Pertraction of neodymium
M. Toure, G. Borda, D. Ode, J. Duhamet, S Pellet-Rostaing

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PERTRACTION OF NEODYMIUM

1,2 TOURE Moussa / 1G. BORDA ; 1D. ODE ; 1J. DUHAMET ; 2S. P-ROSTAING

1 CEA, DEN, DTEC, SGCS, F-30207 Bagnols-sur-Cèze, France
2 ICSM, UMR5257, LTSM, F-30207 Bagnols-sur-Cèze
Presence of rare earth elements (REE) in permanent magnets

<table>
<thead>
<tr>
<th>Elements</th>
<th>Nd</th>
<th>Dy</th>
<th>Pr</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>23-25</td>
<td>3.5-5</td>
<td>0.05-5</td>
</tr>
</tbody>
</table>

Others: Gd; Tb

Prakash and al. ERES2014

NdFeB
Volume = 0.22 cm³

AlNiCo 5-7
Volume = 14 cm³

Source: amold magnetics

Volume needed to generate a field of 1000 gauss from 5 mm of a pole of the magnet

The demand for Nd will rise by 700% over the next 25 years.

Some applications of permanent magnets (NdFeB):

- Phones
- Loud speakers
- Microphones
- Wind turbines
- Generators
Why rare earth’s recycling?

**Source:** Report on Critical Raw Materials for the EU (May 2014)

Targets: Ores and Waste Electrical and Electronic Equipment (WEEE)
Global potential of REE recycling from magnets

<table>
<thead>
<tr>
<th>REE application</th>
<th>Estimated REE stocks in 2020 (tons)</th>
<th>Estimated average lifetime (years)</th>
<th>Estimated REE old scrap in 2020 (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td>300,000.00</td>
<td>15</td>
<td>20,000.00</td>
</tr>
</tbody>
</table>

*Koen and al. JOCP 51(2013) 1-22*

Supply security; no thorium issues.
Solvent extraction (SX) for rare earth recycling

**Advantages of solvent extraction**
- Separation of compounds: with similar properties (REE; Ta-Nb),
- High purity of final products: REE (for optical and electronic products).

**Others processes after leaching**
- Selective precipitation/electrodeposition,
- Separation by ion exchange.

**Some of SX process equipments**: Pulsed column; Centrifugal extractors

**Mixer settlers**: principle

Transfer of interest solute from aqueous phase to the solvent by mixing and settling of two phases.

**Drawbacks related with conventional equipments**:
- Impossible to use very emulsive solvents:
  - which extends the time of settling,
- Density difference required for phases separation:
  - Using of diluent which can cause:
    - third phase formation (avoid by adding a modifier in some cases);
    - and a large volume of solvent in the process
- Pertraction avoids the settling step and offers the possibility to operate without diluent
Contents

Pertraction: principle - interface stabilisation – advantages/drawbacks

Solvent L for neodymium's extraction: selection criteria

Neodymium's extraction: mechanism

Neodymium's extraction: temperature effect

Recycle of REE: from magnets

Taylor Dispersion Analysis (TDA): for neodymium's diffusion coefficient determination in aqueous and solvent L phases

Neodymium's extraction by pertraction: experiments and mass transfer simulation

General conclusion
Pertraction: principle

Solvent wets the hydrophobic membrane pores

Interface solvent – aqueous phase takes place at the pore mouth of the membrane

Mass transfer is governed by:
  - Solute diffusion
  - $\Delta C$ as driving force
Pertraction: solvent – aqueous interface stabilisation

Critical pressure

For maintain interface immobilized at pore mouth of the membrane:

\[(P_{aq} - P_{org}) < \Delta P_c\]

\[\Delta P_c = (P_{aq} - P_{org}) = \frac{2\sigma \cos \theta}{R}\]

\(\sigma\) interfacial tension; \(\theta\) wetting angle; \(R\) pores radius
Pertraction: solvent – aqueous interface stabilisation

By hydrostatic pressure

With low pressure drop related to fluid flow ~75.92 x 10^{-5} bar

\[ P_i = \rho_i \times g \times h_i \]

\[ \Delta P = (P_{\text{aq}} - P_{\text{org}}) \]

\[ i = \text{aq or org} \]
Pertraction : advantages / drawbacks

**advantages**

- Possibility to use incompatible phases systems with conventional equipments:
  - Using very emulsive solvents
  - Operating without diluent
  - No density difference is requered

- Settling step is avoid
- Simple implementation
- Scale up without major difficulty

**Drawbacks**

- Reduction of mass transfer related to the presence of the membrane
- Fouling problems of the membrane
Solvent for neodymium’s extraction: selection criteria

**Selectivity**

**Distribution coefficient** ($K_D$)

$$K_D = \frac{[C]_{\text{org}}}{[C]_{\text{aq}}}$$

**Separation Factor** ($SF_{M1/M2}$)

$$SF_{M1/M2} = \frac{K_D(M1)}{K_D(M2)}$$

**Back-extraction; solvent: solubility, flash point and cost.**

**Viscosity**

As low as possible for minimize pressure drop and enhance mass transfer at aqueous and organic interface:

Fick’s first law

$$J = -D \nabla c$$

Stokes-Einstein

$$D = \frac{k_B T}{R_h 6 \pi \eta}$$

- $k_B$: Boltzmann constant
- $\eta$: viscosity of solvent
- $R_h$: hydrodynamic radius of solvent complexes

**Conditions:**
- Batch process at $T(°C)$, Time, O/A

Diagram:
- org: organic phase
- aq: aqueous phase
- M1: component (extractant)
- M2: component (neutralizer)
Neodymium’s extraction: mechanism

The main mechanisms for neodymium extraction

\[ M_{aq}^{m+} + m\text{HL} \rightleftharpoons ML_n + mH_{aq}^{+} \]

By ion exchange

\[ M_{aq}^{m+} + mA_{aq}^- + nL \rightleftharpoons ML_n A_m \]

By solvation

Marcus and al. have described the four mechanisms in solvent extraction:
« Ion Exchange and Solvent Extraction of Metal Complexes, Wiley-Interscience, 1969 »
Neodymium’s extraction: mechanism

\[ \text{Nd}^{3+} + 3\text{NO}_3^- + n\text{L}_{\text{free}} \leftrightarrow \text{NdL}_n(\text{NO}_3)_3 \]

Law of mass action

\[ K_{\text{ex}}^{\text{app}} \frac{[\text{NdL}_n(\text{NO}_3)_3]}{[\text{Nd}^{3+}].[\text{NO}_3]^3.[\text{L}]_n^{\text{free}}} = \frac{K_D}{[\text{NO}_3]^3.[\text{L}]_n^{\text{free}}} \]

Slope analysis technique

\[ \log K_D = n \log [\text{L}]_n^{\text{free}} + 3 \log [\text{NO}_3] + \log K_{\text{ex}}^{\text{app}} \]

\[ y = A \times x + B \]

Experimental conditions

\[ [\text{HNO}_3] = 0.1 \text{ M} ; [\text{NaNO}_3] = 2.5 \text{ M} ; [\text{Nd}] = 6.1 \times 10^{-3} \text{ M} ; A/O = 1 ; T = 20-22^{\circ}\text{C} \]

\[ \log (K_D) = f(\log [\text{L}]_n^{\text{free}}) \]
Neodymium’s extraction:

Neodymium’s extraction equilibrium:

\[ \text{Nd}^{3+} + 3\text{NO}_3^- + 3\text{L} \leftrightarrow \text{NdL}_3\left(\text{NO}_3\right)_3 \]

Confirm by mass spectroscopy (ESI-MS)

ESI-MS: Mass Spectroscopy by Electrospray Ionization

Graph:

- \( \log K_D \) vs. \( \log \left[ \text{L}_{\text{free}} \right] \text{mol.L}^{-1} \)
- Equation: \( Y = 2.9 \pm 0.1X - 0.77 \pm 0.06 \)
- \( R^2 = 0.99622 \)
Neodymium’s extraction: temperature effect

Experimental conditions
\([\text{HNO}_3] = 0.1 \, \text{M} ; \,[\text{NaNO}_3] = 2.5 \, \text{M} ; \,[\text{Nd}] = 6.10^{-3} \, \text{M} ; \, \text{A/O}=1\)

\[K_D = f(T^\circ \text{C})\]

Exothermic extraction with \(K_D \in [14 - 5]\)
Neodymium’s extraction: temperature effect

Law of mass action

\[ K_{ex}^{app} = \frac{K_D}{[NO_3]^3 \cdot [L]^3} \]

\[ \Rightarrow \ln K_{ex}^{app} = \frac{-\Delta H_{ext}^0}{R} \times \frac{1}{T} + \frac{\Delta S_{ext}^0}{R} + 3\ln[NO_3] + 3\ln[L] \]

\[
\begin{array}{c|c|c|c}
1/T (K^{-1}) & Ln(K_{ex}^{app}) & \\
\hline
3.00x10^{-3} & 1.4 & \\
3.15x10^{-3} & 1.6 & \\
3.30x10^{-3} & 1.8 & \\
\end{array}
\]

\[ Y = 2752 \pm 12 X - 6.59 \pm 0.04 \]

\[ R^2 = 0.99997 \]

\[ \Delta H_{ext}^0 = -22.9 \text{ kJ.mol}^{-1} \]
Recycle of REE

Experimental conditions

\[ [\text{HNO}_3] = 0.1 \text{ M} ; \ [\text{NaNO}_3] = [0.5 \text{ - } 3] \text{ M} ; \ A/O=1 \]

<table>
<thead>
<tr>
<th>Elements /g.L(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd</td>
</tr>
<tr>
<td>0.3</td>
</tr>
</tbody>
</table>

waste model of magnets
NO$_3^-$ favors extraction of Nd, Pr, Dy and Fe
Solvent L extracts significantly Nd, Pr, Dy with $K_D$ ∈ [7 – 12]
Fe is the main impurity with $K_D < 2.5$
Recycle of REE
Separation factors *versus* [NaNO$_3$]

<table>
<thead>
<tr>
<th>[NaNO$_3$] / mol.L$^{-1}$</th>
<th>3</th>
<th>[NaNO$_3$] / mol.L$^{-1}$</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF Nd/Fe</td>
<td>5.44</td>
<td>SF Nd/Pr</td>
<td>1.039</td>
</tr>
<tr>
<td>SF Nd/Ni</td>
<td>116.037</td>
<td>SF Nd/Dy</td>
<td>2.17</td>
</tr>
<tr>
<td>SF Nd/Co</td>
<td>154.03</td>
<td>SF Pr/Dy</td>
<td>2.088</td>
</tr>
<tr>
<td>SF Nd/B</td>
<td>30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

>Selective extraction of REE at NaNO$_3$ (3M) and possibility to separate them each other at NaNO$_3$ (0.5M)

REE back-extraction can be made at low acidity.
Recycle of REE

Scheme of process

Co-extraction of REE

HNO₃ + NaNO₃

Aqueous phase (Nd, Pr, Dy, Fe, Co, Ni, B)

Effluents (Fe, Co, Ni, B, NO₃⁻)

Back-extraction REE

Distilled water

Dy₂O₃

Pr₂O₃

Nd₂O₃

Calcination

Solvent traitement

Liquid-liquid extraction equipment with required stages
Taylor Dispersion Analysis (TDA) : for neodymium’s diffusion coefficient determination in aqueous and solvent L phases

*solvent L name is not mentioned here for confidential aspect*

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Collaboration with 3J. CHAMIEH ; 3H. COTTET

1 CEA, DEN, DTEC, SGCS, F-30207 Bagnols-sur-Cèze, France
2 ICSM, UMR5257, LTSM, F-30207 Bagnols-sur-Cèze
3 IBMM, UMR 5247-UM2, DSBC, place Eugène Bataillon CC 017, 34095 Montpellier Cedex 5, France
Taylor Dispersion Analysis (TDA)

Capillary electrophoresis (CE) for TDA

Theory

Taylor – Aris – Golay equation

\[ H = \frac{2D}{u} + \frac{R_c^2 u}{24D} \]

Axial diffusion

\[ H = \frac{l_D \sigma^2}{t_R^2} \]

H : Plate height
\( t_D \) : average elution time
\( \sigma^2 \) : Variance of the elution profile
U : linear velocity
R_c : capillary radius
ID : capillary Length to the detector

Reduced to:

\[ D = \frac{R_c^2}{24\sigma^2 t_R} \]

Validity:

Satisfied if:
\[ \frac{Dt_R}{R_c^2} \geq 1.25 \]

Satisfied if:
\[ Pe = \frac{R_c u}{D} \geq 40 \]

Taylor Dispersion

\[ u(r) \]

Poiseuille flow

Molecular diffusion

Convection + Molecular diffusion

Capillary

Buffer+solute

Buffer

Polyimide coating

Capillary e = 400 \( \mu \)m

100 \( \mu \)m

UV cell

C^4D cell

Pump

PC

P= mbar
Taylor Dispersion Analysis (TDA)

Capillary electrophoresis (CE) for TDA

Theory

Taylor – Aris –Golay equation

\[ H = \frac{2D}{u} + \frac{R_c^2 u}{24D} \]

Axial diffusion

\[ H = \frac{I_D \sigma^2}{t_R^2} \]

\( H \): Plate height
\( t_\text{D} \): average elution time
\( \sigma^2 \): Variance of the elution profile
\( u \): linear velocity
\( R_c \): capillary radius
\( I_D \): capillary length to the detector

Reduced to:

\[ D = \frac{R_c^2}{24\sigma^2} t_R \]

Validity:

Satisfied if:

\[ \frac{D t_R}{R_c^2} \geq 1.25 \]

Satisfied if:

\[ Pe = \frac{R_c u}{D} \geq 40 \]
Taylor Dispersion Analysis (TDA)

Capillary electrophoresis (CE) for TDA

Theory

Taylor – Aris –Golay equation

\[ H = \frac{2D}{u} + \frac{R_c^2 u}{24D} \]

Axial diffusion

\[ H = \frac{I_D \sigma^2}{t_R^2} \]

\( H \): Plate height
\( t_D \): average elution time
\( \sigma^2 \): Variance of the elution profile
\( u \): linear velocity
\( R_c \): capillary radius
\( I_D \): capillary length to the detector

Reduced to:

\[ D = \frac{R_c^2}{24\sigma^2} t_R \]

In practice, D is calculated by fitting the experimental profile with a Gauss error function for determine \( \sigma \) and \( t_R \):

\[ \frac{C}{C_0} = \frac{1}{2} \pm \frac{1}{2} \text{erf} \left[ \frac{(t - t_R)}{\sigma \sqrt{2}} \right] \]
Taylor Dispersion Analysis (TDA)

Capillary electrophoresis (CE) for TDA

Theory

Taylor – Aris –Golay equation

\[ H = \frac{2D}{u} + \frac{R_c^2 u}{24D} \]

Axial diffusion

\[ H = \frac{t_D \sigma^2}{2t_R^2} \]

\( H \) : Plate height
\( t_D \) : average elution time
\( \sigma^2 \) : Variance of the elution profile
\( u \) : linear velocity
\( R_c \) : capillary radius
\( t_R \) : Length to the detector

Reduced to:

\[ D = \frac{R_c^2}{24\sigma^2 t_R} \]

Validity:

Satisfied if:

\[ \frac{Dt_R}{R_c^2} \geq 1.25 \]

Satisfied if:

\[ Pe = \frac{R_c u}{D} \geq 40 \]

Advantages of TDA

Simple ;
Fast ;
Low sample volume (0.7 nL) ;
Taylor Dispersion Analysis (TDA)

Neodymium's diffusion coefficient in aqueous phase

Validity

\[ Pe \in [255 - 276] \geq 40 \]
\[ \tau \in [66.2 - 71.9] > 1.25 \]
Taylor Dispersion Analysis (TDA)

Neodymium’s diffusion coefficient in aqueous phase

\[ D_{\text{Nd}} \in [5.99 - 5.52] \times 10^{-10} \text{ m}^2\text{.s}^{-1} \]

with RSD < 3%

Same order of magnitude as the one calculated with Nernst–Einstein equation

\[ D_0 = 6.16 \times 10^{-10} \text{m}^2\text{.s}^{-1} \] (with conductivity of Nd \( \sigma = 69.4 \mu\text{S}\text{.cm}^{-1} \))
Taylor Dispersion Analysis (TDA)

Neodymium’s diffusion coefficient in solvent L phase

Validity

Pe = 1910 ≥ 40
τ = 9.58 ≥ 1.25
Taylor Dispersion Analysis (TDA)
Neodymium’s diffusion coefficient in solvent L phase

at 1 g.L⁻¹ with UV-Vis and C⁴D detectors

<table>
<thead>
<tr>
<th>D / 10⁻¹⁰ m².s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>C⁴D</td>
</tr>
<tr>
<td>1.33</td>
</tr>
</tbody>
</table>

with UV-Vis detector

<table>
<thead>
<tr>
<th>[Nd] / g.L⁻¹</th>
<th>D / 10⁻¹⁰ m².s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td>8</td>
<td>0.88</td>
</tr>
<tr>
<td>21</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Neodymium’s extraction by pertraction

with solvent L which name is not mentioned here for confidential aspect
## Pertraction : experimental module

Hollow fiber : hydrophobic polypropylene membrane

<table>
<thead>
<tr>
<th>property</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (L)</td>
<td>0.25</td>
<td>m</td>
</tr>
<tr>
<td>Internal radius ($R_{int}$)</td>
<td>$0.9 \times 10^{-3}$</td>
<td>m</td>
</tr>
<tr>
<td>Thickness (e)</td>
<td>$0.4 \times 10^{-3}$</td>
<td>m</td>
</tr>
<tr>
<td>Tortuosity ($\tau$)</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Volume</td>
<td>$0.635 \times 10^{-6}$</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Interfacial area</td>
<td>$1.148 \times 10^{-3}$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Interfacial volumic area</td>
<td>230</td>
<td>m$^2$.m$^{-3}$</td>
</tr>
<tr>
<td>Porosity ($\varepsilon$)</td>
<td>80</td>
<td>%</td>
</tr>
<tr>
<td>Pore radius ($R_p$)</td>
<td>100</td>
<td>nm</td>
</tr>
</tbody>
</table>

From Alting (France)
## Pertraction: experimental module

Glass potting around the fiber

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length ( (L_p) )</td>
<td>0.26</td>
<td>m</td>
</tr>
<tr>
<td>Internal radius ( (R_{intp}) )</td>
<td>2.5 ( \times 10^{-3} )</td>
<td>m</td>
</tr>
<tr>
<td>Volume</td>
<td>4.984 ( \times 10^{-6} )</td>
<td>m(^3)</td>
</tr>
</tbody>
</table>

Low interfaciale volumic area 230 m\(^2\).m\(^{-3}\)
Pertraction: experimental set-up

Co-current contact – recycle mode

**Diagram:**
- **Solvent Reservoir**
- **Charge Reservoir**
- **Pressure gauge**
- **Teflon tube** $\Phi_{\text{int}} = 0.3 \text{ mm}$
- **Peristaltic pump**
- **Rotary piston pump**
- **Hollow fiber module**
Pertraction: experimental conditions

Hollow fiber module

ΔP = 0.07 bar

Reynolds number and pressure drop

<table>
<thead>
<tr>
<th></th>
<th>Reynolds number</th>
<th>Pressure drop (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>aqueous</td>
<td>solvent</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>75.92x10^{-5}</td>
<td>0.029x10^{-5}</td>
</tr>
</tbody>
</table>

Charge: HNO₃ + NaNO₃ + Nd
Vol = 22 mL

Solvent (L)
Volume = 20.7 mL

40 mL.h⁻¹
Pertraction: experimental conditions

Hollow fiber module

ΔP = 0.07 bar

Residence time

<table>
<thead>
<tr>
<th>Residence time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqueous Reservoir</td>
</tr>
<tr>
<td>33.02</td>
</tr>
<tr>
<td>fibre</td>
</tr>
<tr>
<td>0.95</td>
</tr>
</tbody>
</table>

Equilibrium reaction

\[ \text{Nd}^{3+} + 3\text{NO}_3^- + 3\text{L} \rightleftharpoons \text{NdL}_3(\text{NO}_3)_3 \]

Sample (200 µL) at regular time intervals

Charge: HNO₃ + NaNO₃ + Nd
Vol = 22 mL

40 mL h⁻¹

Solvent (L)
Volume = 20.7 mL
Pertraction : experimental results

Aqueous samples are analysed by ICP-OES to estimate the concentration of Nd ions. Their concentration in solvent L phase is determined by mass balance described below:

\[ V_{aq} \cdot X_e + V_{org} \cdot Y_e = V_{org} \cdot Y_1 + V_{aq} \cdot X_1 \]

\[ V_{aq} \cdot X_e - \sum V_{pe} \cdot X_{n-1} = V_{org} \cdot Y_n + [V_{aq} - (n-1) \cdot V_{pe}] \cdot X_n \]

V: volume of phases (mL), org (solvent L) and aq (aqueous);
V_{pe}: volume of each aliquot (mL);
X: concentration of Nd ions in aqueous phase (g.L^{-1}), inlet (e) and n for the others aliquots;
Y: concentration of Nd ions in solvent L phase (g.L^{-1}), inlet (e) and n for the others aliquots.
Pertraction : experimental results

Nd concentration profile in aqueous and organic phases versus time :

Equilibrium is reached after 2500 minutes (42h) with $K_D$ (Nd) = 16,1±0,1
Pertraction : mass transfer simulation

Continuity equation:
\[
\frac{\partial C_i}{\partial t} + \nabla \cdot (- D_i \nabla C_i + C_i V_i) = 0
\]

Assumptions:
Uniform pore size and fiber porosity throughout the fiber length
Pertraction: mass transfer simulation

**Continuity equation:**

\[ \frac{\partial C_i}{\partial t} + \nabla \cdot ( - D_i \nabla C_i + C_i V_i ) = 0 \]

**Assumptions:**

- Uniform pore size and fiber porosity throughout the fiber length
- Laminar flow with parabolic velocity profile in two phases in the contactor
- Solute is transported by diffusion and convection in the two phases:

\[ \frac{\partial C_i}{\partial t} + \nabla \cdot ( - D_i \nabla C_i + C_i V_i ) = 0 \]

Diffusion is the only transport mechanism in the membrane:

\[ \frac{\partial C_i}{\partial t} + \nabla \cdot ( - D_i \nabla C_i ) = 0 \]
Complexing reaction occurs at the interface aqueous-membrane

\[ \text{Nd}^{3+} + 3\text{NO}_3^- + 3\text{L} \leftrightarrow \text{NdL}_3(\text{NO}_3)_3 \]

This chemical reaction is defined by a kinetic with flux expression:

\[ \phi (\text{mol.m}^{-2}.\text{s}^{-1}) = k_v \cdot \left( \left[ \text{Nd}^{3+} \right]_{\text{aq}} - \left( \frac{[\text{NdL}_3(\text{NO}_3)_3]}{K_{\text{ex}} \cdot [\text{NO}_3]_\text{aq}^3 \cdot [\text{L}]^3} \right) \right) = \frac{\partial [\text{Nd}^{3+}]_{\text{aq}}}{\partial r} \bigg|_{r=r_{\text{int}}} \]

The model is solved by scilab 5.5.1 and is just optimised by one parameter \( k_v \) (m.s\(^{-1}\)) for best fitting experimental results.
Pertraction: mass transfer simulation

Simulation and prediction of Nd concentration in aqueous and solvent L phases

Input parameters

<table>
<thead>
<tr>
<th>Geometric characteristics</th>
<th>Process variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{int}$</td>
<td>$0.9 \times 10^{-3}$ m</td>
</tr>
<tr>
<td>$R_{intp}$</td>
<td>$2.5 \times 10^{-3}$ m</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>$0.4 \times 10^{-3}$ m</td>
</tr>
<tr>
<td>$L$</td>
<td>$0.25$ m</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>$80$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$2$</td>
</tr>
</tbody>
</table>

Neodymium’s diffusion coefficient in solvent L and aqueous phases is determined experimentally by TDA.
Simulation results were in good agreement with the experimental data for a value of $k_v = 5.10^{-7}$ m.s$^{-1}$ which validated the model assumptions. This value of $k_v$ is maintained for predict the influence of geometric characteristics and process variables.
General conclusion

Possibility to use solvent L to selectively extract REE and separate them each other from magnets waste in nitric media;

Neodymium’s extraction mechanism:

\[ \text{Nd}^{3+} + 3\text{NO}_3^- + 3L \rightleftharpoons \text{NdL}_3(\text{NO}_3)_3 \]

Exothermic reaction with \( \Delta H_{\text{ext}}^0 = -22.9 \text{ kJ.mol}^{-1} \)

Taylor Dispersion analysis for determine Nd diffusion coefficient in aqueous and organic phases with RSD \( \leq 3\% \) : simple method fast and few sample volume needed (0,7 nL);

Installation and implementation of pertraction module for Nd extraction with hydrophobic polypropylene membrane which has low interfacial volumic area 230 m\(^2\).m\(^{-3}\);

Mass transfer simulation results were in good agreement with the experimental data for a value of \( k_v = 5.10^{-7} \text{ m.s}^{-1} \) which validated the model assumptions. The value of optimise \( k_v \) is maintained for predict the influence of geometric characteristics and process variables.

Experimental determination of \( k_v \) by Rotative Membrane Cell (RSD) method
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