods, such as precipitation, liquid-liquid solvent extraction, adsorption, ionic exchange, etc. (4–7).

Liquid membrane technique has become one of the alternative methods for this purpose. Removal and recovery of metal ions by supported liquid membranes (SLM) have been widely studied (8,9). Despite the potential advantages of SLM, such as high selectivity, high mass transfer rate, and the possibility of concentration, etc. make SLM receiving increasing attentions (10–14), it has not been adopted in the industrial process, due to the lack of long-term stability caused by the loss of membrane liquid by dissolution into the aqueous phases. Although many studies on the membrane liquid compositions and the optimum technologies of SLM have been performed to make them stable, the issues have not been solved well (15–17).

In order to avoid these difficulties in the conventional LM systems, Zhang et al. proposed a new liquid membrane technique, hollow fiber renewal liquid membrane (HFRLM) (18–21), which is based on the surface renewal theory and integrated the advantages of the fiber membrane extraction process, liquid film permeation process, and other liquid membrane systems. This technique has several potential advantages (21) of high mass transfer rate, high concentration factor, long-time stability, no leakage occurs between phases, no secondary pollution, low extractant consumption, low capital, maintenance and operation costs, low energy consumption, easy scale-up, etc.

The aim of this work was to compare the stability, rate-controlling step, transport results, etc. of HFRLM and HFSLM processes in single-pass mode and recycling mode with the system of $CuSO_4$ + D2EHPA in kerosene + HCl. The transport mechanisms of processes were also studied.

EXPERIMENTAL

Apparatus and Hollow Fibers

All the experiments were conducted using the self-designed systems, and the experimental set-up was shown in Fig. 1. Both for HFRLM and

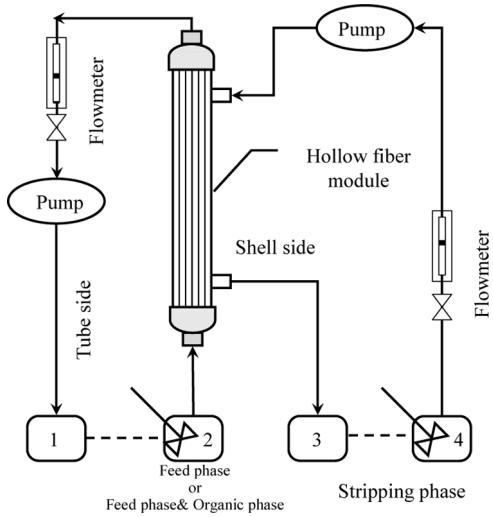

Figure 1. Schematic representation of HFRLM and HFSLM process.

HFSLM processes, hydrophobic PVDF hollow fibers were used, which was supported by Tianjin Polytechnic University. The used hollow fiber modules were self-manufactured with small laboratory scale versions (with two 0–2 $dm^3 \cdot min^{-1}$ peristaltic pumps and flow meters) that were specifically designed for the experimental purposes to avoid the effect of non-idea flow in the shell side. Additional information about these modules was provided in Table 1.

Reagents and Solutions

Di(2-ethylhexyl) phosphoric acid (D2EHPA), from Tianjin Guangfu Chemical Co. Ltd., was of chemical reagent quality with a purity >98.5%. Commercial aviation kerosene, from the Tianjin Damao chemical reagent plant, was washed twice with 20% (vol) H_2SO_4 to remove aromatics and then with deionized water three times. Copper sulphate anhydrous, from the Shanghai Tingxin chemical reagent plant, was an analytical grade reagent with a purity >99.0%. Acetic acid glacial and sodium acetate anhydrous, from Tianjin Fuxing chemical reagent plant, were analytical grade reagents with purity >99.0%. All chemical reagents were used without further purification except the commercial aviation kerosene.

Table 1. Characteristics of the hollow fiber modules

Shell characteristics	
Material	glass
Length, L	20.2 cm
Internal diameterof module #1 and #2, $2R_i$	1.0 cm
Outer diameterof module #1 and #2	1.2 cm
Fiber characteristics	
Material	PVDF
Number of fibers in module #1, N	10
Number of fibers in module #2, N	30
Effective Length L	19.8 cm
Internal diameter, d^{int}	812 μm
External diameter, d^{ext}	886 μm
Effective surface area of module #1, A	$4.18 \times 10^{-3} m^2$
Effective surface area of module #2, A	$1.25 \times 10^{-2} m^2$
Membrane pore size, δ	0.47 μm
Membrane porosity, ε	0.82
Membrane tortuosity, τ	2.0

The feed phase was prepared by dissolving a weighed amount of $CuSO_4$ in acetate buffer media, in which the pH was adjusted. The organic phase was prepared by dissolving D2EHPA in kerosene. And the stripping phase was prepared by diluting HCl with deionized water.

Procedure

Prior to the experiments, the hollow fibers in the module were pre-wetted with organic phase more than 48 h in order to make the pores of fibers fully filled with organic phase. For the HFRLM process, the stirred mixture of the feed phase ($CuSO_4$ aqueous solution at pH of 4.44) and organic phase (10.0 vol% D2EHPA in kerosene) at a high w/o volume ratio of 20:1 (v:v) was pumped through the lumen side, and the stripping phase (6.0 $mol \cdot L^{-1}$ HCl aqueous solution) countercurrently flowed through the shell side of the module. For the HFSLM process, the feed phase flowed through the lumen side, and the stripping phase countercurrently flowed through the shell side. Pressure gauges and valves were used to control flow rates and to ensure that a positive pressure was maintained on the shell side of the module. When a stable state was achieved, aqueous samples (5 ml) were taken from the outlet of the lumen and shell side at preset time intervals.

Since the overall mass transfer coefficient can indicate the mass transfer performance, in spite of various driving forces, the overall mass

transfer coefficient based on the feed phase, $K_{f,\ Cu}$, was used in this paper (21).

$$K_{f,Cu} = \frac{J_{Cu,Exp}}{\Delta C_{lm,Cu}} \tag{1}$$

Where

$$\Delta C_{lm,Cu} = \frac{\Delta C_{1,Cu} - \Delta C_{2,Cu}}{\ln \frac{\Delta C_{1,Cu}}{\Delta C_{2,Cu}}} = \frac{\left(C^{in}_{f,Cu} - \frac{m'}{m} C^{out}_{st,Cu}\right) - \left(C^{out}_{f,Cu} - \frac{m'}{m} C^{in}_{st,Cu}\right)}{\ln \frac{C^{in}_{f,Cu} - \frac{m'}{m} C^{out}_{st,Cu}}{\left(C^{out}_{f,Cu} - \frac{m'}{m} C^{in}_{st,Cu}\right)}} \tag{2}$$

J_{Cu}, the experimental mass transfer flux of the transport of copper(II) across the liquid membrane from the feed phase to the stripping phase, is determined by applying the following:

$$J_{Cu,Exp} = \frac{d(C_{st,Cu} V_{st})}{A \cdot dt} = \frac{L_{st} \Delta C_{st,Cu}}{A} \tag{3}$$

Where $\Delta C_{\mathrm{st,Cu}}$ represents the variation of the copper concentration in the stripping phase at a time interval Δt, L_{st} is the volumetric flow rate of the feed phase, A is the effective mass transfer area, V_{st} is the volume of the stripping solution, and m, m' are the distribution coefficient of extraction and back-extraction processes, respectively (22).

Analysis

The copper(II) concentration in the aqueous phase was analyzed with sodium diethyldithiocabamate spectrophotometric method (GB7474-87, National Standard P.R. China). And a digital precision ionometer model PXS-450 (Shanghai Dapu Co. Ltd.) with a combined glass electrode was used for pH measurements ($\pm$0.01 pH). The pH meter was standardized against 4.01, 6.85, and 9.14 standard buffer solutions.

RESULTS AND DISCUSSION

Stabilities of HFRLM and HFSLM Processes

The stabilities of HFRLM and the HFRLM processes were studied and compared first with the copper transport across the liquid membrane

under the similar experimental conditions. The initial copper(II) concentration in the feed phase were 490.0 $mg \cdot L^{-1}$ and 503.4 $mg \cdot L^{-1}$ for the HFRLM and HFSLM processes, respectively. The solution of 10.0 vol% D2EHPA in kerosene was used as organic phase. The hollow fibers in the modules were pre-wetted by the organic phase for more than 48 h, while both the feed phase and stripping phase were not pre-saturated with organic phase in HFRLM and HFSLM processes.

As shown in Fig. 2, the overall mass transfer coefficient of the HFRLM process could almost keep a constant value under our ranges studied for a long-time, which could suggest that the HFRLM process had a long-term stability (21); while for the HFSLM process, the overall mass transfer coefficient decreases with time after 3 h. With the operation time from 3 to 8 h, the overall mass transfer coefficient decreases from 6.14 $m \cdot s^{-1}$ to 2.14 $m \cdot s^{-1}$. It is because in the HFSLM process, the aqueous phases flowing through both sides are not pre-saturated with the organic phase, and the contact of the liquid membrane phase with more fresh aqueous phase at high flow rate results in great solubility of the carrier and the membrane solvent (23,24). Furthermore, the Reynolds number of lumen side is bigger than 40, the turbulent flow within the lumen side would increase the emulsion entrain caused by the shear force of fluid flowing (25,26). These would cause the loss of the membrane liquid (carrier and/or solvent) from the pores of the support, which led to the destabilization or degradation of the HFSLM process. Also, the bigger pore size of membrane support used in our work is not beneficial

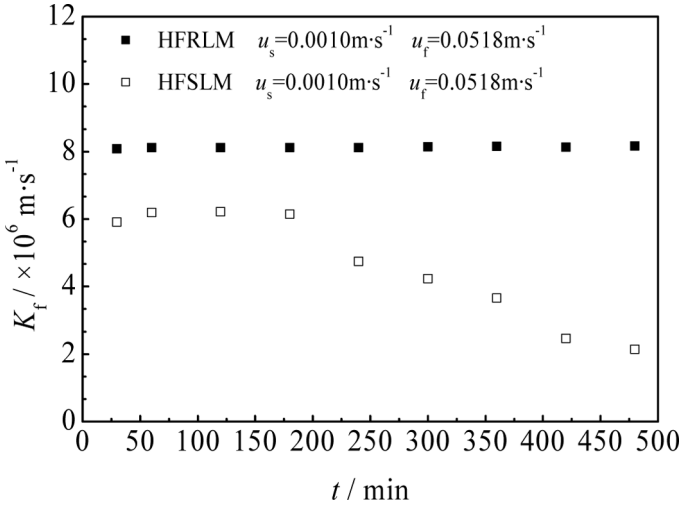

Figure 2. The comparison between HFRLM and HFSLM on stability (module #1).

for the stability of the HFSLM process, while it is beneficial for the transport of HFRLM process. However, in the HFRLM process, the organic droplets dispersed in the tube side fluid could automatically and continuously replenish the membrane liquid filled in the pores of hollow fibers which could avoid the loss of organic phase and keep liquid membrane stable.

Transport Studies in Single-Pass Mode

The transport performance of copper through HFRLM and HFSLM in single-pass mode was compared under similar experimental conditions, the initial copper(II) concentration in the feed phase was 475.6 $mg \cdot L^{-1}$ and 486.7 $mg \cdot L^{-1}$, respectively.

In our previous work (21), it was indicated that the renewal effect of the HFRLM process could greatly reduce the mass transfer resistance in the lumen side, which was the main part of the total mass transfer resistance. As expected, the overall mass transfer coefficient of the HFRLM process was higher than that of HFSLM process as shown in Fig. 3. The overall mass transfer coefficient of the HFRLM processes increased with increasing flow rate in the lumen side, because the higher shear force due to higher lumen side flow rate could enhance the renewal rate of the liquid membrane and lead to a thinner liquid membrane layer, which

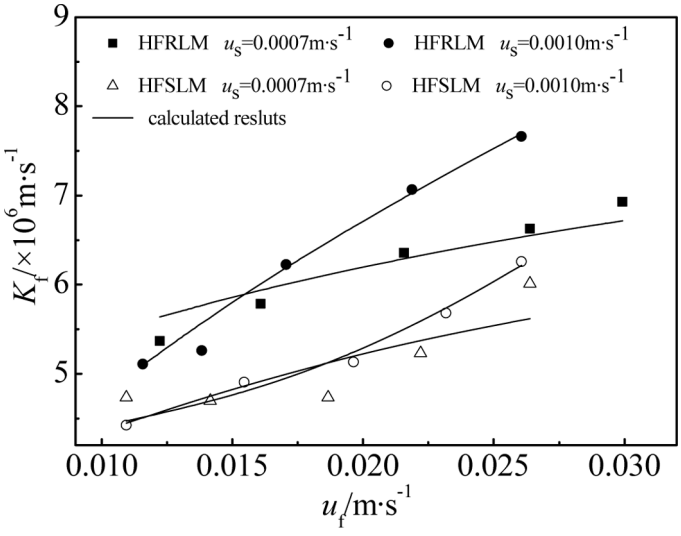

Figure 3. The comparison between HFRLM and HFSLM on mass transfer performance in single-pass mode (module #1).

could greatly reduce the mass transfer resistance of the aqueous boundary layer in the lumen side. Also, the renewal process of the liquid membrane could replenish the loss of membrane liquid. However, for the HFSLM process, the overall mass transfer coefficient decreased with increasing flow rate of the tube side, mainly because the destabilization or degradation of the liquid membrane caused by the loss of membrane liquid as discussed above.

Rate-Controlling Step

In a HFRLM process, the total mass transfer resistance mainly included three fractional resistances (21), the resistances of renewal process of liquid membrane layer in the lumen side R_R, diffusion resistances of copper-D2EHPA complex across the membrane phase R_m, and copper ions through the aqueous boundary layer within the shell side R_S. In a HFSLM process, the total mass transfer resistance also mainly included three fractional resistances (27), which were the resistances of the aqueous layer diffusion on the tube side R_T, diffusion in the membrane phase R_m, and the aqueous layer diffusion on the shell side R_S.

In order to study the rate-controlling step in the transport of copper through HFRLM and HFSLM, the fractional resistance of each step of HFRLM and HFSLM processes was calculated for the above experiments.

According to model of resistance in series and mass balance law, the overall mass transfer coefficient based on the feed phase in the HFRLM process was (21):

$$\frac{1}{K_{f,Cu}} = \frac{1}{mk_{R,CuR_2}} + \frac{1}{mk_{m,CuR_2}} + \frac{1}{\frac{m}{m'}k_{S,Cu}} \tag{4}$$

The individual mass transfer coefficient in the renewal process of liquid membrane layer, k_R, could be obtained using following empirical correlation base on the surface renewal theory (21):

$$k_R = aD_{Cu}{}^{0.5}\mathrm{Re}_T^{0.25}\Phi^{-0.25} \tag{5}$$

Where a is enhancement factor of 0.005, which was obtained by model fitting from experimental data; the diffusivity of copper ions in aqueous solution, D_{Cu}, is 7.40×10^{-10} $m^2 \cdot s^{-1}$ (27), ρ is the density, μ is the viscosity of the organic phase, u_T is the flow rate of lumen side, Re is the Reynolds number of the lumen side, and Φ is the hold-up of organic droplets in the mixture flowing through the lumen side.

The individual mass transfer coefficient in the membrane phase, k_m, could be approximated as follow (28):

$$k_m = \frac{D_m \varepsilon}{\tau(r^{ext} - r^{\text{int}})} \tag{6}$$

Where ε and τ are the porosity and tortuosity of the hollow fiber membrane support, respectively. r^{ext} and r^{int} are the external and internal radii of hollow fibers, respectively, the diffusivity of copper-D2EHPA in kerosene, D_{CuR2}, is 4.70×10^{-10} $\text{m}^2 \cdot \text{s}^{-1}$(27).

To calculate the individual mass transfer coefficient on the shell side, k_{S}, the correlation developed by Hu and Wiencek (29) was used:

$$\frac{4r_h k_s}{D_{\text{Cu}}} = 0.245\left(\frac{4r_h u_{Shell}}{\nu}\right)^{2/3}\left(\frac{\nu}{D_{\text{Cu}}}\right)^{1/3} \tag{7}$$

Where ν is the kinematic viscosity of the stripping phase, which is $8.94 \times 10^{-7}\text{m}^2 \cdot \text{s}^{-1}$, r_{h} is the hydraulic radius of the shell that is calculated as the cross-sectional flow area divided by the wetted perimeter, $(R^2 - N(r^{\text{ext}})^2)/(R + Nr^{\text{ext}})$, and u_{Shell} is the flow rate in the shell side.

In HFSLM process, according to principles of resistance in series and mass balance law, the overall mass transfer coefficient based on the feed phase was (27):

$$\frac{1}{K_{f,Cu}} = \frac{1}{k_{T,CuR_2}} + \frac{1}{mk_{m,CuR_2}} + \frac{1}{mk_{S,Cu}} \tag{8}$$

The individual mass transfer coefficient of tube side, k_T, depends on the mean flow velocity u according to (27):

$$\frac{2r^{\text{int}}k_T}{D} = 1.62\left[\frac{4(r^{\text{int}})^2 u_T}{DL}\right]^{1/3} \tag{9}$$

The diffusion of species through the membrane phase was approximated by diffusion through a cylindrical wall. Thus, the individual mass transfer coefficient of the membrane phase, k_m, could be expressed as (28):

$$k_m = \frac{D_m \varepsilon}{\tau(r^{ext} - r^{\text{int}})} \tag{10}$$

For the shell side, the mass transfer correlation was (29):

$$\frac{4r_h k_s}{D} = 0.245\left(\frac{4r_h u_{Shell}}{\nu}\right)^{2/3}\left(\frac{\nu}{D}\right)^{1/3} \tag{11}$$

The terms on the right sides of eqs. (4) and (8) in sequence were the mass transfer resistances in the lumen side R_R or R_T, diffusion resistance across the membrane phase R_m, and the aqueous boundary layer diffusion resistance on the shell side R_S. The fractional resistance of each step to the overall process of HFRLM could be calculated, e.g. Δ_m, by

$$\Delta_m = \frac{R_m}{R_R + R_m + R_S} \times 100\% \tag{12}$$

By using the models above, for the experiments data shown in Fig. 3, the calculated fractional resistance of each step was listed in Table 2. For the HFSLM process, the mass transfer resistance of the lumen side contributed more than 80 percent of the total mass transfer resistance, and then the mass transfer in the lumen side, that is, the diffusion of copper ions through

Table 2. Fractional resistances for the transport of copper(II) through HFRLM and HFSLM in module #1

HFRLM Process				
$u_T/m{\cdot}s^{-1}$	$u_S/m{\cdot}s^{-1}$	Δ_R	Δ_m	Δ_S
0.0122	0.0007	55.24%	8.91%	39.35%
0.0161	0.0007	54.31%	5.69%	39.99%
0.0216	0.0007	53.68%	6.05%	40.26%
0.0264	0.0007	52.75%	6.26%	40.99%
0.0299	0.0007	52.58%	6.44%	40.98%
0.0109	0.0010	60.99%	5.89%	33.12%
0.0129	0.0010	59.97%	6.05%	33.97%
0.0171	0.0010	59.25%	6.30%	34.45%
0.0200	0.0010	57.53%	6.51%	35.96%
0.0264	0.0010	56.66%	6.70%	36.64%
HFSLM Process				
$u_T/m{\cdot}s^{-1}$	$u_S/m{\cdot}s^{-1}$	Δ_T	Δ_m	Δ_S
0.0109	0.0007	86.19%	1.79%	12.03%
0.0142	0.0007	85.13%	1.92%	12.95%
0.0187	0.0007	83.93%	2.08%	13.99%
0.0222	0.0007	83.13%	2.18%	14.69%
0.0264	0.0007	82.31%	2.29%	15.04%
0.0109	0.0010	88.22%	1.83%	9.96%
0.0154	0.0010	86.97%	2.02%	11.01%
0.0196	0.0010	86.04%	2.17%	11.80%
0.0232	0.0010	85.36%	2.27%	12.37%
0.0261	0.0010	84.86%	2.35%	12.79%

the aqueous boundary layer in the lumen side, was the rate-controlling step for this process. Also, for the HFRLM process, the mass transfer in the lumen side, that is, the renewal process of liquid membrane layer in the lumen side, was the rate-controlling step, and contributed more than 50 percent of the total mass transfer resistance. Then for this system, the transport of copper from the feed phase to the stripping phase was governed by the transport of copper ions from the feed phase to the organic phase, i.e. the diffusion through the aqueous boundary layer of the feed phase.

In the HFRLM process, the renewal effect of the liquid membrane layer and the larger mass transfer area due to directly mixing of organic droplets and the aqueous phase could greatly reduce the resistance of mass transfer in the lumen side. Therefore, the overall mass transfer coefficient of the HFRLM process was higher than that of the HFSLM process under similar conditions as expected. The fractional resistance of the lumen side in the HFRLM process, which was lower than 60 percent, was less than that in the HFSLM process. Furthermore, for the HFRLM process, the fractional resistance of the lumen side decreased with increasing flow rate on the lumen side of the module. It was mainly because the higher flow rate of the lumen side led to the higher shear force and the higher degree of turbulence in the lumen side, where the Reynolds number was from 10 to 25. These led to the higher renewal rate of the liquid membrane, and a thinner liquid membrane layer, which could reduce the mass transfer resistance in the lumen side.

Transport Studies in Recycling Mode

The transport performance of both processes was also studied in the recycling mode. For the HFSLM process, feed phase ($CuSO_4$ aqueous solution with the copper(II) concentration of 405.0 $mg \cdot L^{-1}$ at pH of 4.44, 2000 ml) flowed through the lumen side, and the stripping phase (2.0 $mol \cdot L^{-1}$ HCl aqueous solution, 400 ml) countercurrently flowed through the shell side of the hollow fiber module. The volumetric flow rates in the tube side and the shell side were 28.0 $ml \cdot min^{-1}$ and 20.0 $ml \cdot min^{-1}$, respectively. For the HFRLM process, the stirred mixture of the feed phase ($CuSO_4$ aqueous solution with the copper(II) concentration of 449.0 $mg \cdot L^{-1}$ at pH of 4.44, 2000 ml) and the organic phase (10.0 vol% D2EHPA in kerosene) with the stirred mixture of the organic phase and feed phase at a w/o volume ratio of 20:1 (v:v) flowed through the lumen side, and the stripping phase (2.0 $mol \cdot L^{-1}$ HCl aqueous solution, 400 ml) countercurrently flowed through the shell side of the module. The volumetric flow rates in the tube side and the shell side were 33.0 $ml \cdot min^{-1}$ and 26.0 $ml \cdot min^{-1}$, respectively. The results were shown in Fig. 4.

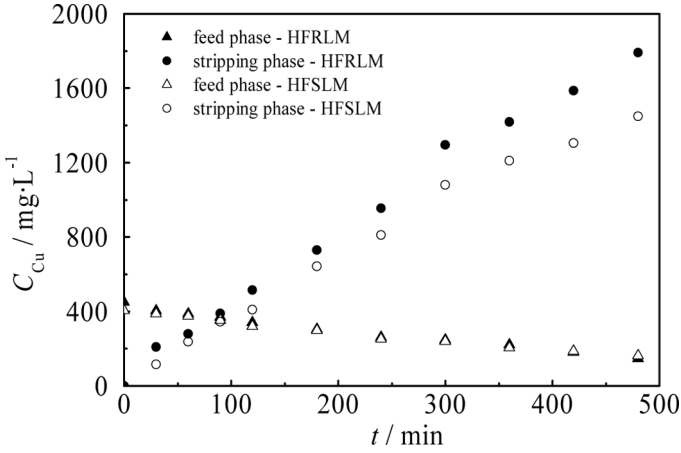

Figure 4. Variation of copper concentration with time for HFSLM and HFRLM process in recycling mode (module #2).

For both processes, after 1.5 h, the copper(II) concentration in the stripping phase was higher than that in the feed phase, that is, the up-hill effect was observed.

In the HFSLM experiment, after 8 h, the removal efficiency of copper(II) was up to 59.0%, and copper(II) concentration in the stripping

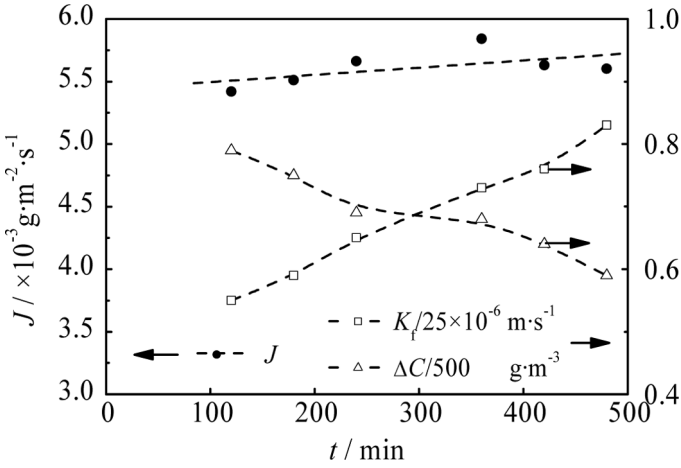

Figure 5. Variation of J, K_f, and ΔC with time for HFRLM process in recycling mode (module #2).

phase was 1448.0 mg·L^{-1}. While in the HFRLM experiment, after 8 h, the removal efficiency of copper(II) was up to 67.1%, and the copper(II) concentration in the stripping phase was 1790.0 mg·L^{-1}, the enrichment factor was up to 4.0. The transport results showed that the HFRLM was more efficient than HFSLM in the process of removal and recovery of copper from wastewater. It is mainly because in a HFRLM recycling experiment, although the mass transfer driving force decreased with time, the overall mass transfer coefficient increased with time. This leads to the mass transfer flux of HFRLM process keep a relative constant value under our ranges studied as shown in Fig. 5.

CONCLUSION

The comparison of copper(II) transport through hollow fiber renewal liquid membrane and hollow fiber supported liquid membrane was investigated. The system of $CuSO_4$ + D2EHPA in kerosene + HCl was selected for this study.

As a new liquid membrane technique for simultaneous extraction and stripping processes based on surface renewal theory, the hollow fiber renewal liquid membrane was more stable than the hollow fiber supported liquid membrane process, because the organic droplets dispersed in the lumen side fluid in the HFRLM process could automatically and continuously replenish the membrane liquid which filled in the pore of the hollow fiber during the renewal process of the liquid membrane layer, which could avoid the loss of the membrane liquid.

And the overall mass transfer coefficient of the HFRLM process was higher than that of the HFSLM process under the similar experimental conditions. Although in these two processes the rate-controlling step of mass transfer was located in the mass transfer of the lumen side, the renewal effect of the liquid membrane layer and the larger mass transfer area due to directly mixing of organic droplets and aqueous phase could greatly reduce the mass transfer resistance of the lumen side in the HFRLM process. The fractional resistance of the lumen side in the HFRLM process, which was less than 60 percent, was less than that in the HFSLM process, which was higher than 80 percent.

In the recycling experiments of both processes, the ''up-hill'' effect was achieved at 1.5 h. At 8 h, the removal efficiency of copper(II) was up to 67.1% in the HFRLM process, the enrichment factor was up to 4.0, which were faster and higher than that of the HFSLM process. The results showed that the HFRLM technique was a

prospective method of simultaneous removal and recovery of copper from aqueous solution than HFSLM.

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NOMENCLATURE

Symbols Used

a	enhancement factor in Eq.(5)
A	effective mass transfer area, m^2
C	concentration, $mg \cdot L^{-1}$
ΔC	driving force of mass transfer
D	diffusivity, $m^2 \cdot s^{-1}$
d	diameter, m
d_H	hydraulic diameter, m
J	mass transfer flux, $mg \cdot m^{-2} \cdot s^{-1}$
k	individual mass transfer coefficient, $m \cdot s^{-1}$
K_f	overall mass transfer coefficient base on the feed phase, $m \cdot s^{-1}$
L	effective length, m
L_f, L_{st}	volumetric flow rate of the feed phase and the stripping phase, $m^3 \cdot s^{-1}$
L_S, L_T	volumetric flow rate of shell side and lumen side, $m^3 \cdot s^{-1}$
m	distribution coefficient of extraction process
m'	distribution coefficient of back-extraction processs
n	the number of experimental data
N	number of hollow fibers in module
R	resistance of mass transfer, $s \cdot m^{-1}$
Re	Reynolds number
R_i	internal radius of the shell side of the module, m
r_o	external radius of hollow fiber, m
t	time, s
u	velocity, $m \cdot s^{-1}$
V	volume, m^3

Greek Letters

β	constant in Eq.(5)
ρ	density, $kg \cdot m^{-3}$
μ	viscosity, Pa·s
Φ	dispersed phase hold-up in HFRLM
ε	porosity of hollow fiber membrane
τ	tortuosity of hollow fiber membrane
ϕ	packing fraction of hollow fiber module
Δ	fractional resistance in Eq.(12)

Superscripts

in	inlet
out	outlet
ext	external
int	internal
init	initial
o	organic phase
R	renewal liquid membrane phase or renewal process of liquid membrane
m	membrane phase
S	shell side

Subscripts

aq	aqueous phase
eq	equilibrium
Ex	extraction
f	feed phase
m	membrane phase
oi	interface between aqueous phase of shell side and membrane phase
R	renewal liquid membrane layer or renewal process of liquid membrane
Roi	interface between renewal liquid membrane phase and membrane phase
st	stripping phase
S	shell side
T	lumen side
Ti	interface between aqueous phase of lumen side and renewal liquid membrane phase

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