

Membrane Solvent Extraction of Some Rare Earth Elements

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Studies on the membrane solvent extraction consisting of source and membrane, and membrane and receiving phases in extraction and stripping processes of praseodymium, samarium and yttrium in hollow fiber membrane one after the other, have been investigated. Different experimental variables, such as the pH, carrier, metal ion and stripping agent concentrations have been explored. However, the solvent and membrane solvent extraction methods were compared based on the equilibrium extraction constant. The pre-concentration by the ion transport based on enrichment factor (EF) with the consideration of controlled parameters, were predicted. The ion transport of praseodymium, samarium and yttrium in the receiving or membrane phase envisages the determination of extraction equilibrium constant for these elements.

Keywords:

Membrane; extraction; stripping; praseodymium; samarium; yttrium.

Introduction

Membranes are species that are selective barriers for transport. The recent investigations with microporous membranes have shown that these membranes can be efficiently used for traditional equilibrium-based separation process. However, solvent extraction process which is an equilibrium-based separation process requires the dispersion of one phase in another immiscible phase for efficient contacting. Moreover, the coalescence problems arise often along with the disadvantages of loading, flooding and third phase formation. A novel microporous membrane based, dispersion free, solvent extraction technique has been developed and presented by *Sirkar et. al.*¹

The major advantages of this versatile technique over conventional dispersion based technique are: dispersion free operation, modular design eases scale up and retro fitting of equipment, very high contact surface area per unit extractor volume is provided by micro-porous hollow fibers, independent control of process strain flow rates eliminating loading and flooding, non requirement of density difference of the phases and able to handle particulates.

The advantages of hollow fibers have led several investigators to examine their application to liquid-liquid extraction.^{2–6} They have successfully applied this technique for the purification of poly-saturated long chain acids, for the removal of organic solutes from very dilute aqueous waste

streams, and for the decontamination of ground water.⁷ It is proved that membrane solvent extraction is technically and economically feasible for racemic leucine separation. They obtained on isomer yield per equipment of racemic separation the volume which is 100 times greater than that in a continuous rotating extractor, and 1000 times greater than that in a conventional packed tower. An excellent review on membrane solvent extraction for drinking water treatment has been published.⁸ Several other applications of liquid membrane processes have been reported.^{9–11}

In membrane solvent extraction an organic phase which wets a microporous hydrophobic membrane passes through one side and the other side of the membrane flows a non wetting aqueous phase at a pressure higher than that of the organic phase but lower than the pressure needed for the aqueous phase to displace the organic phase in the pores of the membrane. The aqueous-organic interface is essentially immobilized at the pore mouth of the membrane. The solute transfer simultaneously takes place through such interfaces. Here the membrane does not function as a species selective transport medium. It merely prevents the dispersion of one phase into the other. Also it influences the species extraction rate.

In this study, a non-dispersive, microporous membrane based solvent extraction technique has been explored to study the metal ion transport of some rare earth elements, since, it is worthwhile to study the ion transport behavior of these elements using such a technique which combines the advantages of two extraction-separation techniques viz. liquid membrane and solvent extraction

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Experimental

Reagents

The commercial acidic chelating extractant 2-ethylhexyl phosphonic acid mono-2-ethylhexyl ester (PC-88A, EHPNA) (Diahachi Chemical Industry Co. Ltd., Japan) was used in appropriate concentrations utilizing the diluents xylene (AnalaR), praseodymium, samarium and yttrium solutions were prepared by dissolving suitable quantities of these metal trioxides in hydrochloric acid. After evaporating any excess acid, the individual solutions were diluted to the appropriate volume using distilled water. The solutions were standardized complexometrically¹² at pH 5.0 with xylenol orange as the indicator. All the other chemicals used were of analytical grade.

Apparatus

The hollow fiber membranes (CELGARD X-10, Hoechst Celanese Separations Products Division, Charlotte, NC) utilized for the permeability measurements in extraction and stripping process as shown schematically in Fig. 1. The characteristics of these membrane modules are given in Table 1. The modules contained hydrophobic polypropylene hollow fibers with epoxy resin potting are fixed in a nylon casting.

A digital pH meter, type 120 (ELICO, India) with glass and calomel electrodes was utilized for the pH measurements. A Hitachi 220 double beam microprocessor controlled spectrometer was used for

Table 1 – Hollow fiber module features

Hollow fiber	Material / Dimensions
Specification of fiber	
Hollow fiber type	CELGARD X-10
Material of hollow fiber	Hydrophobic polypropylene
Fiber internal diameter, d_i	240 μm
Fiber wall thickness, δ	30 μm
Effective wall thickness, δ_e	0.05 μm
Porosity, ϵ	30 %
Effective fiber length, l_e	16 cm
Specifications of module	
Length of module, L	30 cm
Diameter of module, D	2.5 cm
Number of fibers, N	2100
Area per unit volume, a	40 $\text{cm}^2 \text{cm}^{-3}$

the quantification of metal ion concentration. Peristaltic pumps PP 20 (Miclins India Ltd) were used for the circulation of organic and aqueous solutions.

Procedure

The feed solution at desired flow rate was passed through the tube side of the hollow fiber module and the organic solution containing extractant was passed counter currently through the shell-side at desired flow rate with the help of peristaltic pumps in the extraction system. While the enriched organic solutions were passed counter currently through the shell side at desired flow rate and stripping solution through the tube side of the second hollow fiber for the stripping system. Extraction and stripping processes for the individual metal ions were carried out simultaneously one after the other with two modules. The extraction and stripping processes were carried out for certain time in order to attain steady state of this membrane dynamic process. The outlet solutions were analyzed for the metal ion. Metal ion concentration in the aqueous solution and after stripping from organic solution was estimated by measuring the absorbance at 575 nm after color development with Arsenazo I indicator at pH 7.5.

Results and discussion

Configuration of hollow fiber membrane solvent extraction

A conventional solvent extraction system, which is carried out in two steps either for separation or pre-concentration of rare earth ions from its

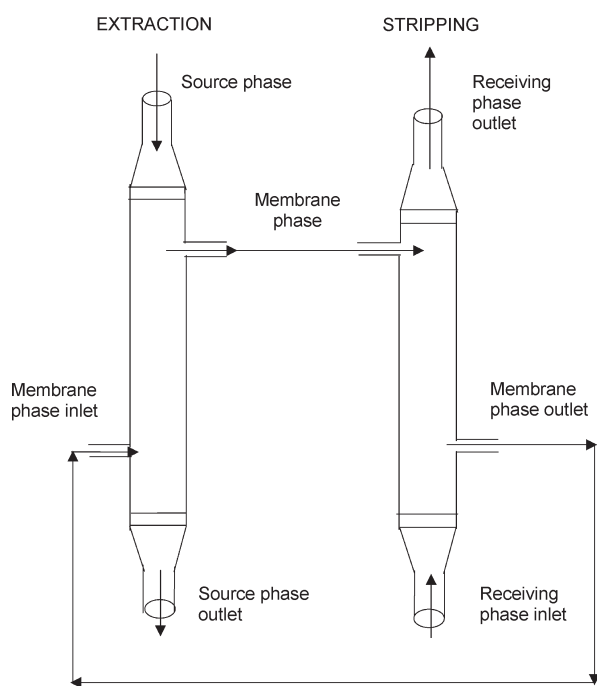


Fig. 1 – Systematic presentation of hollow fiber membrane systems

source solution, can be illustrated in bulk solutions as shown in Fig. 2. A bulk liquid membrane system that consists of source(s), membrane (m) and receiving (r) phases is illustrated in Fig. 2. The extraction and stripping processes are carried out one after the other, after the equilibrium equilibration and separation of two phases. However, during these processes, different modes of occurrence involved are dispersion of one phase as drops in another phase, subsequent to coalescence of dispersed phase and phase separation. This mode of operation frequently leads to solvent loss by emulsion formation. This may cause the loss of costly carriers or chelating agents, and extractant loading. The dispersion free solvent extraction technique, i.e. membrane technique which eliminates all such shortcomings. Fig. 2 illustrates the transport of trivalent rare earth ions (M^{3+}) from source phase through liquid membrane to receiving phase. This ion transport process of metal ion can be represented by two extraction processes, namely, transport of rare earth ion from the aqueous to organic phase as a forward extraction process, and lanthanide ion transport from organic phase to the aqueous phase as a backward extraction process. These extraction processes can be carried out in hollow fiber membrane extractors as extraction and stripping processes in two stages.

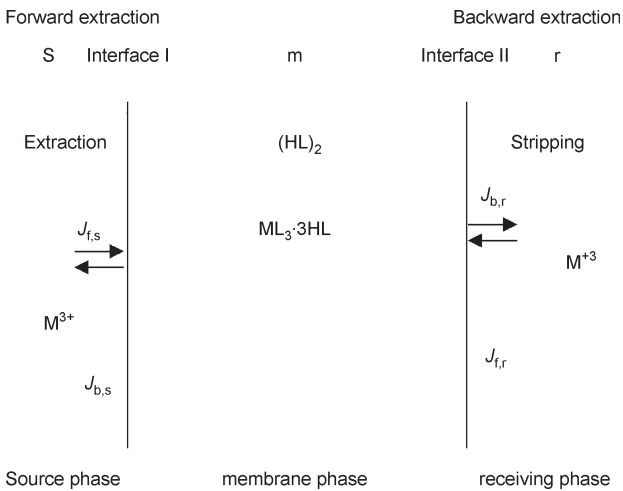
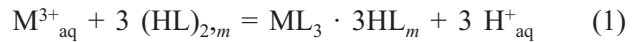


Fig. 2 – The illustration of metal ion transport in extraction and stripping bulk liquid membrane

Reactions and ion transport

The ion transport rates of rare earth elements in extraction and stripping processes were measured at 25 °C with the membrane extractor. The aqueous and organic solutions were fed concurrently along the inner and outer sides of the hollow fiber, respectively, with a peristaltic pump. Two modules were used for the extraction and stripping processes as shown in Fig. 1. The enriched extractant from the

extraction process is passed through second module for the stripping process. Thus extraction and stripping processes were operated simultaneously. Since the hollow fibers are hydrophobic, the pores of the hollow fibers are filled with the organic solution containing extractant. The equilibrium study shows that the rare earth metal ion was extracted with the dimer of EHPNA, $(HR)_2$, as follows.



The extraction equilibrium constant (K_{ex}) can be represented by

$$K_{ex} = [ML_3 \cdot 3HL]_m [H^+]^3_{aq} / [M^{3+}]_{aq} [(HL)_2]_m^3 \quad (2)$$

The distribution ratio of the metal ion (K_M^{3+}), Nernst low distribution, is expressed by

$$K_M^{3+} = [ML_3 \cdot 3HL]_m / [M^{3+}] \quad (3)$$

Substituting K_M^{3+} in the equation (2) we have

$$K_{ex} = K_M^{3+} [H^+]^3_{aq} / [(HL)_2]_m^3 \quad (4)$$

Taking logarithm on both sides of the equation (4) we have

$$\text{Log } K_M^{3+} - 3 \text{ pH} = \log K_{ex} + 3 \log [(HL)_2]_m \quad (5)$$

The transport rate of ions (J) in the proposed extraction and stripping studies can be calculated by plotting the values of concentration of metal ion vs. time and using values of V and S . Equation (7) gives the forward ion transport rate (J_f) of the extraction process, and Equation (8) gives the backward ion transport rate (J_b) of the extraction process.

$$J = (V/S)(dc_M^{3+} / dt) \quad (6)$$

The flux J_f for the extraction process is defined by

$$J_f = - (d[M^{3+}]_s / dt) (V_s/A) \quad (7)$$

The flux J_b for the stripping process is defined by

$$J_b = (d[M^{3+}]_r / dt) (V_r/A_r) \quad (8)$$

The extraction and stripping rate constant can be calculated from following equations

$$J_f = k_f [M^{3+}][HL]_m^3 \quad (9)$$

$$J_b = k_b [ML_3 \cdot 3HL]_m [H^+]^3 \quad (10)$$

At the equilibrium state where $J_f = J_b$, K_{ex} is given by

$$K_{ex} = k_f / k_b \quad (11)$$

To discuss the results of continuous transport of metal ion, the apparent permeabilities for the extraction and stripping of rare earth metal, P_M and $P_{M'}$, respectively, were defined as follows:

$$P_M = J_M / c^s_M = E \cdot Q_{aq} / 2 \pi \cdot l \cdot d_i \quad (12)$$

$$P_{M'} = J_{M'} / c^m_M = E' \cdot Q_{org} / 2 \pi \cdot l \cdot d_i \quad (13)$$

Where J_M and $J_{M'}$ are the average extraction and stripping rates, c_M^s and c_M^m are initial metal concentrations in respective phase, Q_{aq} and Q_{org} are the volumetric flow rates of the aqueous and organic solutions, E and E' are the extents of metal extracted and stripped, l stands for number of hollow fibers, and d_f is the diameter of hollow fiber. In order to access the significant role of acidic extractant during the metal ion extraction and stripping processes, the following mechanisms are illustrated.

Factors influence ion transport in liquid membrane system

In the membrane system, membrane phase acts as barrier for ion transport from source to receiving phase. Thus membrane phase as its design and thickness plays a significant role in designing membrane system. When designed bulk source and membrane phases brought in contact and operated as metal extraction then it becomes extraction bulk liquid membrane. When metal extracted membrane phase and receiving phase brought in contact and operated as metal stripping process in a stripping bulk liquid membrane. In other way in design, the dimension and thickness of membrane, phase is reduced and supported on support and brought into contact of source and receiving phases, it becomes supported membrane system for continuous operation as long as membrane phase is stable on support. However, in such system, stability of membrane phase is an important factor. Moreover, small dimension and volume of source, membrane (suitable support) and receiving phases can be continuously used in order to design the different supported membrane for the efficient and economically viable operation with the stability of membrane. The stability of immobilized membrane phase on support is questionable for a long run due to its de-immobilization on support during the operation of membrane process. Thus extraction and stripping processes can be continuously used one after the other in hollow fiber for long run operation. This process has minimum loss of membrane phase, it is easy to operate, has a minimum volume of source and receiving phase with higher concentration of metal ions. Thus micro-system of membrane solvent extraction may be very efficient in commercial application in which overcoming the problem of blocking of micro-pores and holes by using pure solvents as ultra-pure grade solvents.

Ion transport is controlled by diffusion of ions in bulk and interfaces, and chemical reactions at interfaces. Diffusion equilibrium of ions in hollow fiber membrane process is obtained by flowing source, membrane and receiving phases through hollow fibers. The dependency of chemical reaction on chemical species concentration has been explored.

Since, extraction and stripping processes are carried out one after the other, here first extraction process is described and its data have been represented in part in Figure a (e. g. Fig. 3–7 a), however, the stripping process is carried out afterwards, it is explained latter and its data are presented in part in Figure b (e. g. Fig. 3–7 b).

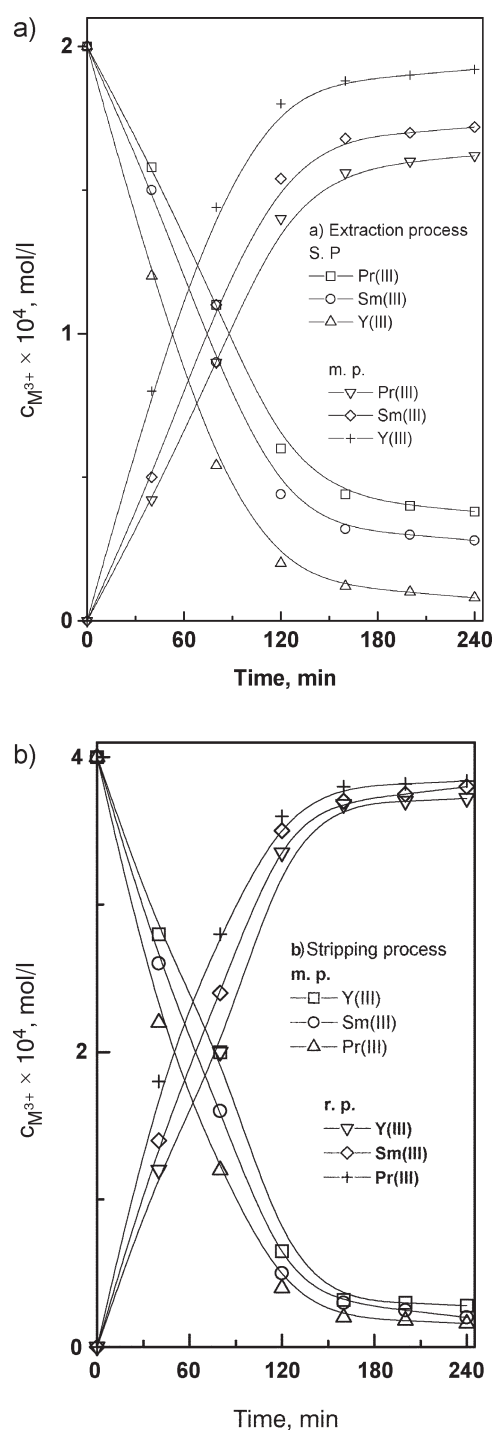


Fig. 3 - Metal ion concentration variation with respect to time, $[M(III)] = 2 \times 10^{-4} \text{ mol dm}^{-3}$, $[(HL)_2]_m = 0.01 \text{ mol dm}^{-3}$, $[ML_3 \cdot 3HL] = 4 \times 10^{-4} \text{ mol dm}^{-3}$, $Q_s = 4 \text{ cm}^3 \text{ min}^{-1}$, $Q_m = 4 \text{ cm}^3 \text{ min}^{-1}$, $Q_r = 0.25 \text{ cm}^3 \text{ min}^{-1}$, $pH_s = 6.5$ and $c_{HClr} = 1.0 \text{ mol dm}^{-3}$

Extraction process

The extraction of metal ion has been carried out in hollow fiber membrane using metal ion, carrier, aqueous and membrane phases. Occurred different modes have been explained.

Diffusion controlled parameters in extraction process

To achieve diffusion equilibrium in bulk solution is essential in order to precede, simultaneously, further chemical reactions at interfaces. The flow rates of source and membrane phases were varied.

Variation of metal ion concentration in extraction process with respect to time

The variation of metal ion concentration with respect time for extraction process is shown in Fig. 3a. The p values have been calculated from the extent of metal ion transferred from source to membrane phase.

Effect of variation of flow rates of source and membrane phases on P in extraction process

It is necessary to establish diffusion equilibrium in source and membrane phases and their interface in order to optimize the ion transport. It is achieved by variation of flow rates of source and membrane phases. Thus the flow rate of source solution is a significant quantity to transport the maximum concentration of praseodymium, samarium and yttrium in membrane phase in a hollow fiber membrane extractor. The variation of flow rate of source solution was carried out from 0 to 10 $\text{cm}^3 \text{min}^{-1}$. It was observed that as the flow rate increases from 0 to 8 $\text{cm}^3 \text{min}^{-1}$, the permeability of these metal ions increase and, above a flow rate of 8 $\text{cm}^3 \text{min}^{-1}$, a slight increase in permeability was observed (Fig. 4a).

In order to transport praseodymium, samarium and yttrium in membrane solution, it is essential to study the effect of flow rate of membrane solution on permeability. The effect of membrane phase flow rate on permeability was studied from 0 to 5 $\text{cm}^3 \text{min}^{-1}$ (Fig. 5a). It was observed that the permeability of these metal ions increases from 0 to 4 $\text{cm}^3 \text{min}^{-1}$. Above the flow rate 4 $\text{cm}^3 \text{min}^{-1}$, the permeability of these metal ions remain nearly the same.

Ion transport controlled by chemical species concentration in extraction process

The rate of extraction of metal ion with acidic extractant into membrane phase is assumed to fasten at interface of source and membrane phases. The dependency of ion transport of metal from

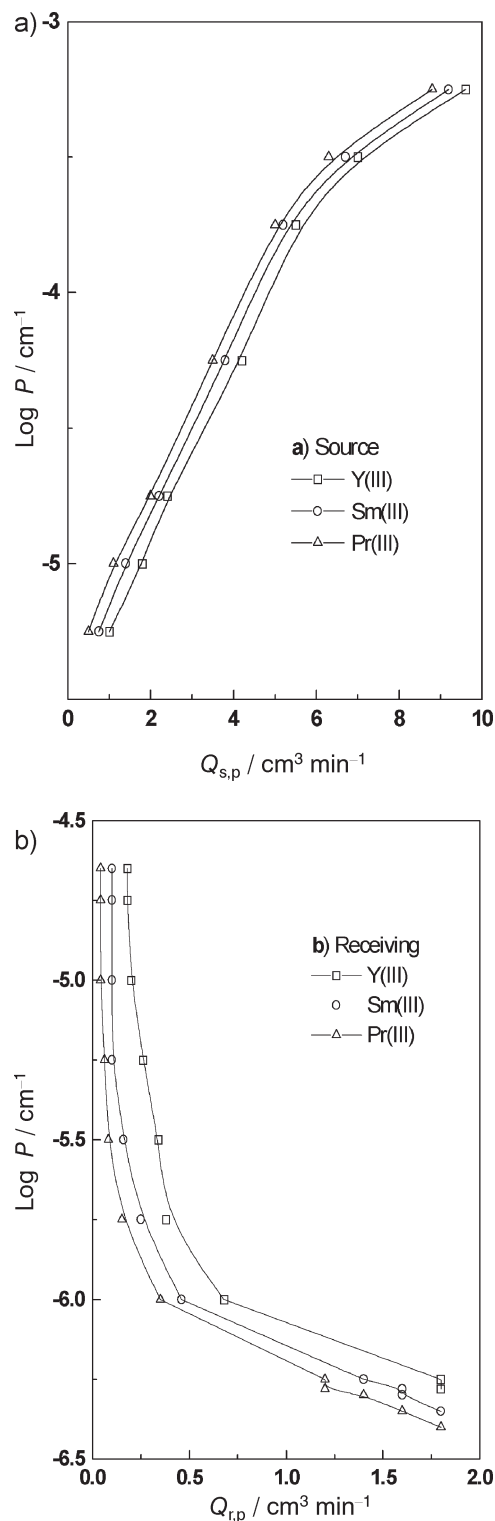


Fig. 4 – Effect of (a) source and (b) receiving phase flow rate on permeability of yttrium, samarium and praseodymium during the extraction and stripping processes, (a) Extraction, $[M(\text{III})] = 2 \times 10^{-4} \text{ mol dm}^{-3}$, $\text{pH } 6.5$, $[(\text{HL})_2]_{\text{m}} = 0.1 \text{ mol dm}^{-3}$, $Q_{\text{m}} = 1 \text{ cm}^3 \text{min}^{-1}$; (b) Stripping, $[\text{ML}_3 \cdot 3\text{HL}] = 4 \times 10^{-4} \text{ mol dm}^{-3}$, $c_{\text{HCl}} = 0.5 \text{ mol dm}^{-3}$, $Q_{\text{m}} = 1 \text{ cm}^3 \text{min}^{-1}$

source to membrane phase on chemical species concentration has been explained in the following sections.

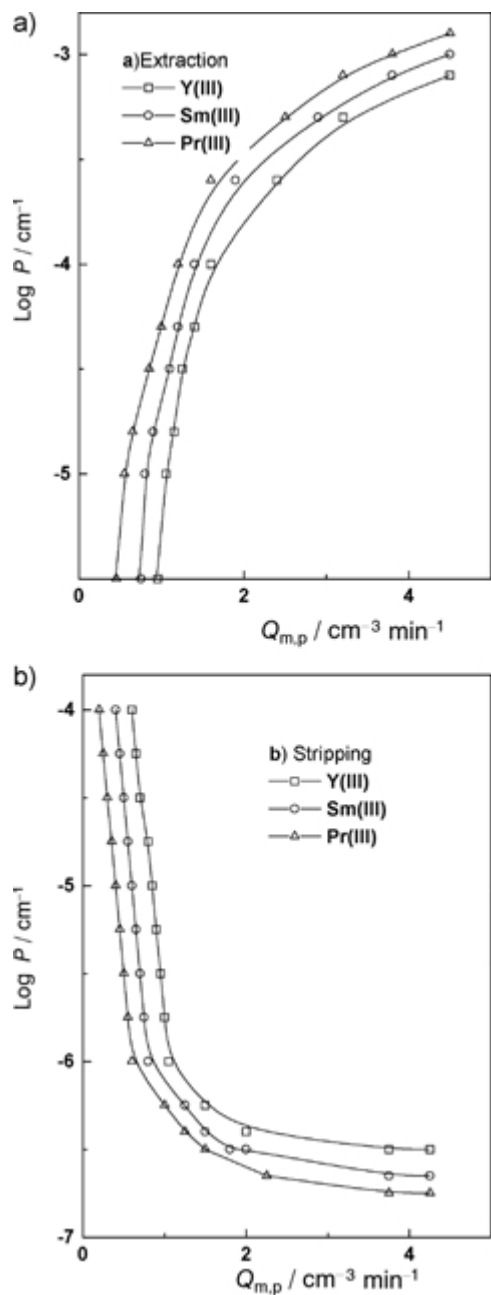


Fig. 5 – Effect of membrane phase flow rate on the permeability of yttrium, samarium and praseodymium during the extraction and stripping processes (a) extraction, $[M(III)] = 2 \times 10^{-4} \text{ mol dm}^{-3}$, pH 6.5, $[(HL)_2]_m = 0.01 \text{ mol dm}^{-3}$, $Q_s = 5 \text{ cm}^3 \text{ min}^{-1}$ (b) Stripping, $[ML_3 \cdot 3HL] = 4 \times 10^{-4} \text{ mol dm}^{-3}$, $c_{HCl} = 0.5 \text{ mol dm}^{-3}$, and $Q_r = 0.2 \text{ cm}^3 \text{ min}^{-1}$

Effect of the source solution pH on P in the extraction process

The pH of the source phase is one of the significant experimental variables during the exploration of membrane solvent extraction studies of praseodymium, samarium and yttrium with EHPNA as an extractant. Under the same flow rates Q_s and Q_m of both the source and membrane solutions respectively, the investigations on variation of pH of

source solution were carried out. The effect of source solution pH in the range 1–6.5 was studied. The dependency of permeability on the initial pH of source phase is shown in Figure 6a. It was observed that the permeability coefficient increases in the pH range 0–4. However, after pH 4, it remained unaffected. It indicates that complexation and transport of metal ion at the interface of the source and membrane solutions is favored by an increase in the pH of the source phase.

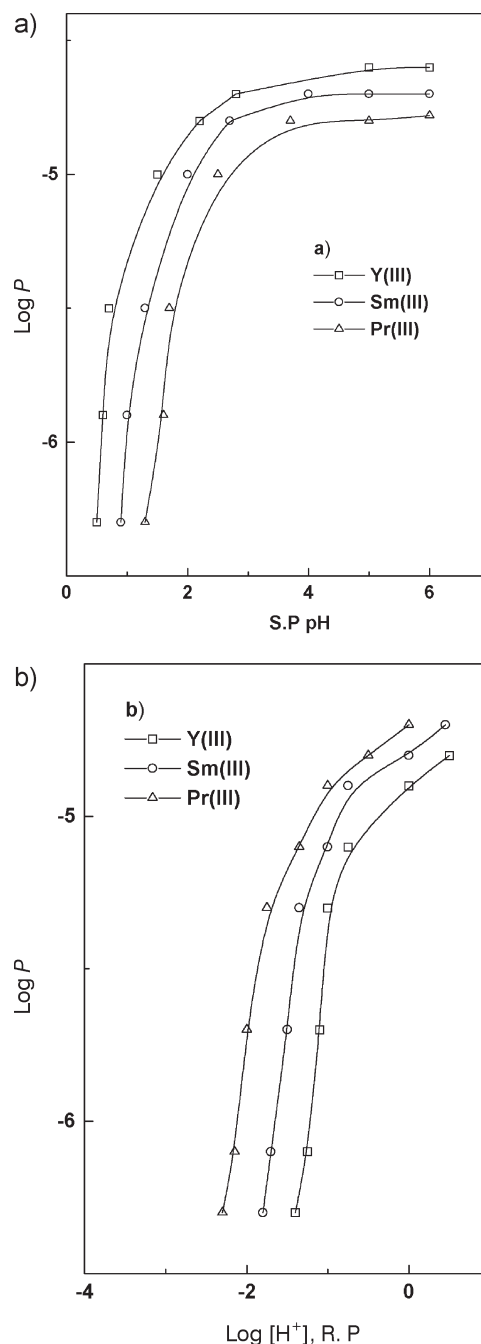


Fig. 6 – Effect of hydrogen ion concentration on the permeability of yttrium, samarium and praseodymium (a) extraction, $[M(III)] = 2 \times 10^{-4} \text{ mol dm}^{-3}$, $[(HL)_2]_m = 0.01 \text{ mol dm}^{-3}$ (b) stripping, $[ML_3 \cdot 3HL] = 4 \times 10^{-4} \text{ mol dm}^{-3}$, $Q_m = 4 \text{ cm}^3 \text{ min}^{-1}$, $Q_r = 4 \text{ cm}^3 \text{ min}^{-1}$

Effect of the carrier concentration on P in extraction process

The metal ion extractant plays an important role in the extraction process for achieving effective transport and economical utility. It is necessary to explore the effect of the extractant concentration on the permeability coefficient. The effect of the EHPNA concentration on the permeability has been studied over the range 10^{-4} to 1 mol dm^{-3} , the permeability coefficient increases along with an increase in the extractant concentration up to $10^{-2} \text{ mol dm}^{-3}$ for praseodymium, samarium and yttrium (Fig. 7a). However, above this concentration range the permeability remains the same.

Stripping process

The stripping of metal ion has been carried out in hollow fiber membrane using metal ion carrier complex, aqueous and membrane phases. Different involved experimental variables have been explained.

Diffusion controlled parameters in stripping process

The achievement of diffusion equilibrium in bulk solution is essential in order to precede, simultaneously, further chemical reactions at interfaces. The flow rates of membrane and receiving phases were varied.

Variation of metal ion concentration in stripping process with respect to time

The variation of metal ion concentration with respect to time for stripping process is shown in Fig. 3b. The p values have been calculated from the extent of metal ion transferred from membrane to receiving phase.

Effect of variation of flow rates of membrane and receiving phases on P in stripping process

It is essential to establish the diffusion equilibrium during the stripping process of praseodymium, samarium, and yttrium, in the hollow fiber membrane extractor. Therefore, the effect of receiving phases flow rate in order to achieve effective transportation and pre-concentration of metal ion from membrane to receiving phase has been investigated. The variation of flow rate of receiving phase was carried out from 0 to $2 \text{ cm}^3 \text{ min}^{-1}$ at constant flow rate of membrane phase. It was observed that as the flow rate of receiving phase increases, the permeability of stripping decreases until the flow rate reaches $0.5 \text{ cm}^3 \text{ min}^{-1}$. After $0.5 \text{ cm}^3 \text{ min}^{-1}$ of flow rate, it remains unaffected (Fig. 4b).

At constant flow rate of receiving phase, it is significant to study the effect of membrane phase

flow rate on the permeation of praseodymium, samarium and yttrium from membrane to receiving phase. The flow rate of enriched membrane phase was varied from 0 to $5 \text{ cm}^3 \text{ min}^{-1}$. It was observed that the stripping permeability decreases for the range of flow rate 0 to $2 \text{ cm}^3 \text{ min}^{-1}$. Above $2 \text{ cm}^3 \text{ min}^{-1}$ flow rate, it remains same (Fig 5b).

Ion transport controlled by chemical species concentration in stripping process

The rate of stripping of metal ion from membrane phase to receiving phase is assumed to fast at interface of these phases. The dependency of ion transport of metal from membrane to receiving phase on chemical species concentration has been explained in the following sections.

Effect of the hydrochloric acid concentration on P in stripping process

Under the constant flow rates Q_m and Q_r of membrane and receiving solutions, respectively, during the stripping process, the hydrochloric acid concentration in the receiving phase plays a significant role for the transportation of metal ion from membrane to receiving phase. The effect of hydrochloric acid concentration on permeability was carried out in the range 0.01 to 2.5 mol dm^{-3} (Fig. 6b). The permeability of stripping of metal ion increase with increase in hydrochloric acid concentration in the receiving phase in the studied range from 0.01 to 1 mol dm^{-3} . However, above 1 mol dm^{-3} hydrochloric acid concentration permeability is slightly affected.

Effect of the metal-EHPNA complex concentration on P in stripping process

The effect of variation of metal-EHPNA complex concentration in the range 10^{-5} to $10^{-1} \text{ mol dm}^{-3}$ on stripping permeability of metal ions from membrane to receiving phase was explored at constant pH of receiving phase. As the concentration of metal-EHPNA increases in the membrane phase until $10^{-2} \text{ mol dm}^{-3}$, the stripping permeability increases. However, above this range, it is slightly increased. Thus during the stripping process, the concentration of metal ion in the membrane phase decreases with the increase of free concentration of carrier. This process proceeds until it reaches equilibrium. The stripping permeability of metal ion is dependent on the metal-EHPNA complex concentration in the membrane phase (Fig. 7b).

Comparison of solvent and membrane solvent extraction methods

The separation factors for praseodymium, samarium and yttrium metals are determined by sol-

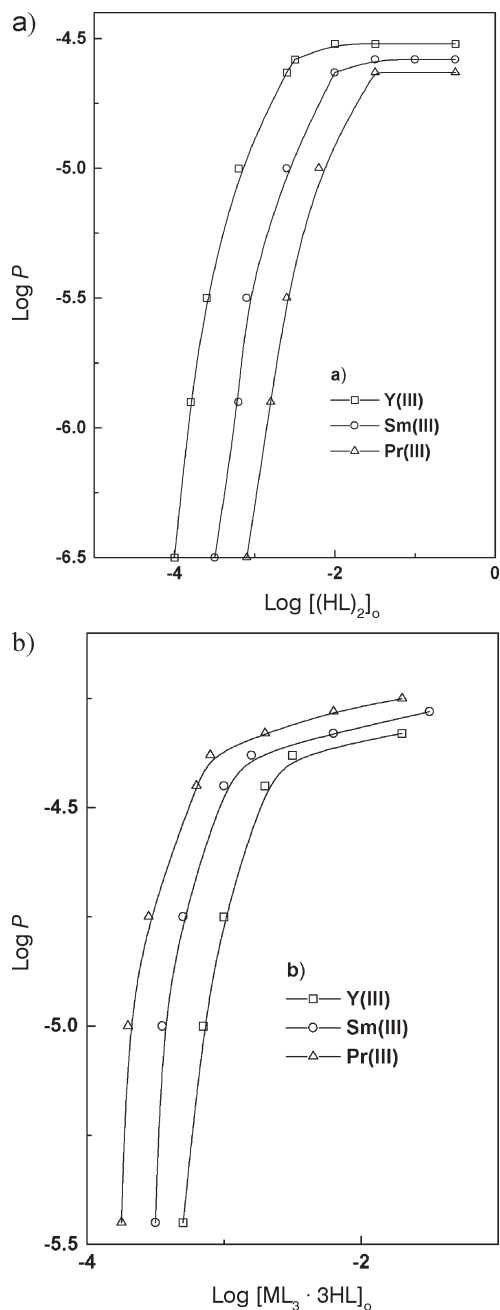


Fig. 7 – (a) Effect of extractant concentration on permeability of yttrium, samarium and praseodymium, $[M(III)] = 2 \times 10^{-4} \text{ mol dm}^{-3}$, $\text{pH } 6.5$, $Q_s = 4 \text{ cm}^3 \text{ min}^{-1}$ and $Q_m = 4 \text{ cm}^3 \text{ min}^{-1}$ (b) Effect of metal ion complex concentration on permeability of yttrium, samarium and praseodymium, $c_{\text{HCl}} = 0.5 \text{ mol dm}^{-3}$, $Q_m = 4 \text{ cm}^3 \text{ min}^{-1}$ and $Q_r = 4 \text{ cm}^3 \text{ min}^{-1}$

vent extraction method and are listed in Table 2. At the equilibrium condition, forward extraction and backward stripping rates are equal. The plot of $\log D-3\text{pH}$ vs. $\log [(HL)_2]_m$ is shown in Fig. 8. The determined values of extraction equilibrium constant are given in Table 2. The obtained data indicates the effective mutual separation of rare earths and it can be achieved by using number of stages with hollow-fiber extractor.

Table 2 – Equilibrium constants and separation factors (with respect to praseodymium) for samarium and yttrium

Metal	K_{ex}	α_D
Praseodymium	0.05	24 (Sm/Pr)
Samarium	1.0	133.4 (Y/Pr)
Yttrium	169	

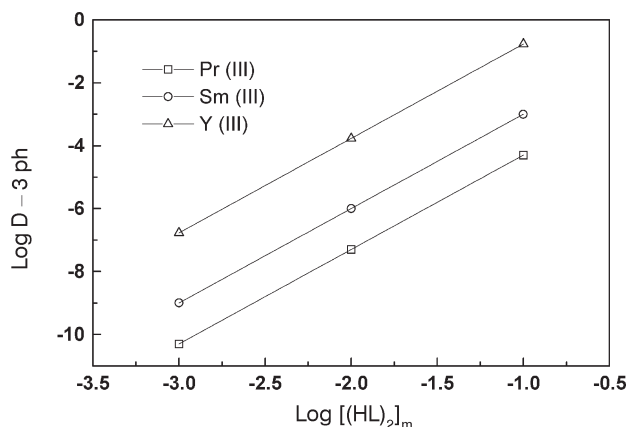


Fig. 8 – The plot of $\log D-3\text{pH}$ vs. $\log [(HL)_2]_m$ for praseodymium, samarium and yttrium

The pre-concentration of metal ion with membrane solvent extraction

After optimizing the experimental conditions, the combination of extraction and stripping processes were explored for the development of pre-concentration and removal of metal ion from the source solution.

The effect of variation of metal ion concentration in source solution was carried out from 10^{-7} to $10^{-2} \text{ mol dm}^{-3}$. The value of enrichment factor, EF, (metal concentration in receiving phase at 170 min / metal concentration in source phase at 170 min) was plotted against initial metal ion concentration in source solution (Fig. 9). When the initial metal ion content in the source solution exceeds $10^{-3} \text{ mol dm}^{-3}$, the EF is slightly affected. These results can be attributed towards the hindrance of metal ion transport due to the limited loading capacity of the carrier in the membrane phase. The EF value for the dilute solutions observed was considerably high in comparison to that of at the high concentration of metal ion. This indicates that hollow fiber membrane system can be successfully utilized to pre-concentrate dilute solutions with the uphill ion transport mechanism at the optimized conditions.

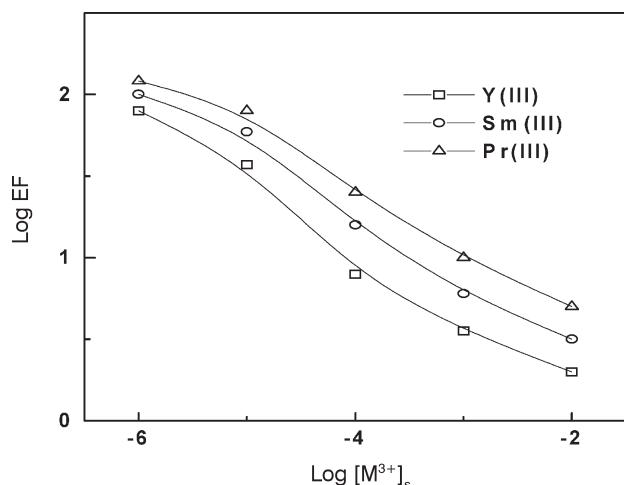


Fig. 9 – The relation between enrichment factor and initial metal ion concentration in the source phase for yttrium, samarium and praseodymium in the operation of extraction and stripping processes, $Q_s = 6 \text{ cm}^3 \text{ min}^{-1}$, $Q_m = 1 \text{ cm}^3 \text{ min}^{-1}$, $Q_r = 0.25 \text{ cm}^3 \text{ min}^{-1}$, $[(HL)_2]_m = 0.01 \text{ mol dm}^{-3}$, $\text{pH } 6.5$ and $c_{\text{HCl}} = 2 \text{ mol dm}^{-3}$

Conclusions

A kinetic study on the solvent extraction of some rare earth metals with EHPNA in xylene was carried out using a microporous hydrophobic hollow-fiber membrane extractor. The following significant points were observed. The interfacial reaction was composed of cation exchange and solvation reactions. Varying flow rates of source, membrane and receiving phases achieve the diffusion equilibrium in bulk and interfaces. Effect of concentration of chemical species on P has been observed. The separation factors and extraction equilibrium constants for praseodymium, samarium and yttrium have been determined.

Nomenclature

- A – Contact surface area, cm^2
 c – concentration, mol dm^{-3}
 E – extent of metal extracted for extraction
 E' – extent of metal extracted for stripping
 EF – enrichment factor
 HL – extractant or carrier
 J – ion transport flux of rare earth elements, $\text{mol cm}^{-2} \text{ s}^{-1}$
 K – distribution ratio of M^{3+}

- K_{ex} – extraction equilibrium constant
 M^{3+} – rare earth metal ion
 d_i – inner diameter of hollow fiber, cm
 P_e – permeability of extraction, cm s^{-1}
 P_s – permeability of stripping, cm s^{-1}
 Q – flow rate, $\text{cm}^3 \text{ min}^{-1}$
 V – volume, dm^3
 l – length of hollow fiber, cm
 α – separation factor

Subscripts

- a – association
b – backward extraction process
f – forward extraction process
m – membrane phase
p – phase
r – receiving phase
s – source phase
aq – aqueous solution
org – organic solution
ini – initial concentration

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