

Removal of Heavy Metals and Organic Compound using Hollow Fiber supported Liquid Membrane: A Review

Arvind B. Madavi

*Department of Technology,
Shivaji university, Kolhapur, Maharashtra, India.*

Anil C. Ranveer

*Department of Technology,
Shivaji university, Kolhapur, Maharashtra, India.*

Siddharth M. Lokhande

*Department of Technology,
Shivaji university, Kolhapur, Maharashtra, India.*

Abstract- The generation of liquid effluents containing organic and inorganic residues from industries present a potential hazardousness for environment and human health, being mandatory the elimination of these pollutants from the respective solutions containing them. In order to achieve this goal, several techniques are being used and among them, supported liquid membranes technologies are showing their potential for their application in the removal of metals contained in liquid effluents. Supported liquid membranes are a combination between conventional polymeric membranes and solvent extraction. Chemical and metallurgical industries are the main producers of metal-bearing liquid effluents that due to the toxic character of metals. Several drawbacks of the often known as classical removal or separation technologies reduced the grade of effectiveness in the elimination of metals, principally when the aqueous solution is complex in its composition or when the metal is presented in the liquid solution at very low concentrations. Industrial processing of chemicals almost invariably leads to streams with multiple components that must then be subjected to a train of separation or purification operations to isolate the desired product. As an alternative method to wastewater pretreatment technology, supported liquid membrane (SLM) has been paid extensive attention due to its specific characteristics. As a result, SLM has been considered as a promising technology. The future of these technologies seems to be highly exciting and promising.

Keywords – Supported liquid membrane, Alternative method, Hollow fiber, Heavy metals, Organic compound.

I. INTRODUCTION

Chemical and metallurgical industries are the main producers of metal-bearing liquid effluents that due to the toxic character of many of the metals contained in them need be treated before final discharge. Thus, industries are increasingly being forced either by the administration, regulatory, cost pressures and social pressures to reduce the amount and environmental sensitivity of the liquid waste they produce. Several drawbacks of the often known as classical removal or separation technologies reduced the grade of effectiveness in the elimination of metals, principally when the aqueous solution is complex in its composition or when the metal is presented in the liquid solution at very low concentrations[1].

Industrial processing of chemicals almost invariably leads to streams with multiple components that must then be subjected to a train of separation/purification operations to isolate the desired product. Components from fermentation broths, pharmaceutical processing streams, chemical synthesis, and metal working fluids have all been successfully purified using some form of supported liquid extraction. Extraction is also a promising technology to couple to biodegradation. The successful treatment of synthetic waste streams has been demonstrated for a wide range of pollutants. The large-scale application of bacteria-based systems has met with limited success due to the nature of industrial waste streams, which may contain high salt concentrations, exhibit extreme pH conditions, or consist of a complex mixture of organic compounds. In addition, the concentration of the target pollutant may be too

dilute to serve as an effective carbon source for the biomass. As a result, separation of organic pollutants from the waste stream using extraction-based processes may facilitate effective bio-treatment [2].

As an alternative method to wastewater pretreatment technology, supported liquid membrane (SLM) has been paid extensive attention due to its specific characteristics. First, supported liquid membrane can simultaneously carry out the extraction and stripping processes in one step. Second, the process can only use chemical energy as a driving factor, instead of transmembrane pressure or voltage. Third, because of non-equilibrium mass-transfer characteristics, solute can move from low-to-high concentration of solutions. In SLM, the membrane only acts as a barrier without significant effect on selectivity, and organic extractant which aims at target compound is imbedded in small pores of membrane and is kept in these pores by capillary forces. During the SLM process, aqueous solution flows on one side (donor side) of the membrane, the target compound migrates to the other side (acceptor side), where they are collected by organic extractants. The process takes advantage of the chemical property of the organic extractant, such as polarity and hydrophobic/hydrophilic characters. The transfer of target compound from one phase to the other is driven by a deviation from thermodynamic equilibrium, and the equilibrium state depends on the interactions between the target compound and the organic extractant. So the extraction process depends on strong chemical interactions and highly specific selectivity. The success of the SLM process mainly based on the permeation rate of the target compound and this is decided depending on the nature of the organic extractant and the extraction kinetics. As a result, SLM has been considered as a promising technology. In general, SLM is classed to flat sheet supported liquid membrane (FSSLM) and hollow fiber supported liquid membrane (HFSLM). At the present time, many attentions have been paid to HFSLM due to much high surface area in a module[3].

Advantages of HFSLM technique

- Liquid membrane phase exists in micro pores of hollow fibers, which can resist great pressure;
- As a result of the carrier agents existence, it is essentially one selective promotion transmission process, thus HFSLM has very high selectivity and efficiency;
- Relatively low consumption of energy compared to other separation processes such as distillation;
- High flux when comparing with solid membrane due to the high porosity and maximum active surface area;
- Low capital and operating costs; and
- Easy scale-up etc.

Owing to these advantages, HFSLM has been used in a wide variety of applications involving extraction and/or removal of many species such as metal, phenol, chlorophenol, aroma compounds, salbutamol and terbutaline, herbicides, pesticides, and penicillin G and so on[3].

II. TECHNIQUES OF SUPPORTED LIQUID MEMBRANE

A. *Non-dispersive solvent extraction (NDSX)* –

In non-dispersive solvent extraction technology with single hollow fiber module (Fig. 1), the aqueous and organic phases are contacted co- or counter currently in the module for carrying out extraction or stripping runs, either in recirculation or one through modes. In the extraction module, the feed solution flows through the tube side of the fibers, whereas the organic phase circulates through the shell side, wetting the wall of the fibers. In the stripping module, the metal-loaded organic phase flows through the shell side, whereas the stripping solution flows through the tube side. Then, the metal-free organic solution is recirculated to the first or extraction module. For the correct maintaining of the interface, the pressure of the aqueous phases is typically held 0.2-0.5 bar higher than the pressure in the organic phase. In dual function modules, the extraction and stripping of the metal are carried out simultaneously in a single hollow fiber module containing one set of fibers for extraction and another set for stripping [1].

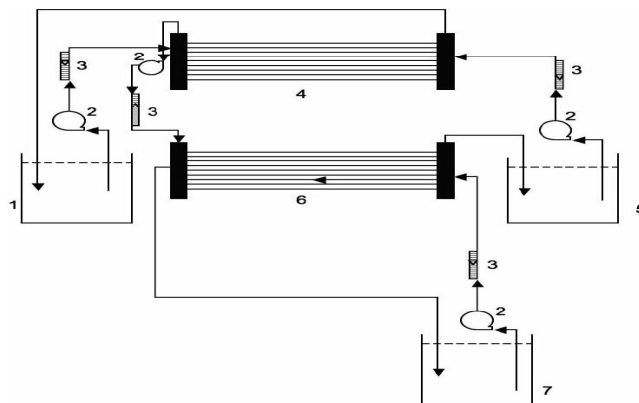


Figure1: schematic view of an integrated NdSX membrane process using two hollow fiber contactors.
 (1) Feed phase reservoir tank (2) pumps, (3) flow-meters, (4) extraction module, (5) organic phase reservoir tank, (6) stripping module, (7) strip phase reservoir tank. Operation in counter-current and recirculation of the solutions.

B. Non- dispersive solvent extraction with strip phase dispersion (NDSXSD) –

The hollow fiber strip dispersion process comprises a single module for extraction and stripping (Fig. 2). A pseudo-emulsion phase is prepared in a stirred tank, this pseudo-emulsion is formed by the organic solution and the dispersed stripping solution. Once pumped to the module for the shell side, the organic phase wets the porous wall of the fiber because of its hydrophobic nature. The feed solution is fed into the module through the tube side of the fibers. The differential pressure is always kept below the breakthrough pressure, thus in the feed phase the pressure is maintained in the 0.2-0.5 bar range higher than in the pseudo-emulsion phase. The characteristics of the pseudo-emulsion should be such that it should have clear and fast (in the order of a few minutes) phase separation when mixing in the tank is stopped (Fig. 3). Then the recovery of the metal from the stripping solution can be achieved. Recently, this technology had been implemented in a flat-sheet configuration and cell operational mode for the transport of chromium (VI) from acidic solutions using the tertiary amine Hostarex A327 as carrier and NaOH solutions as strippant [1].

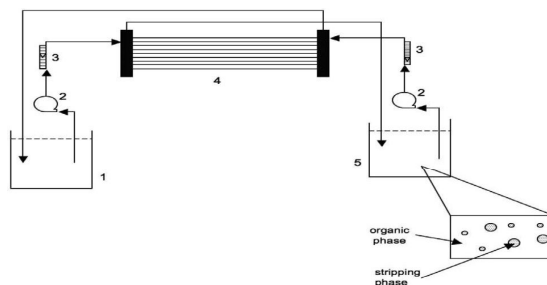


Figure2: Schematic view of non-dispersive solvent extraction with strip dispersion process using a hollow fiber module.
 (1) Feed phase reservoir tank, (2) pumps, (3) flow meters, (4) hollow fiber module, (5) pseudo-emulsion phase reservoir tank.
 Operation in counter-current and recirculation of the phases.

C. Hollow fiber renewal liquid membrane (HFRLM)-

In this technology, the stirred mixture of organic phase and feed phase (or stripping phase) is pumped through the tube side of the fibers, the organic phase is uniformly dispersed in the corresponding aqueous solution and wets and fills the pores of the module (Fig. 3). The stripping phase (or the feed phase) flows through the shell side, co- or counter currently. The flows are controlled to maintain a positive pressure on the shell side, in order to prevent penetration of the organic phase into the shell side [1].

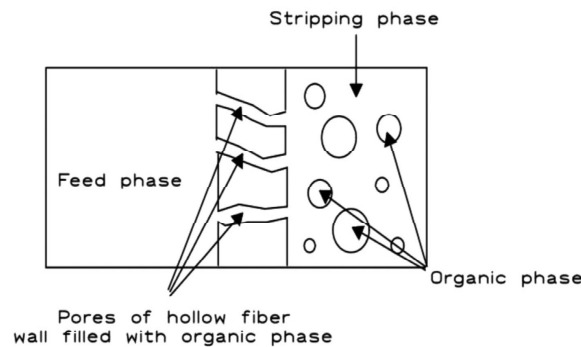


Figure 3: Schematic view of HFRLM operation with organic phase dispersion and formation of a pseudo-emulsion between the organic and strip solutions.

II. CARRIERS IN ORGANIC PHASES AND TRANSPORT IN HFSLM

The organic phase is formed by organic diluents, which is non-miscible in water, and dissolved the carrier which is the active substance in the metal transport process. At first, it is accepted that the organic diluents does not take part or has no influence in the transport process, but this rule is sometimes far from reality and in fact the properties of the diluents can determine the results and performance, with respect to metal transport, of a given organic solution. Normally, diluents used in membrane transport are the same as those used in liquid-liquid extraction technology, which in many cases are aromatic or aliphatic petroleum fractions. Extractants in liquid-liquid extraction terminology or carriers in membrane terminology are, of course, organic compounds. During all these years, carriers are becoming increasingly selective, allowing the specific separation of some solutes from another. The carriers employed in supported liquid membranes are nearly the same as the extractants used in liquid-liquid extraction, though due to the characteristics of supported liquid membranes technology some specific or more expensive carriers can be used for metal transport in membrane operation [1].

A. Types of transport-

a) *Counter-transport*:-Feed solution containing the transported metals and stripping solution counter ion. They apply in opposite direction. Counter ion concentration difference is the driving force between feed and strip phase. On this transport type cationic exchanger's extractants are observed [1].

b) *Co-transport*:- Feed solution containing the transported metals and stripping solution co- ion. They apply in same direction. Co-ion concentration difference is the driving force between feed and strip phase [1].

B. Steps in Transport mechanism-

- i) Solute diffusion occurs to the feed phase side diffusion layer,
- ii) Feed/Membrane interface in which chemical reaction takes place between metal species and carrier,
- iii) Complex of metal-carrier diffuses between membrane and membrane/stripping interface,
- iv) Stripping reagents chemically reacts and broken down the complex metals. In the stripping phase metals are liberated and simultaneously carrier is reform.
- v) Diffusion of the stripped metals to the bulk stripping phase,
- vi) When Transport process recycles then diffusion carried out for the reform carrier through membrane to feed/membrane interfaces [1].

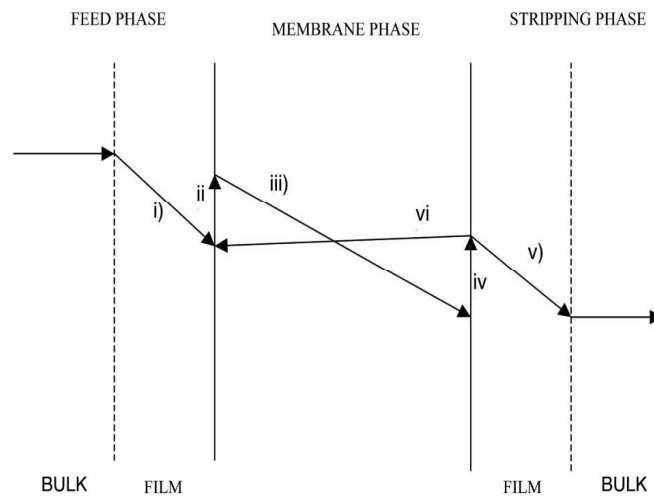


Figure 4: Metals transport steps.

C. Technical Aspects related to HFSLM-

- Due to the wetting affinity of the organic phase and hydrophobic fibers. The shear force caused by the flowing fluid in the lumen side will influence the coalescence and breakage of organic droplets during the stirred mixture flowing through the lumen side. That is, the shear force will cause the film liquid to form microdroplets on the surface of the liquid membrane layer, which will peel off from the surface of the liquid membrane layer and enter into the lumen side fluid. At the same time, the organic droplets will fill the surface of the liquid film. Then the renewal of the liquid membrane is continuously proceeding. This can enhance the mass transfer rate and greatly reduce the diffusion resistance across the aqueous boundary layer within the lumen side. The thickness of the developed liquid membrane film is thin due to the effects of shear forces caused by fluid flowing in the HFRLM process. The solute can be selectively transported across the liquid membrane from the feed phase to the stripping phase. Furthermore, the dispersed organic droplets in the lumen side fluid can automatically and continuously replenish the loss of membrane liquid caused by solubility and emulsification to prevent liquid membrane degradation. The leakage between phases is less than 0.01%. Then the HFRLM process can provide good stability [4].
- Hansen solubility parameter theory was applied to analyze and explain the different transport phenomena with different modifiers. If the Hansen solubility parameters for a solvent lie within the solubility sphere for the complex, then the complex is probably soluble in the solvent. According to the Hansen model, the distance between solvent and center of complex solubility sphere can be expressed as

$$\Delta \delta_{(S-P)} = [4(\delta_{dS} - \delta_{dP})^2 + (\delta_{pS} - \delta_{pP})^2 + (\delta_{hS} - \delta_{hP})^2]^{1/2}$$
 where $\Delta \delta_{(S-P)}$ = the distance between solvent and the center of complex solubility sphere; δ_{dS} = Hansen component parameter for solvent; δ_{dP} = Hansen component parameter for complex. The reason was that when the pressure difference exceeded a certain critical value, the liquid membrane phase could be pushed out of the pores. The critical displacement pressure was defined for an SLM as the minimum transmembrane pressure required displacing the liquid membrane phase out of the largest pore [5].
- In hollow fibre modules the overall mass transfer resistance for a diffusion controlled process depends on the mass transfer resistances inside the fibre, across the membrane and outside the fibre. In order to identify the limiting step of the mass transfer process, experiments were carried out maintaining the flow rate of one phase constant while varying the flow rate of the other phase.

Another limitation of the Wilson-plot method comes from the fact that it involves a two-step calculation carried out in a sequential mode: in first place the estimation of the overall mass transfer coefficient and secondly, the determination of the correlation coefficients. This procedure leads to a loss of information and possible accumulation of errors. Additionally, as the variables' inverse is represented, a distortion on the magnitude of the variables can occur [6].

- On the other hand, the renewal and regeneration of the liquid membrane layer can automatically and continuously replenish the loss of membrane liquid caused by solubility and emulsification to prevent liquid membrane degradation. The flow rates of two sides are controlled to maintain a positive pressure on the shell side with respect to the lumen side to prevent the leakage between two sides when the hydrophobic fibers are used. The HFRLM process is stable and can run for long-term without any difficulty. The removal efficiency and the mass transfer flux increase with the increasing amount of organic phase in the lumen side fluid, because of the renewal effect of liquid membrane in the lumen side and the large mass transfer area arising by the direct contact between organic droplets and aqueous phase. While at the higher O/A volume ratio, the consumption of the organic phase is large, this will increase the thickness of the developed liquid membrane layer and the mass transfer resistance within the lumen side. There is a favorable O/A range from 1:10 to 1:7 for the HFRLM process under the range studied, in which the removal efficiency and the mass transfer flux are higher, and the consumption of the organic phase is smaller. As the rate of complex reaction at interfaces is faster, the mass transfer resistance resulted from complex reaction can be ignored compared to the mass transfer resistance of diffusion mobility across the aqueous phase or organic phase. The mass transfer model based on the surface renewal theory is presented by considering the renewal process of liquid membrane layer, diffusion across membrane phase and aqueous boundary layer on the shell side [7].

Table 1: Selected published work on heavy metals separation by HFSLM

Sr. no	References	Metals	Feed phase	Organic phase with carrier	Stripping phase	Parameters
1	[8]	Rh(III)	10^{-3} M Rh(SCN) $_6^{3-}$	0.15M Aliquat 336 in dodecane with 4% dodecanol	NaSCN and mixture of NaHSO $_3$ /Na $_2$ SO $_3$	pH=5, flow rate of both=0.35 ml/min, 0.2M HSO $_3^-$ / 0.8M SCN $^-$.
2	[9]	Cu(II)	CuSO $_4$ solution (1-10mol/m 3)	LIX64N in kerosene (0.1-0.4 mol/m 3)	HCL (0.4-4mol/dm 3)	Feed pH=(2-6), Pressure=2-5 psig, Aqueous phase flow rate=3.7 cm 3 /s, Organic phase recirculation=3.5 cm 3 /s.
3	[10]	Pu(IV)	Pu(IV) with sodium nitrite(1.5 \times 10 $^{-5}$ M)	30%TBP in dodecane	0.3M HNO $_3$	Flow rate =1-3ml/min, Feed acidity=3M HNO $_3$, 1.09M TBP, surface area=33.91 cm 2
4	[11]	Zr and Hf	Zr and Hf in HCL (5-10M)	0.5M TONA and 0.2M Aliquat 336 in kerosene	2M HCL	Speed=1000rpm, Contact time=5-10 min, Phase ratio=1:1, Flow rate=0.8-8.8 ml/min.
5	[12]	Au(I)	Au(I) in alkaline cyanide(1000ppm)	12%LIX79 in n heptanes	0.2M NaOH	Speed=400rpm, Pressure=0.2-0.45 bar, pH=10.5, Feed and strip flow rate=5.56 and 3.33cm 3 /s, Feed:Strip =4:1, P $_{Au}$ =5.32-7.53 \times 10 $^{-5}$ cm/s, feed=1000-5000ppm.

6	[13]	Cr(VI)	Cr(VI) stock solution from solid $K_2Cr_2O_7$	Aliquat 336 (0.05-0.5M) in dodecane	0.5M HNO_3 and 0.5M $NaNO_3$	Feed Cr(VI)=1mg/l, pH=2, flow rate=1ml/min ⁻¹ .
7	[14]	U ion	U ion(45ppm) in trisodium phosphate solution	0.1M Aliquat 336 in kerosene with 0.06M TBP	(0.1-0.5M) HNO_3	Flow rate = 100ml/min, Aliquqt336 =(0.02-0.14M),
8	[15]	Cu(II)	$CuSO_4$ IN acetate buffer media	D_2EHPA in kerosene	6mol/L HCL	Tube velocity=0.001-0.04m/s, Shell velocity=0.003-0.007m/s, pH=4.44, Feed Cu=150-800mg/l, Organic phase=(1:9)
9	[7]	Cu(II)	$CuSO_4$ solution (64.03-91.72mg/L)	10%LIX984N in kerosene	H_2SO_4 (2mol/L)	Volume ratio=(1:10to1:7), pH=0.5-5.5, Flow rate tube=2.7-2.9ml/min and shell=2.2-2.3 ml/min,
10	[16]	Co(II)	Co(II) in Acidic sulphate solution	DP-8R in Exxsol D100(0.16-1.28M)	0.1M H_2SO_4	pH=3-7, Co(II) in feed=0.17-1.7 $\times 10^{-3}$ M, Feed flow rate=200-400cm ³ /min, Pseudo emulsion=200 cm ³ /min,

Table 2: Selected published work on organic compounds separation by HFSLM

Sr .No	References	Organic compound	Feed phase	Organic phase with or without carrier	Stripping phase	Parameters
11	[17]	Lactate	Lactate solution (280 mM)	Quaternary ammonium salt carder, Aliquat 336 and hydrocarbon mixture as diluents	1 M Sodium chloride solution	Agitation=400rpm, T=22.5-40 ⁰ C, aliquat(%)=5-50, organic phase concentration=0-7g/L
12	[6]	Phenylalanine	90 mM phenylalanine and 0.1 M KCL	Micellar phase (n-heptane solution 125M in TOMAC) and 1.25% v/v 1-hexanol as co surfactant	2M KCL	Feed phase (V=900 ml, flow rate=73ml/min, Re=3.4, pH=9.9), Organic phase(V=900ml, flow rate=113 ml/min, Re=3.9), Stripping phase(V=300ml, flow rate=125.3 ml/min, Re=5.9)

13	[18]	Lipase	(10-20mM) equimolar PAA and MAs or 6-APA and 850mM ethanol	PPL (20v/v% octanol in heptane)	0.1-0.2M phosphate buffer (pH=7.57-7.60)	Flow rate feed side(0.2-5ml/min) and strip side (0.2-4ml/min),pH=6.10-6.27 feed phase, shell and tube side pressure=5 and 6-9psi,
14	[2]	p-Nitro phenol	p-Nitro phenol in aqueous buffer solution	1-octanol	Aqueous with 50mM buffer	Feed and strip phase volume=4000 and 500ml,flow rate=490 and 170ml/min, Ret=12.1
15	[19]	Phenol	3000mg/L phenol in aqueous solution	1-decanol with different extractants 5%(v/v)	1.8M NaOH	$Re_o=0.1-0.65$, $Re_a=4-7$ and $Re_s=7$, $V_a=61$, $V_o=0.71$, $V_s=0.41$, $V_a: V_o=1:1$ and $2:1$, $Q_o=8-50l/h$, $Q_a=28l/h$, $P=0.6-0.8$ bar(aqueous phase)
16	[20]	Amino acids and dipeptides	Trp, Phe, Trp-Leu and Phe-Leu in sodium acetate Phosphoric acid buffer, hydrolysate solution (25 g/l)	10% AOT in oleyl alcohol (for single solute)and 30% AOT in oleyl alcohol (for hydrolysate study)	0.1M Na_2CO_3 added to the organic solution (Only use in hydrolysate solution)	Feed pH=3-4.5,flow rate organic solution=10ml/min,P=15-25kPa,feed concentration=upto 4mM,
17	[21]	Amino acids	Equimolar phenylalanine and laspartic acid in deionized water (5 mol/m ³)	D2EHPA in kerosene (100-500 mol/m ³)	HCl in deionized water(0.1-2mol/dm ³)	Feed and organic phase flow rate (120–600 cm ³ /min)and (180–480 cm ³ /min),strip phase(240–600 cm ³ /s), feed pH (3–5), and stripping acidity (0.1–2 mol/dm ³)
18	[4]	Citric acid	0.1 mol/L Citric acid solution.(300	30%N235+20% n-octanol+50% Kerosene.	(0.11-0.2) mol/L NaOH aq solution.	Shell side velocity=0.10cm/s,N235 concentration=5%-40%,aqueous/organic volume

			ml)	(15ml)	(150ml)	ratio=20:1,
19	[5]	Fumaric acid	([H+] 0.022-0.631 mol/L) Fumaric acid waste water (V=100ml)	Trialkyl amine carrier in kerosene and n-octanol (V=50)	(2-20%) NaOH, (V=100ml)	0.7137 mol/L N ₇₃₀₁ in kerosene and n-octanol, volume ratio of kerosene/ n-octanol=7/6, Δp=7.5- 10psi, pH=1-1.67, stirring speed=200-400 rpm, flow rate feed and strip=3.6 and 3 L/h

IV.CONCLUSION

Supported liquid membranes are the interesting field for the study as well as research for the scientists and industry peoples. The practical use of the SLM is not possible yet but the smart supported liquid membranes technologies can be used in near futures with some modification for removal of heavy metals and organic compounds from the effluent which contains heavy metals. By using the proper solvent we can improve the overall mass transfer coefficient of desired solution. The type of HFSLM with strip is generating some pollution as it is soluble in both aqueous as well as strip solution, thus some modifications can be suggested for it.

REFERENCES

- [1] D.de Agreda, I. Garciadiaz, F.A. Lopez, F.J. Alguacil, "Supported liquid membranes technologies in metals removal from liquid effluents", *Revista de metalurgia*, Volume No. 47(2), pp. 146-168, 2011.
- [2] S.W. Peretti, C.J. Tompkins, J.L. Goodall, A.S. Michaels, "Extraction of 4-nitrophenol from 1-octanol into aqueous solution in a hollow fiber liquid contactor", *Journal of Membrane Science*, Volume No. 195, pp 193-202, 2001.
- [3] Y. Liu, B. Shi, "Hollow fiber supported liquid membrane for extraction of ethylbenzene and nitrobenzene from aqueous solution: A Hansen Solubility Parameter approach", *Separation and Purification Technology*, Volume No. 65, pp 233-242, 2009.
- [4] Z. Ren, W. Zhang, H. Li, W. Lin, "Mass transfer characteristics of citric acid extraction by hollow fiber renewal liquid membrane", *Chemical Engineering Journal*, Volume No. 146 pp. 220-226, 2009.
- [5] S. Li, H. Lin, L. Zhang, "Recovery of fumaric acid by hollow-fiber supported liquid membrane with strip dispersion using trialkylamine carrier", *Separation and Purification Technology*, Volume No. 66, pp 25-34, 2009.
- [6] M.M. Cardoso, R.M.C. Viegas, J.P.S.G. Crespo, "Extraction and re-extraction of phenylalanine by cationic reversed micelles in hollow fiber contactors", *Journal of Membrane Science*, Volume No. 156, pp 303-319, 1999.
- [7] W. Zhang, C. Cui, Z. Ren, Y. Dai, H. Meng, "Simultaneous removal and recovery of copper(II) from acidic wastewater by hollow fiber renewal liquid membrane with LIX984N as carrier", *Chemical Engineering Journal*, Volume No. 157, pp 230-237, 2010.
- [8] C. Fontas, C. Palet, V. Salvado, M. Hidalgo, "A hollow fiber supported liquid membrane based on Aliquat 336 as a carrier for rhodium(III) transport and preconcentration", *Journal of Membrane Science*, Volume No. 178, pp 131-139, 2000.
- [9] S. Lin, R. Juang, "Mass-transfer in hollow-fiber modules for extraction and back-extraction of copper(II) with LIX64N carriers", *Journal of Membrane Science*, Volume No. 188, pp 251-262, 2001.
- [10] N.S. Rathore, J.V. Sonawane, Anil Kumar, A.K. Venugopalan, R.K. Singh, D.D. Bajpai, J.P. Shukla, "Hollow fiber supported liquid membrane: a novel technique for separation and recovery of plutonium from aqueous acidic wastes", *Journal of Membrane Science*, Volume No. 189, pp 119-128, 2001.
- [11] X.J. Yang, A.G. Fane, C.Pin, "Separation of zirconium and hafnium using hollow fibers Part I. Supported liquid membranes", *Chemical Engineering Journal* Volume No. 88, pp 37-44, 2002.
- [12] J.V. Sonawane, Anil Kumar Paddy, A.M. Sastre, "Au(I) extraction by LIX-79/n-heptane using the pseudo-emulsion-based hollow-fiber strip dispersion (PEHFSD) technique", *Journal of Membrane Science*, Volume No. 300, pp 147-155, 2007.
- [13] R. Guell, E. Antico, V. Salvado, C. Fontas, "Efficient hollow fiber supported liquid membrane system for the removal and preconcentration of Cr(VI) at trace levels", *Separation and Purification Technology*, Volume No. 62 (2008) 389-393.
- [14] A.W. Lothongkum, P. Ramakul, W. Sasomsub, S. Laoharochanapan, U. Pancharoen, "Enhancement of uranium ion flux by consecutive extraction via hollow fiber supported liquid membrane", *Journal of the Taiwan Institute of Chemical Engineers*, Volume No. 40, pp518-523, 2009.
- [15] Z. Weidong, C. Chunhua, H. Zisu, "Transport Study of Cu(II) Through Hollow Fiber Supported Liquid Membrane", *Chinese Journal of Chemical Engineering*, Volume No. 18(1), pp 48-54, 2010.
- [16] F.J. Alguacil, I. Garcia-Diaz, F. Lopez, A.M. Sastre, "Cobalt(II) membrane-extraction by DP-8R/Exsol D100 using pseudo-emulsion based hollow fiber strip dispersion (PEHFSD) processing", *Separation and Purification Technology*, Volume No. 80, pp 467-472, 2011.

- [17] I.M. Coelho, P. Silvestre, R.M.C. Viegas, J.P.S.G. Crespo, M.J.T. Carrondo, "Membrane-based solvent extraction and stripping of lactate in hollow-fibre contactors", *Journal of Membrane Science*, Volume No. 134, pp 19-32, 1997.
- [18] X. Dai, Z. Yang, R.G. Luo, K.K. Sirkar, "Lipase-facilitated separation of organic acids in a hollow fiber contained liquid membrane module", *Journal of Membrane Science*, Volume No. 171, pp 183-196, 2000.
- [19] M.J. Gonzalez-Munoz, S. Luque, J.R. Alvarez, J.Coca, "Recovery of phenol from aqueous solutions using hollow fiber contactors", *Journal of Membrane Science*, Volume No. 213, pp 181-193, 2003.
- [20] Md.M. Hossain, "Reactive extraction of amino acids and dipeptides using an extra-flow hollow-fiber module", *Separation and Purification Technology*, Volume No. 42, pp 227-236, 2005.
- [21] S. Lin, C. Chen, "Simultaneous reactive extraction separation of amino acids from water with D2EHPA in hollow fiber contactors", *Journal of Membrane Science*, Volume No. 280, pp 771-780, 2006.