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Evaluation of mass transfer for metal removal via a liquid membrane-based process in a hollow-fiber membrane contactor

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ABSTRACT

The extraction of metals using membrane-based solvent extraction processes offers many advantages over conventional technology. Hollow-fiber contactors have demonstrated great potential in large-scale application of this concept in extracting and recovering dissolved metals. In this process, the metal is extracted from an aqueous solution to an organic solvent through the walls of porous fibers. The organic solution can be composed of a diluent alone or a carrier dissolved in a diluent. The overall mass transfer of the extracted component is an important parameter that will provide guidelines in designing such a process. The value of the overall mass transfer coefficient can be calculated using correlation and analysis of the experimental data. In this work, a simplified equation is derived and is applied to the extraction of metals using liquid membranes in a hollow-fiber contactor. The analysis was conducted on the experimental data of (i) extraction of boron from groundwater using sunflower-based liquid membrane and (ii) extraction of zinc using a kerosene-based liquid membrane (literature data). The values of the overall mass transfer coefficient determined from the simplified equation are smaller, compared to those calculated from the mass transfer correlations in the literature.

Keywords: Metal extraction; Mass transfer coefficient; Sunflower oil; Groundwater; Hollow-fiber contactor

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1. Introduction

Metals are widely distributed in seawater, groundwater, and wastewaters from various chemical industries. For example boron exists in the form of boric acid B(OH)$_3$ or borate ion B(OH)$^{-4}$ and its concentration in seawater is around 4.5 ppm [1] and requires removal in high percentage to make the treated water suitable for agriculture. World Health Organization (WHO) recommends the value of boron concentration in drinking water to be below 0.5 ppm and for irrigation should not exceed 0.2 ppm [1]. Boron has harmful effects on human health depending on the exposure time and frequency [2]. Consequently, the boron removal is very important to be within the recommended limit. The recovery of boron is expected to create additional sources of this raw material for the production of boric oxide that has used in the industry such as ceramics, glass, enamels, cosmetics, textiles, paint wood processing, detergents and insecticides [1].

The other metal, zinc is widely used in industries such as galvanization, paint, batteries, smelting, fertilizers and pesticides, fossil fuel combustion, pigment, polymer stabilizers, and the wastewaters from these industries are polluted with zinc [3]. Zinc-polluted waters, in many cases are discharged to rivers and cause deposition of zinc-polluted sludge on their banks, which can increase the acidity

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of waters and are considered harmful to fish and aquatic animals [4]. The maximum limit for zinc concentration in wastewater at the point of discharge into the sea is 0.5 mg/L [5].

For removal of boron and other metal ions, the methods such as precipitation–coagulation, ion exchange resins, solvent extraction, electrodialysis, reverse osmosis (RO), and hybrid of any of these techniques [6–12] are available. The processes based on RO have been studied by a number of researchers [13–16]. The processes are effective but suffer from the disadvantage of removing the other ions (potassium, calcium, and magnesium) in significant proportions. These ions are considered essential for drinking and irrigation waters and are to be added in sufficient amounts at the end of the treatment. The other methods have the disadvantages that include the production of concentrated waste, uneconomic at low wastewater concentrations, difficulties in scaling up, and not adaptable to continuous processing options. Liquid–liquid extraction method, especially in combination with membrane separation processes, has shown to be more efficient and economical by overcoming some of the above-mentioned disadvantages [17–20].

The processes based on liquid–liquid extraction, especially reactive extraction using ionic or non-ionic molecules as carriers, have shown some success in selective removal of metals [17,21]. The reactive extraction systems offer advantages over conventional techniques because of their selectivity, efficiency, compatibility with commercially available modules, and production of minimal wastes. In most cases of metal ion removal, the solvent or diluent used was of hydrocarbon-based, for example, hexane, kerosene, toluene), halogenated organics (chloroform, dichloromethane) and alcohols (2-octanol, *n*-amyl alcohol [3–5,19,20]. Most of these solvents work effectively in small-scale processes, but they are unsuitable due to the impact on the environment, health, and safety point of view in the industrial operations. Therefore, research continues to examine reactive extraction-based membrane processes with sustainable solvent and operator-friendly characteristics, and compatibility to the commercially available equipment.

The reactive extraction processes require a "carrier" in the solvent phase. Neutral polyolic compounds such as 1,3-diols have been successfully tested [21–24]. They form neutral 1:1 complexes at neutral pH because with boron/boric acid as it exists as undissociated form and reacts with 1,3-diols. The reaction is reversible [Eq. (1)] and allows its re-extraction in alkaline pH where the predominant ion is charged [21].

$$H_3BO_3 + PD \leftrightarrow H_3BO_3 - PD \tag{1}$$

Recently, a feasibility study is reported [25] on the recovery of metal ions from a simulated effluent using Alamine 336 in refined palm oil. The results are encouraging and applicable to wastewaters at acidic pH. Therefore, in this study, a system with a diol in sunflower oil is tested at near-neutral pH (6.8 pH) that exists in many natural water and wastewater [26].

The study plan includes the following stages:

- Examine the effectiveness of sunflower oil in the extraction of boron in a hollow-fiber membrane contactor.
- Apply an approximate equation for simplified diffusion and extraction to determine the overall mass transfer coefficient in the membrane contactor.
- Apply the simplified equation to determine the overall mass transfer coefficient from the experimental data of other metal (reported in the literature).

2. Mathematical model of the process

A recycling mode operation is considered in the membrane contactor process. In this mode of operation, the feed and the organic solutions are recirculated through the fiber side and shell side of the module, respectively (Fig. 1). The extraction of solute (boron or any other metal) from the aqueous phase to the organic phase (solvent and carrier) occurs through diffusion to the membrane pores, the reaction in the solvent phase, and diffusion back to the outer shell. A schematic diagram representing the steps of the diffusion-extraction process in a pore of the contactor is shown in Fig. 2. The mathematical model for the process is formulated by considering the following assumptions [27]:

- Isothermal process and quasi-steady-state exist in the process.
- Volumes of the feed and the extraction solutions are large compared to that of the volume inside the hollow-fibers of the membrane contactor.
- Plug flow pattern for the fluids in the contactor.
- Solutions are considered to be at the perfect mixing mode and recycled.

The mathematical model consists of two main equations describing (i) the change in metal concentration in the contactor and (ii) the change in metal concentration in the feed reservoir. The model equations are presented below:

Mass balance in the hollow-fiber contactor:

$$u_f \left(\frac{V}{A}\right)_{\text{in}} \frac{\partial C_{\text{Mc}}}{\partial Z} = K_{\text{of}} \left(\frac{1}{L}\right) \left(C_{\text{Mc}} + \frac{C_{\text{MO}}}{D_E}\right) \tag{2}$$

Mass balance in the reservoir:

$$\frac{dC_{\text{Mt}}}{dt} = \frac{q_f}{v} \left(C_{\text{Mc}}\big|_{z=L} - C_{\text{Mc}}\big|_{z=0}\right) \tag{3}$$

where $(V/A)_{\text{in}}$ is the ratio of the volume to the inner area of mass transfer in the fibers, L is the length of the fiber, u_f is the linear velocity, q_f is the feed flow rate and v^t is the tank volume, C_M is the concentration of metal in the solution. The superscripts c and t refer to the membrane contactor and tank, respectively.

The apparent distribution constant, D_E, is defined as the ratio of the concentration of solute in the organic phase over that in the aqueous phase at equilibrium and can be described by the following expression:

$$D_E = \frac{C_M(\text{org})}{C_M(\text{aq})} \tag{4}$$

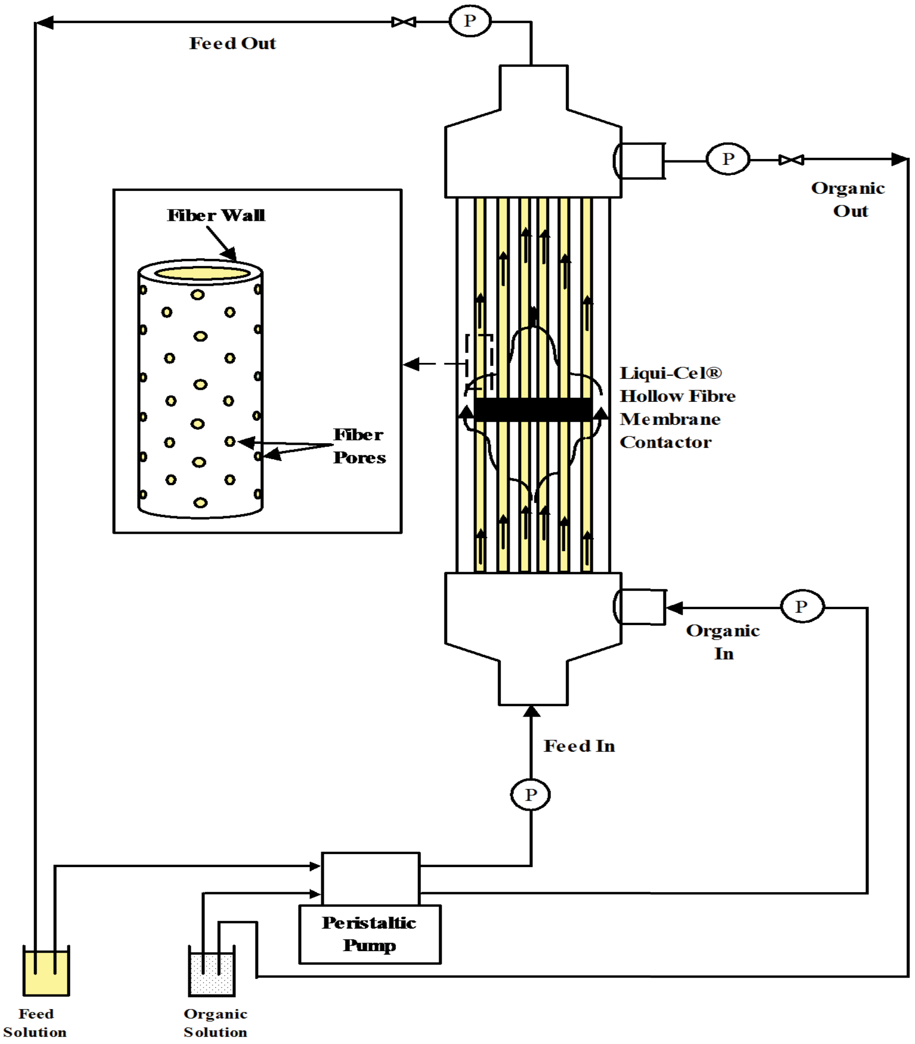

Fig. 1. A schematic diagram of the experimental set-up for the hollow-fiber membrane contactor.

Assuming a slow rate of change of concentration, Eq. (2) can be simplified and integrated to:

$$\mathrm{Ln}\left\{\frac{C_{\mathrm{Mi}}}{\left(1+1/D_E\right)C_{\mathrm{Mt}}-\dfrac{C_{\mathrm{Mi}}}{D_E}}\right\}=\frac{q}{v}\left\{1-\exp\left(-BK_{\mathrm{of}}\right)\right\}t \tag{5}$$

where B has been defined by the following equation:

$$B=\frac{\left(1+\dfrac{1}{D_E}\right)}{\left(\dfrac{V}{A}\right)_m u} \tag{6}$$

The overall mass transfer coefficient (K_{of}) can be determined from the value of the slope of the linear plots of the left-hand side (LHS) of Eq. (5) vs. t (time). This method requires (i) the experimental values of the concentrations, (ii) the distribution coefficient of the solute, and (iii) reactor volume and hollow-fiber characteristics. The values of K_{of}, are calculated from the individual correlations [17,28]:

$$\frac{d_i k_i}{D}=1.62\left(\frac{d_i^2 u_{\mathrm{tube}}}{DL}\right)^{\frac{1}{3}} \tag{7}$$

$$\frac{d_h k_o}{D}=0.56\left(d_h\frac{u_{\mathrm{shell}}}{v}\right)^{0.62}\left(\frac{v}{D}\right)^{0.33} \tag{8}$$

$$\frac{1}{K_{\mathrm{theo}}}=\frac{1}{k_a}+\frac{1}{D_E k_m}+\frac{1}{D_E k_o} \tag{9}$$

where d_i, d_h, u_{shell}, D, k_a, k_m and k_o are the inside diameter, hydraulic diameter, velocity on the shell side, velocity inside the fibers, diffusivity, mass transfer coefficients on the aqueous, in the membrane and on the shell side, respectively.

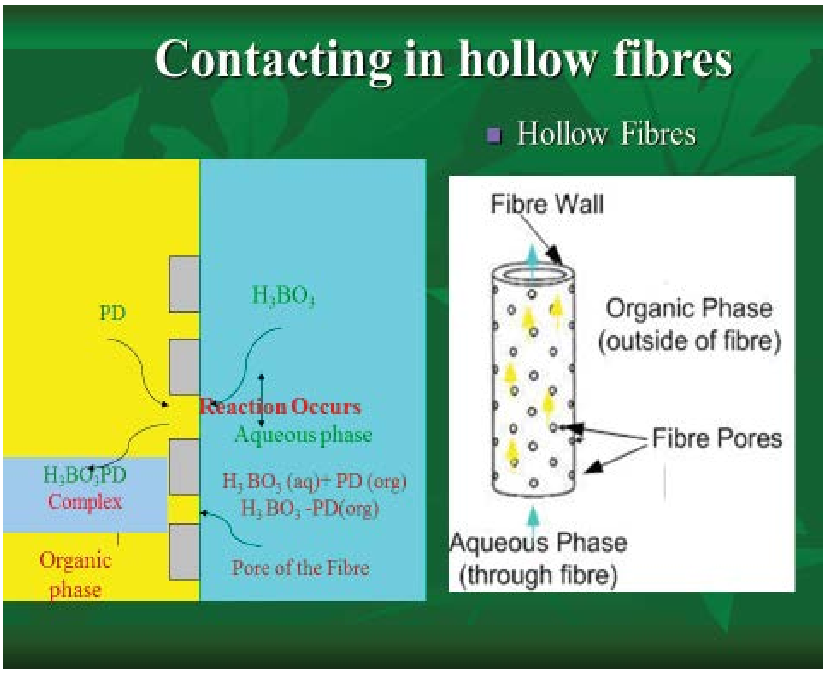

Fig. 2. A schematic diagram of the boron extraction process through the membrane pores of the membrane contactor.

3. Materials and methods

3.1. Chemicals and reagents

Boric acid (99.5% pure) and 2-butyl-2-ethyl-1,3-propanediol (BEPD, known as 'diol') (99% pure) were purchased from Sigma-Aldrich, (USA). The groundwater sample was supplied by a local company in Al Ain, Abu Dhabi, UAE. Sunflower oil (Noor brand, Dubai) was purchased from Emirates Refining Co., UAE.

Sunflower oil is high in monounsaturated fatty acids that include stearic acid (50%–55%), palmitic acid (4%–7%), oleic acid (27%–30%) and linoleic acid (0%–1%). Sunflower oil brand (Noor brand, Dubai) used in this investigation has no trans-fatty acid and has a flashpoint in the range 160°C–170°C. This provides good physical and chemical properties for industrial applications.

The experiments in the membrane module were conducted using the Hoechst Celanese Liqui-Cel hollow-fiber membrane contactor. The contactor has a shell-and-tube configuration with approx. 10,000 microporous hollow-fibers potted in a shell of 2.5 cm internal diameter. A schematic diagram of the experimental set-up is shown in Fig. 1. The characteristics of the contactor are listed in Table 1.

3.2. Preparation of solutions

Boron feed solution – the standard solution of boric acid was prepared by dissolving a known amount of this chemical in distilled water. Thermo Orion pH meter (USA) was used for measuring pH. The ICP spectrophotometer was 710-ES 03 from Varian (Australia) was used for measuring boron concentration. The water bath used was from Grant Industry (Cambridge Ltd., England) and the magnetic stirrer hotplate was from StuartCo, England.

3.3. Procedure for equilibrium measurements of solutes at ambient temperature

All the extraction experiments were conducted at room temperature of 25°C. A feed solution containing boric acid contacted with the organic phase, that is, diol in sunflower oil or pure sunflower oil at a volume ratio of 1:1 in the 25 mL centrifuge tubes. The aqueous feed concentration was set as required and the organic phase concentrations were varied from 0%–10% v/v of BEPD in sunflower oil. The solution in the tubes was mixed for a period of 2 h using a magnetic stirrer. After mixing the solutions were allowed to settle for 60 min to separate the two phases and obtain a clear bottom aqueous phase. The bottom aqueous layer was removed using a Pasteur pipette and analyzed for its boron content using the atomic absorption spectrophotometer, fuelled by argon at a wavelength of 267.7 nm.

3.4. Procedure for mass transfer experiments in the hollow-fiber contactor

In these experiments the aqueous feed solution was passed through the tube side and the organic phase containing the carrier was passed through the shell side of the membrane using peristaltic pumps controlled by a variable speed drive unit. The operation mode was concurrent. A positive pressure difference of 20–25 KPa was maintained on the aqueous side of the membrane to prevent the displacement of the organic phase into the aqueous side. The experiments were carried out by recycling the feed and solvent solutions. Prior to the extraction experiment, the organic phase was pumped at a slow rate (10 mL/min) on the shell side for 2–3 h to allow full saturation of pores in the module. Upon the end of organic loading, deionized water was

Table 1
Hollow-fiber membrane contactor (PCM218)

Effective pore size (μm)	0.05
Porosity	40%
Contactor characteristics	
Cartridge length (cm)	16
Shell inner diameter (cm)	6.3
Effective mass transfer area (m^2)	1.4
Priming volumes	
Tube side (cm^3)	145
Shell side (cm^3)	195

passed through the aqueous side to rinse out any organic phase that may have leaked through to the tube side, and to achieve a steady flow. The deionized water was replaced by the feed containing the solute (boron or any other metal) at the desired concentration. The flow rates of the aqueous and organic phases were at 120 ± 20 mL/min. A schematic diagram is shown in Fig. 1 that represents the flow around a microporous hollow-fiber, where solute molecules from the flowing aqueous side are extracted in the pores filled with the organic phase and transported to the bulk organic phase. Aqueous samples (of 3 mL) were taken, periodically, from the reservoir and the concentration was measured by the atomic absorption spectrophotometer. At the end of each experiment, the samples were checked for any leakage, a very small amount of oil was observed floating in the aqueous phase. All the extraction experiments were repeated and the results are within 5% of error.

4. Results and discussion

The results are presented as (i) the concentration vs. time during the experiment in the hollow-fiber membrane contactor, distribution coefficient (D_E) for the equilibrium experiments, and (ii) as plots for the overall mass transfer coefficient (K_{of}).

Sunflower oil performed well at the natural pH of 6.8 for all boron concentrations. With the solvent system of BEPD (the carrier) in sunflower oil the values of the distribution coefficient were good in the range of 2.2–4.77. The extraction percentage was in the range (89%–96%) for initial boron concentrations (5 and 20 ppm) with 10% diol in sunflower oil. Because of its effectiveness, the solvent system (BEPD in sunflower oil) has been used in the experiments with the hollow-fiber membrane contactor.

These results reported here are comparable to those obtained by previous researchers using toxic solvents like chloroform, toluene, and chlorobenzene [23,24]. It is noted that these results were obtained with sunflower oil (a renewable source and environmentally benign solvent) at normal room temperature and pressure and without a change in the natural feed pH (i.e. no addition of chemicals). Hence, it is suggested that this solvent system has the potential to replace other solvents like kerosene and toluene (that are considered toxic and corrosive with added environmental issues) for the removal of boron. The other favorable factors are: sunflower oil is a non-volatile substance, is obtained from a sustainable source, and does not contribute to the emission of volatile organic compounds.

4.1. Removal of boron from a groundwater sample using a hollow-fiber membrane contactor

In the real examples, the other metal ions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, and Sr^{2+} are present in groundwater sources, domestic and industrial effluents [26]. The experiments in this section were purely designed to investigate the organic carrier's affinity for boron in the presence of other metal ions (i.e. metal salts) during the extraction or removal process. The composition of a groundwater sample at a pH 7 obtained from a local distribution company is presented in Table 2. The initial concentration of boron varied from sample to sample and they were used as supplied. The feed concentration of boron was low (0.9 and 1.55 ppm). Two experiments with sample sizes of 1 L were conducted: (i) without BEPD in sunflower oil (for feed with 0.9 ppm boron) and (ii) with BEPD in sunflower oil (for feed with 1.55 ppm). The removal of boron with sunflower only (without diol) was small (ca. about 8%). It is observed that all other ions, except for chromium, were removed in minute proportions with the organic system of BEPD-sunflower oil (Table 2). The extraction percentage of boron was high, about 45% boron removal was possible within 10 min of treatment in a single stage. This result is encouraging as the sample conditions (pH, temperature, and ionic composition) were not adjusted and the other ions (considered as essential components) of the groundwater sample were only slightly removed (Table 2).

Table 2
Concentrations of the components of a local groundwater sample, initial and final values

Components of the groundwater sample	Concentration (ppm) of metal components (initial)	Concentration (ppm) of metal components (final)
Calcium (Ca)	50.9	55.2
Potassium (K)	39.8	36.0
Magnesium (Mg)	45.1	50.8
Sodium (Na)	223.7	220.0
Strontium (Sr)	13.9	12.7
Chromium (Cr)	0.81	0.61
Boron (B)	1.57	0.87

Because of the specific nature of the reaction–extraction system, the other metals present in the feed are extracted in minimal quantities. The wastewater/groundwater samples are in the low to medium concentration ranges in metals, where other methods (such as adsorption) are not so effective. Higher concentrations of other ions have been examined earlier and reported in the literature [29–31].

This analysis is for diffusion-reaction with specific extractants used for the targeted ion (Fig. 2) and the co-extraction of other ions is minimal. Although diffusion of target ion in the aqueous phase (fiber side) may be affected due to the presence of other ions, diffusion in the membrane pores and on the shell side organic phase will have less effect. Because in these last two diffusion processes only the target metal-extractant complex is involved and because of the non-specificity of co-ions the extractant complex does not form for the co-ions. Values of D_E (partition coefficient) is an indirect measure of the formation of the complex and the analysis would be less applicable if the co-ions would have comparable values of D_E. This was not found in the experiments (very small D_E values of co-ions were determined, suggesting the validity of the analysis).

This new extraction system is expected to reduce the cost of the overall treatment process, as the reactive separation step is selective and retains the other ions instead of removing them. In the removal of boron-based on the RO process, multiple stages are required and the essential components are also removed along with boron [32]. This is a clear advantage of boron removal by reactive extraction, especially a sustainable solvent like sunflower oil is used. More work is required to optimize the conditions (the effect of flow rate and the composition of the organic phase) of extraction and possible scale-up of the process. This new removal process when optimized will allow the treated water to be recycled and reused in the processes where they are generated or sourced.

4.2. Overall mass transfer coefficient in hollow-fiber membrane contactor

The concentration of boron at various times from the experiment in the hollow-fiber contactor is presented in Fig. 3. The data over an initial period of 6–8 min were analyzed to determine the overall transfer coefficient (K_{of}). First a plot of the LHS of Eq. (5) vs. time was constructed, using the experimental parameters (flow rate, solution volume, the concentration of boron) and the apparent distribution coefficient. Fig. 4 shows that a good correlation has been obtained over this period. Using the value of the slope of the plot and the value of B in Eq. (6), the overall mass transfer coefficient for the extraction was calculated. The overall mass transfer coefficient is ca. 1.66×10^{-6} cm/s and lower than the values in the literature. Using this value of mass transfer coefficient the predicted concentration vs. time data, is plotted in Fig. 4. The predicted values follow closely with the concentrations obtained experimentally.

Because the organic phase was sunflower oil, the hollow-fiber contactor has to be made from hydrophobic fibers with micropores that will allow establishing the aqueous-organic interface in the pore mouth. Because of this nature of the fibers, the phases are not dispersed into one another. The contactor used in this study is made from microporous polypropylene fibers (hydrophobic). As long as the contactor is of this type where the diffusion-reaction processes can take place and maintain steady-state, the model and the analysis is applicable. How good the final values are, that needs to be compared, with those calculated using established correlations of mass transfer coefficient.

The simplified equation for the overall mass transfer coefficient (K_{of}), was tested on the experimental data for extraction of zinc using a similar hollow-fiber membrane contactor with di-(2-ethylhexyl)phosphoric acid (DEHPA) in kerosene system from the literature [31]. The values of the experimental zinc concentration vs. time (min) are shown in Fig. 5. From the values for the first 15 min and using other operating parameters, the LHS of Eq. (5) was calculated. The values are plotted in Fig. 6 and it shows a good fit with the experimental data for the initial period. The value of the overall mass transfer coefficient was calculated as $(2–16) \times 10^{-6}$ m/s with a small standard deviation.

The values of the mass transfer coefficient were then calculated for three flow rates in the membrane contactor for the experimental data reported [33], using the procedure described in the above paragraphs. These values are plotted

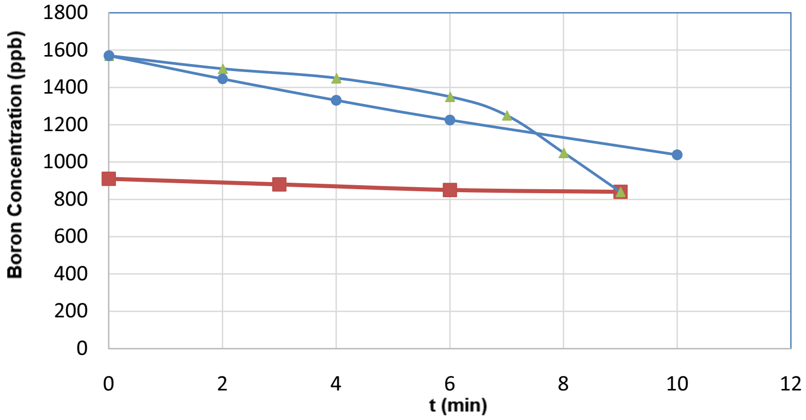

Fig. 3. Boron concentration (ppb) vs. time (min) for extraction without diol (■), with diol in sunflower oil (▲) and calculated results (●) using overall mass transfer coefficient in the hollow-fiber membrane contactor.

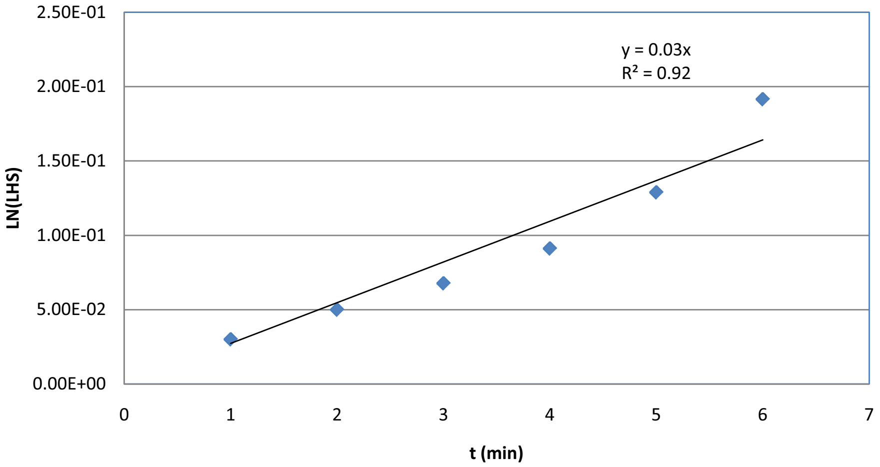

Fig. 4. LHS of Eq. (5) vs. time for the hollow-fibre experiment with boron-containing ground water sample.

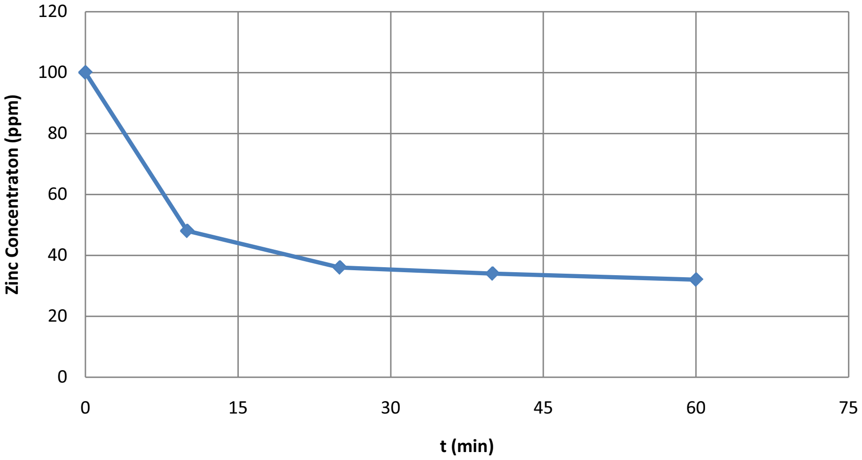

Fig. 5. Zinc concentration (ppm) vs. time (min) in the hollow-fiber contactor [31]. The conditions Zn initial concentration 100 ppm at pH 2.01, organic phase flow rate 220 mL/min, aqueous phase flow rate 800 mL/min and carrier (D2EHPA) concentration 8% v/v in isodecane [33].

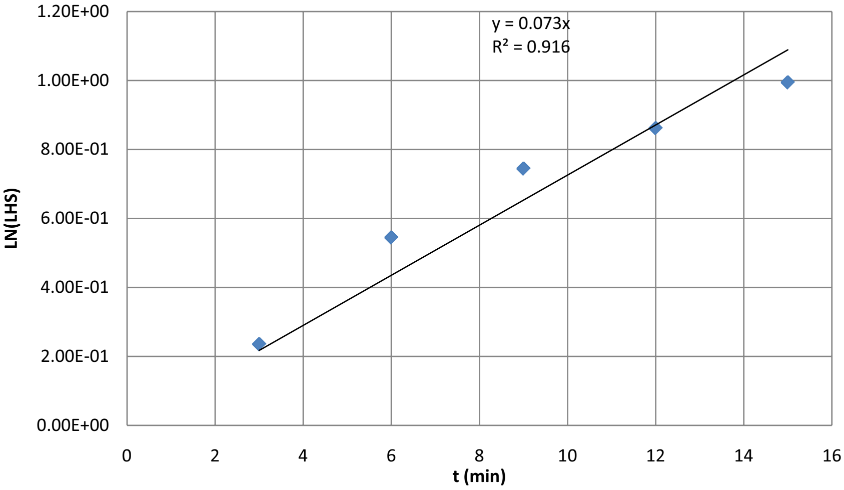

Fig. 6. LHS of Eqn. (5) vs. time (min) for zinc concentration in the hollow-fiber contactor. The conditions are the same as in Fig. 5.

in Fig. 7 and a good correlation is shown. As expected the values of the overall mass transfer coefficient increases with the increase in the aqueous flow rate in the membrane contactor. This could be due to the decrease in the mass transfer resistance at higher flow rates on the aqueous side, which is the main resistance in the overall process. Therefore, the effect of the aqueous flow rate (the main operating parameter) can also be determined using the equation presented in this paper. These values are similar to those of the experimental values, they are in the range (1.2–21) × 10^{-6} m/s [31] and the maximum error is approximately 30%.

The values of the overall mass transfer coefficient (K_{theo}), were also calculated using the correlations reported in the literature, they are presented in Eqs. (7)–(9). The comparison of the values is shown in Fig. 8 and the values predicted by the simplified equation (presented in this paper) are in good agreement with the ones calculated by using the correlations. It is emphasized that the equation derived in this paper, uses the mass balance equations in the hollow-fiber membrane contactor, not any other devices/apparatus as used in the development of the correlations.

The simplified model presented and used in this manuscript to determine the overall mass transfer coefficient from the concentration of metal vs. time data, is applicable for any metal-membrane extraction system. In order for 'target' metal to be extracted selectively, the extraction-reaction system must provide a faster rate than the extraction (only) system and must be specific to the metal ion for effective separation. For these extraction-reaction systems, if the concentration-time data over the initial period are available, this simplified method should apply regardless of what metal-reaction system has been used.

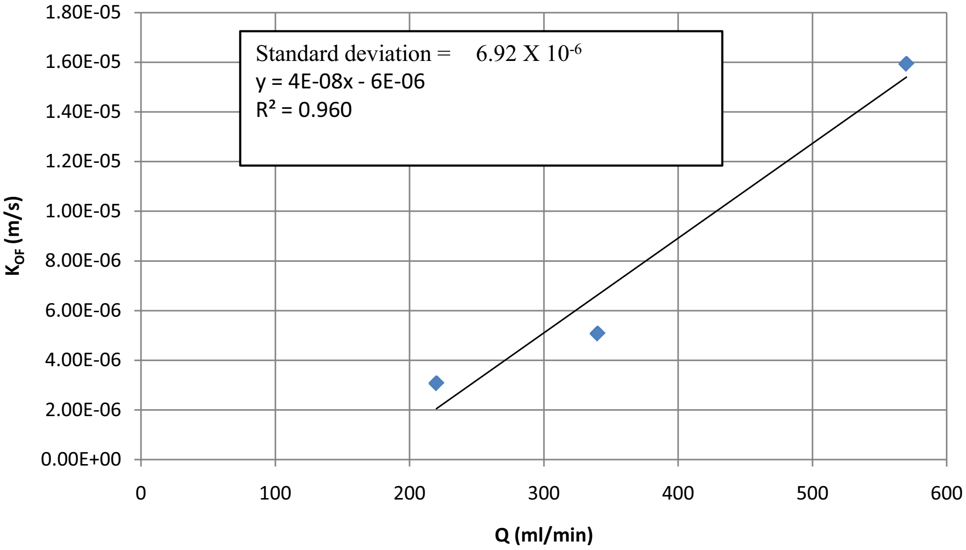

Fig. 7. Effect of the organic phase flow rate on the overall mass transfer coefficient (K_{of}). The conditions are the same as in Fig. 5 except for the organic phase flow rate.

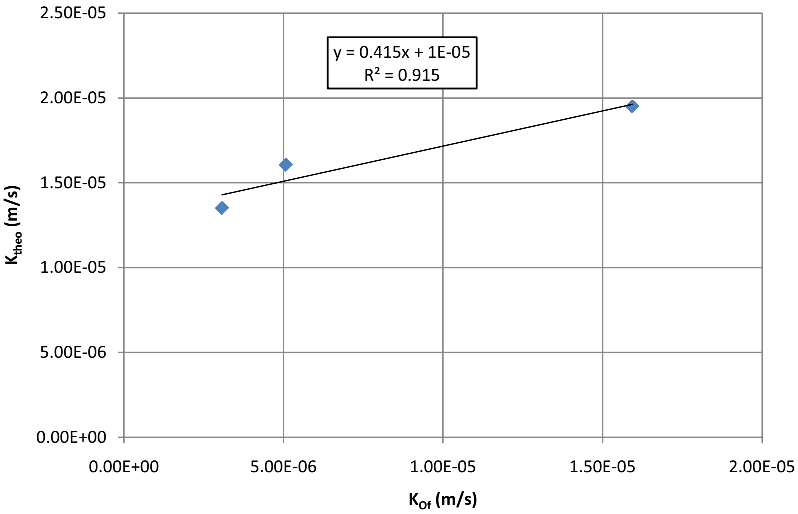

Fig. 8. Comparison of the values of overall mass transfer coefficient (m/s), K_{theo} (literature correlation) and K_{of} (this work).

5. Conclusions and recommendations

Analysis of experimental results is reported for the (a) removal of boron using BEPD in sunflower oil and (b) removal of zinc in a hollow-fiber membrane contactor. The main concluding remarks are:

- The removal of boron with BEPD in sunflower oil was approx. 45% at the natural pH of 6.8 and this was achieved in a single-stage operation within 10 min. Without the carrier the removal was slow and in low percentages.
- An overall mass transfer coefficient of 1.8×10^{-6} cm/min was determined from the experimental data of boron concentration at various times. The value is comparable to those reported in the literature for the extraction of metals.
- Using this value of the mass transfer coefficient, the calculated data of boron extraction has been predicted with a trend similar to the experimental values.
- Using the simplified equation of this work, an overall mass transfer coefficient was also calculated as 1.59×10^{-5} m/s from experimental data of zinc concentration at various times (literature data). This value is slightly lower than that calculated by using the mass transfer correlations in the literature but they are correlated with are very similar trend and determined from the mass balance equations in the hollow-fiber membrane contactor.
- The simple method described in this paper can provide a good initial estimate for the overall mass transfer coefficient at low concentration feed (boron results) as well as medium concentration feed (zinc experimental data) samples. Further analysis of a wide range of conditions and for more systems are required to determine the applicability of the simplified equation in a wide range.

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Symbols

A — Surface area, m^2
B — Defined in Eq. (5)
BEPD — 2-butyl-2-ethyl-1,3-propanediol
B(OH)^3 — Boric acid
B(OH)$_4^-$ — Borate ion
C — Metal concentration, mg/L
Ca^{2+} — Calcium cation
Cl^4 — Chloride ion
d_i, d_o — Inner diameter, outer diameter of a hollow-fiber, cm
D_E — Distribution coefficient of boron defined in Eq. (4a)
K_a — Aqueous phase mass transfer coefficient in Eq. (5), cm/sec
K_o — Organic phase mass transfer coefficient in Eq. (6), cm/sec
K_m — Membrane phase mass transfer coefficient in Eq. (7), cm/sec
K_{of} — Overall mass transfer coefficient in Eq. (1), cm/sec
K_{theo} — Theoretical overall mass transfer coefficient in Eq. (7), cm/sec
L — Length of the fiber, cm
Mg^{2+} — Magnesium cation
Na$^+$ — Sodium cation
t — Time, s
ppm — Parts per million
q — Flow rate, m^{-1}
RO — Reverse osmosis
u — Linear velocity in the hollow-fibers, cm/s
V — Volume, L
WHO — World Health Organization
Z — Axial distance in the module, cm

Subscripts

aq — Aqueous phase
Mc — Aqueous phase in the hollow-fiber contactor
Mi — Aqueous phase in the hollow-fiber contactor at the initial time
MO — Organic phase in the hollow-fiber contactor
Mt — Aqueous phase in the tank (reservoir)
f — Feed (aqueous) phase
i — Initial condition
org — Bulk organic phase
o — Outer
s — Shell
sol — Solvent
ov — Overall value
theo — Theoretical value

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