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Environmental Science: Water Research & Technology

Water Impact Statement

Arsenic contaminated drinking water is a major health risk for millions of people throughout the world. Most of them live in underdeveloped cities or rural areas. Efficient nanofiltration process with low energy consumption and financial cost can be used for arsenic removal from groundwater. In this work, a composite hollow fiber nanofiltration membrane with sulfonated poly (ether ether ketone) coating was developed and evaluated for arsenic removal. The estimated overall water treatment cost could be affordable for many Chinese communities.
Arsenate removal using a sulfonated poly (ether ether ketone) coated hollow fiber nanofiltration membrane

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Abstract

A new composite hollow fiber nanofiltration (NF) membrane with a thin sulfonated poly (ether ether ketone) (SPEEK) active layer was prepared and used for arsenic removal. The effects of the feed concentration, pH and transmembrane pressure on arsenate removal were systematically examined. The obtained SPEEK hollow fiber NF membrane could achieve As (V) rejection of over 95% and water permeability of 11 L/(m².h.bar). These excellent As (V) rejection and high water permeability were attributed to the highly negatively charged surface of the SPEEK membrane, which could enhance As (V) rejection through the Donnan exclusion mechanism or electrostatic repulsion between the negatively charged arsenate species and the negatively charged SPEEK membrane surface. A preliminary techno-economic assessment of a 1000 m³/h plant suggests that using the proposed SPEEK hollow fiber membrane, the treatment cost was 0.15 US$/m³, thus could be economically viable for arsenic removal applications in China.

Keywords: Arsenic removal; Nanofiltration (NF); Donnan exclusion; sulfonated poly (ether ether ketone) (SPEEK); Drinking water treatment.
1. Introduction

Arsenic occurs naturally in groundwater in many parts of the world, particularly in South and South East Asia (e.g., China, India, Bangladesh, and Thailand), North America (e.g., USA and Canada), and part of Europe (e.g. Italy and Spain). Most arsenic compounds are toxic. Chronic exposure to arsenic at a low level can cause lung and bladder cancer, muscular weakness, and the black-foot disease. In 1993, the World Health Organisation (W.H.O.) adjusted the maximum contaminant level (MCL) of arsenic in drinking water from 50 to 10 \( \mu g / L \).

Many treatment methods, including coagulation, adsorption, ion exchange, bacterial treatment, and membrane processes, can be applied for arsenic removal. Cost, efficiency, technical complexity and physical footprint are amongst the most important criteria for selecting these treatment methods. Among these methods, pressure driven membrane processes such as reverse osmosis (RO) and nanofiltration (NF) can offer probably the highest treatment efficiency. Moreover, these membrane processes are also compact, can be fully automated, and do not require extensive maintenance. Compared to RO, NF process operates at a much lower pressure thus is more economical. However, NF membranes are commercially available mostly in spiral-wound modules. The spiral-wound module is prone to channel clogging. Thus, they require extensive pre-treatment by either sand filtration or a low pressure membrane process such as microfiltration or ultrafiltration, adding significant treatment cost. Therefore, cost-effective NF membranes with high stability under a wide pH range are highly desirable.

Hollow fiber membranes have well-defined flow channels and variable inner diameters.
They show advantages over spiral-wound membrane module because of easy cleaning, highly tolerant to turbidity and particulates, and consequently less demanding on the pre-treatment. The preparation of hollow fiber NF membranes has been reported either by using direct spinning or direct spinning followed by surface coating. Direct spinning has been widely studied using a single polymer solution or simultaneous co-extrusion of two polymeric solutions. Coating an ultrathin layer onto an existing membrane could also be achieved by interfacial polymerization, UV-photo grafting, and direct dip-coating. In particular, dip-coating has been employed for the preparation of NF hollow fiber membranes with thin active layer of sulfonated polyether ether ketone (SPEEK) on commercial polyethersulfone (PES) support. The resulting composite membranes showed high sodium sulfate rejection and low magnesium chloride rejection. These SPEEK coated PES membrane could be used to separate sodium chloride from glyphosate. The same membrane showed a stable performance (for more than 2000 h) owing to cross-linking of the coating active layer.

In an aqueous solution, inorganic arsenic can be present as either As (III) or As (V). The transformation between As (III) and As (V) depends on the redox condition of the solution. In a reducing condition such as an underground aquifer, arsenic exists mostly in the form of arsenite or As (III). However, once groundwater has been extracted to the surface, As (III) can be readily oxidized by oxygen in the air into arsenate or As (V). Because of the prevalent oxidation of As (III) to As (V) when exposing to air, this work will focus exclusively on the removal of As (V).

Based on the Donnan exclusion mechanism, SPEEK composite NF membrane can potentially offer a high removal of multivalent ions such as HAsO$_4^{2-}$. However, the actual
separation performance of the SPEEK NF membranes towards As (V) is largely unknown, particularly in the presence of interfering ions. In this report, the SPEEK membrane performance is investigated for the As (V) removal in the presence of interfering ions, including Na$^+$, Ca$^{2+}$, Cl$^-$, NO$_3^-$, SO$_4^{2-}$, and others. Effects of the arsenic concentration, pH and operational pressure on the rejection of As (V) were investigated. Rejections to other cations and anions were determined in order to assess the role of the Donnan exclusion mechanism. Finally, the treatment cost related to the As (V) removal was estimated to evaluate the potential of the present SPEEK hollow fiber NF membrane for drinking water production from arsenic contaminated groundwater.

2. Experimental

2.1 Materials and Membranes

SPEEK powder (VESTAKEEP 4000P) was kindly provided by Evonik Degussa. PES hollow fiber ultrafiltration membrane was kindly provided by Altrateck Co. Ltd. Key characteristics of this PES hollow fiber membrane are summarized in Table 1. All other chemicals (e.g., Na$_3$AsO$_4$.12H$_2$O, methanol Na$_2$SO$_4$, H$_2$SO$_4$) were from Sinopharm Corporation Ltd and were of analytical grade. De-ionized water was used to prepare all experimental solutions.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID/ OD</td>
<td>mm</td>
<td>0.78/1.28</td>
</tr>
<tr>
<td>MWCO</td>
<td>Da.</td>
<td>70000</td>
</tr>
</tbody>
</table>
2.2 Preparation of composite hollow fiber nanofiltration membrane

The detailed procedure for the preparation of SPEEK (SPEEK-S48) and composite hollow fiber NF membrane was reported elsewhere.\textsuperscript{18} Briefly, SPEEK coating solutions (concentration 1.5 wt. %) in methanol was filtrated and dip-coated onto the inner surface of the hollow fiber PES UF membranes. The initial composite membrane was dried and cured for an hour at 65 °C. The membranes were then stored under ambient environment for subsequent analysis and filtration experiments.

2.3 Characterization of the composite membranes

A hollow fiber membrane module was prepared by epoxy potting six fibers (effective length of 16-20 cm) into a nylon tube (inner diameter/outer diameter = 9/12 mm). A schematic diagram of the hollow fiber NF set-up is shown in Fig.1\textsuperscript{17,18}

A Na\textsubscript{2}SO\textsubscript{4} feed solution of 500 mg/L was used. Pressure and flow rate at the lumen side were controlled manually. The cross-flow velocity in the lumen was kept at 0.25 m/s. The solution temperature was maintained at 25 ±2 °C. At each operating condition, the system was stabilised for at least 1 h before permeate and feed sample collection for rejection
determination and permeability measurement. All experiments were conducted in duplicate and the deviation between two replicates was always less than 10%.

A stock solution containing 9 mg/L As (V) in de-ionized water was prepared and used for the NF filtration experiments. This stock solution was then diluted to obtain a working solution with a desirable As (V) concentration to study the effects of interfering ions and pH on Arsenate rejection. To study the effects of pH, the solution pH was adjusted by adding a small volume of either 1 M HCl or 1M NaOH solution. The trans-membrane pressure was set at 4 bar.

![Fig.1. Scheme of a cross-flow nanofiltration setup (1. A feed tank; 2. Magnetic stirrer; 3. Filter; 4. Control valve; 5. Gear pump; 6. Pressure gauge; 7. Membrane module; 8. Feed container; 9. Rotameter).](image)

The permeate flux ($J$) was determined by the permeate weight through the membrane at unit time and unit membrane area. The water permeability was calculated by the permeate flux divided by the trans-membrane pressure. The observed rejection ($R_{obs}$) was determined as reported in equation 1:
\[ R_{\text{obs}} = \left(1 - \frac{C_p}{C_f}\right) \times 100\% \]  

(1)

Where \( C_p \) and \( C_f \) are the permeate and feed concentration in the bulk, respectively.

2.4 Water quality Analysis

Conductivity and pH were measured using a Mettler Toledo (LE703) conductivity meter and a Sartorius pH meter (PB-10), respectively. A Shimadzu Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP AES, ICPE-9000) was used to determine cation and As (V) concentration. Total hardness was determined using disodium ethylene diamine tetraacetate (EDTA-2Na) titration method. COD was determined by digestive degradation and measured by spectrophotometer (Hach DR2800) based on the standard methods. All samples were analyzed in triplicate and the standard deviation of 3 replicate measurements was always less than 10%.

2.5 Scanning Electron Microscopy \(^{26}\) and Zeta Potential

Prior to scanning electron microscopy \(^{26}\) analysis, samples were coated with a thin layer of gold. A Field Emission Scanning Electron Microscopy (FESEM, HITACHI S-4800) (for high magnifications) were used for characterizing the membrane morphology.

Surface zeta potential of the membrane was measured using a Surpass (Anton Paar) electro-kinetic analyser.

3. Results and discussion

3.1 Characteristics of SPEEK coated composite NF membrane

Fig. 2 shows the inner surface of the PES hollow fiber membrane before and after SPEEK coating. PES surface shows aligned spindle-like polymer aggregates of width about...
20-50 nm (Fig. 2A). Pores are distinctly shown as the gap between the polymer aggregates. After coating with a SPEEK solution of 1.5 wt. %, the membrane inner surface shows a very smooth surface (Fig. 2B). This observation indicates that the SPEEK is homogeneously coated on the PES membrane support.

![Image of inner surfaces of PES hollow fiber membrane before (A) and after (B) SPEEK coating.](image)

**Fig. 2.** (A) Inner surfaces of the PES hollow fiber membrane before (A) and after (B) SPEEK coating.

The PES membrane was negatively charged with the surface zeta potential in the range of -12 to -35 mV (Fig. 3). After coating with SPEEK, the membrane surface was much more negatively charged and surface zeta potential was in the range of -105 to -120 mV. This significant change of surface charge is attributed to the deprotonation of the sulfonate group of SPEEK. The results in figure 3 also confirm that the SPEEK surface coating was successful.
Fig. 3. Zeta potential of the support PES ultrafiltration membrane (BLANK) and SPEEK composite NF membrane at different pH.

SPEEK coating also resulted in a marked reduction in water permeability. Indeed, as can be seen in Table 2, the SPEEK coated membrane water permeability was 11.5 L/(m².h.bar) while water permeability of the PES membrane (which was used as the base) was 400 L/(m².h.bar). In addition, inorganic salt rejections by the SPEEK coated membrane were comparable to those of a traditional NF membrane (Table 2). The high rejection to Na₂SO₄ evidenced the integrity of the coating layer. Based on the surface charge of the NF membrane, a high rejection to Na₂SO₄ and low rejection to NaCl were expected, according to Donnan exclusion. A rejection of 34.0% of CaCl₂ was not in line with the effect of the Donnan exclusion: in fact the large amount of sulfonic acid groups on the main chain of SPEEK polymer presumably should allow the transport of a bivalent Ca²⁺ through the coating; therefore, lower than measured rejection value was expected. Therefore, this deviation may indicate that Donnan exclusion was not the only separation mechanism for the SPEEK
membrane, other separation mechanism may also play a role.

Table 2: Characteristics of the SPEEK composite NF membrane (average ± standard deviation of triple measurements).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water permeability</td>
<td>11.5±1.0</td>
</tr>
<tr>
<td>Rejection (%)</td>
<td></td>
</tr>
<tr>
<td>NaCl</td>
<td>42.0±0.8</td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>96.0±1.2</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>34.0±0.6</td>
</tr>
<tr>
<td>MWCO (Da.)</td>
<td>4000-6000</td>
</tr>
<tr>
<td>Pore radius (nm)</td>
<td>1.22-1.43</td>
</tr>
<tr>
<td>Burst pressure (bar)</td>
<td>13 ± 1</td>
</tr>
</tbody>
</table>

¹ Reference ¹⁸.

3.2 Removal of arsenic

3.2.1 Effect of pH

As (V) stock feed solution prepared using DI water was tested in the NF process. NF tests showed that the membrane permeability was 11.5±0.3 L/(m².h.bar) and was independent of the solution pH (Fig 4-b). This small variation in the permeability is probably due to slight variation in the swelling state of the SPEEK. The effect of pH solution on the As (V) rejection is shown in Fig. 4. The rejection of arsenic increased from 89% to 96.4% following the increase of pH from 4 to 9. This can be explained by anionic nature of the SPEEK NF membrane that can selectively repulse anions of higher charging states and the different
dissociation states of As (V) with pH. Arsenate exists mainly as a monovalent ion $\text{H}_2\text{AsO}_4^-$ at pH=4 and divalent $\text{HAsO}_4^{2-}$ at pH=9. Based on Donnan effects, the rejection of the divalent ions is higher than monovalent ions by the membrane of the same charge$^{13, 17, 27-29}$. Therefore, the rejection of divalent $\text{HAsO}_4^{2-}$ is higher than monovalent $\text{H}_2\text{AsO}_4^-$. 

![Graph](image)

**Fig. 4.** Effect of the pH solution on the As rejection (a) and water flux (b) (Feed As conc. = 650 µg/L; temp. = 25 °C, trans-membrane pressure = 3 bar).

### 3.2.2 Effect of feed concentration

The rejection of As (V), at different feed concentration, was further investigated at pH = 9 (Fig. 5). The rejection increased from 95 to 98% increasing the feed arsenic concentration from 0.10 to 9.00 mg/L. This is expected for a NF membrane, where Donnan exclusion dominates the separation mechanism, as a result of weakened exclusion effect due to increased electrolyte concentration.$^{21}$ It should be noted that the arsenic concentration variation in this investigation covers the main arsenic contaminated drinking water sources. The results are therefore potentially valuable for practical water purification cases.
Fig. 5. Effect of feed concentration on the rejection. Feed solution pH 9.0, at 25 °C, trans-membrane pressure, 3 bar.

3.2.3 Effect of operation pressure

Effect of the trans-membrane pressure on the membrane performance (rejection and flux) is shown in Fig. 6. Following the increase in the operational pressure from 3 to 8 bar, the arsenic rejection gradually increased from 96.9% to 99.6%, and consequently the arsenic in the permeate declined from 11.2 µg/L to 1.44 µg/L, at a feed arsenic concentration of 360 µg/L, far below the MCL value recommended by WHO of 10 µg/L. The water flux increased linearly from 32.7 L/(m².h) to 85.4 L/(m².h) with the operation pressure as shown in Fig. 6. The increased flow velocity as a result of increased operation pressure was ascribed as the main reason for water flux increase. On the other hand, the flow velocity effect on the transport of arsenic ions was not affected in a similar trend as water molecules, resulting in a high rejection.

These results demonstrated that the SPEEK NF membranes have shown a high rejection to arsenic without the presence of interfering ions, and the Donnan exclusion can rationally be
applied to understand the rejection of As.

![Graph](image)

**Fig. 6.** Effect of operating pressure on the As (V) rejection (a) and water flux (b) of SPEEK NF membranes. Feed concentration: 360 µg/L at 25 °C.

### 3.3 Effects of interfering ions on As(V) removal

Arsenic was spiked into tap water and used as a model solution to illustrate the effect of interfering anions and cations on As rejection using SPEEK hollow fiber NF membranes. Table 3 lists the major water quality data analyzed in the NF experiments. The pH of the feed tap water was adjusted to 8.78. The permeate arsenic concentration was 9.0 µg/L, below the MCL required by WHO. The rejection is similar to the one obtained without the presence of other ions. Significant reduction in the turbidity (75%) and conductivity (32.7%) was observed with a slight decrease in pH. The reduction of turbidity and conductivity is a direct result of membrane rejection. As reported in Table 3, for monovalent ions, e.g. Cl⁻, NO₃⁻, the rejection was below 20%. The rejection of Si was close to that of Cl⁻, which was probably due to the predominantly presence of HSiO₄⁻ at pH 8.78. Surprisingly, SO₄²⁻ rejection was
86.4% and was below the value when no interfering ions were present in the bulk feed solution. The rejection of Na\(^+\) was about 30%, which is comparably lower than the rejection of Ca\(^{2+}\) (51.5%) and Mg\(^{2+}\) (43.1%). For the trivalent ferric ions, a rejection over 94% was found, which is expectable because ferric may associate with OH\(^-\) to form colloidal particles to be rejected by the membrane\(^{31}\).

**Table 3.** Comparison of the removal rate of the different chemical species from tap water with the SPEEK composite membrane.

<table>
<thead>
<tr>
<th>Analytes</th>
<th>Feed</th>
<th>Permeate</th>
<th>Rejection (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>8.78</td>
<td>8.67</td>
<td>-</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>0.4</td>
<td>75.0</td>
</tr>
<tr>
<td>Conductivity</td>
<td>µs/cm</td>
<td>574</td>
<td>383</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>12.9</td>
<td>5.90</td>
</tr>
<tr>
<td>As</td>
<td>µg/L</td>
<td>380</td>
<td>9.0</td>
</tr>
<tr>
<td>Ca</td>
<td>mg/L</td>
<td>69.1</td>
<td>33.5</td>
</tr>
<tr>
<td>Fe</td>
<td>mg/L</td>
<td>1.9</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Mg</td>
<td>mg/L</td>
<td>8.91</td>
<td>5.05</td>
</tr>
<tr>
<td>Na</td>
<td>mg/L</td>
<td>31.4</td>
<td>22.3</td>
</tr>
<tr>
<td>Si</td>
<td>mg/L</td>
<td>5.22</td>
<td>4.30</td>
</tr>
<tr>
<td>Cl(^-)</td>
<td>mg/L</td>
<td>66.5</td>
<td>54.3</td>
</tr>
<tr>
<td>HCO(_3^+)</td>
<td>mg/L</td>
<td>0.12</td>
<td>0.09</td>
</tr>
</tbody>
</table>
The hydrated radii (Table 4) of the main cation and anions are significantly smaller (0.2-0.43 nm) than the pore radius of the SPEEK NF membrane (1.2-3.3 nm). Thus, steric exclusion of the cations and anions is not significant. Suppose Donnan exclusion effect is still valid for the model system, the rejection of $\text{SO}_4^{2-}$ would be much higher than 86.4% (compared to the results listed in Table 2), and the rejection of positively charged divalent ions, Ca$^{2+}$ and Mg$^{2+}$, would be much lower than those listed in Table 3. In addition, the rejection of Na$^+$ would be much higher than the value listed in Table 3 (referring to rejection values for NaCl reported in Table 2). The rejection (51.5%) for Ca$^{2+}$ in model solution is significantly higher than that without interfering ions (34.0%). Above results seem to be contradictory to that expected by Donnan exclusion alone. The other striking phenomenon was that for the negatively charged SPEEK membrane, the rejection of monovalent anions (e.g., Cl$^-$, NO$_3^-$) is even much lower than monovalent cations. The discrepancy between the Donnan exclusion and the observed results indicate that, for a mixture solution, other separation mechanisms may play an important role as well.

By analyzing the data in Table 3 and 4, the relationship between the hydrated radii values of various ions and their rejection rates is not apparent. For example, Mg$^{2+}$ has the largest hydrated radius among the cations but its rejection is lower than Ca$^{2+}$; for anions, the smallest HAsO$_4^{2-}$ has the highest rejection. Furthermore, there is no monotonic correlation between the diffusivity and rejection either. In order to explain such results, the separation mechanisms...
have to be reviewed.

Saliha et al. \(^{32}\) has incorporated the steric/electric model with dielectric exclusion, and their results show that the surface charge density in the nanopores within a NF membrane is lower than those experimentally determined streaming potential. This difference could be caused by the adsorption of counter ions \(^{33}\), or even more significantly by multivalent ions \(^{34}\). For a single salt, the adsorption of counter ions is probably less important. However, when interfering ions were present, the adsorption of counter ions partially weaken the surface charges of the membrane, thereby leading reduced rejection toward \(\text{SO}_4^{2-}\) and increased rejection to bivalent cations.

Moreover, according to dielectric exclusion principles, the exclusion energy is proportional to the square of the charge. Therefore, it is expectable that higher rejection for bivalent than monovalent ions (both cation and anions) was observed. For the bivalent anions \(\text{HAsO}_4^{2-}\) and \(\text{SO}_4^{2-}\), although similar effect of dielectric exclusion was anticipated, the much lower diffusivity of \(\text{HAsO}_4^{2-}\) than \(\text{SO}_4^{2-}\) is more effective in retaining the former anions, leading to a higher rejection. Similarly, the higher rejection of \(\text{Na}^+\) than \(\text{Cl}^-\) or \(\text{NO}_3^-\) could be explained by the greater diffusivity of the former. Slightly higher rejection of \(\text{HCO}_3^-\) may be originated from the association with cations as \(\text{Ca}^{2+}\) and \(\text{Mg}^{2+}\). Overall, based on principles of dielectric exclusion theory, the data in Table 3 can be rationally explained, indicating that in the presence of interfering ions, dielectric exclusion is the main mechanism for the separation performance of SPEEK NF membranes.

Table 4. Summary of solute characteristics\(^{23,30,35}\).
<table>
<thead>
<tr>
<th>Species</th>
<th>Hydrated radii (nm)</th>
<th>D ($10^{-9}$ m$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca$^{2+}$</td>
<td>0.41</td>
<td>0.92</td>
</tr>
<tr>
<td>Mg$^{2+}$</td>
<td>0.428</td>
<td>0.71</td>
</tr>
<tr>
<td>Na$^+$</td>
<td>0.36</td>
<td>1.33</td>
</tr>
<tr>
<td>Cl$^-$</td>
<td>0.33</td>
<td>2.03</td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>0.335</td>
<td>1.90</td>
</tr>
<tr>
<td>HCO$_3^-$</td>
<td>0.20-0.22</td>
<td>1.19</td>
</tr>
<tr>
<td>HAsO$_4^{2-}$</td>
<td>0.200-0.202</td>
<td>0.32</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>0.379</td>
<td>1.07</td>
</tr>
</tbody>
</table>

3.4 Cost evaluation

A preliminary cost estimation for the removal of arsenic from drinking water source was conducted assuming a treatment capacity of 1000 m$^3$/h and a working time of 300 d/year. The assumptions and key cost parameters for such a treatment system are listed as follows:

1. Membrane permeability: 10 L/(m$^2$.h.bar); operation pressure: 5 bar, which is lower than the burst pressure of the hollow fiber membranes (13 bar); the membrane lifetime: 5 years, because the underground drinking water quality is rather high;

2. Module geometry: 8 inch× 1.5 m with an area of 35 m$^2$; cost of the hollow fiber membrane: 70 $/m^2$; this cost is an optimal evaluation of the membrane in large scale production; the cost includes ultrafiltration membrane and coating layer and is predicted to be more realistic than previous optimistic value.
(3) Water recovery rate: 80%; this is realistic because the TDS and scaling potential of surface water is generally low;

(4) Life time of the membrane system: 20 years, and the cost for a membrane system: 3 times as that of the membranes; 

(5) Labor cost: 80K $/year for 4 full time operators for the large plant because the membrane plant is fully automatic;

(6) The cost of electricity is assumed to be 0.1 ($/KWhr) for rural areas. Above parameters were input into an excel sheet. The cost break down of the nanofiltration system (Fig. 7) shows that the membrane, system depreciation and power takes 71% of the total treatment cost for producing drinking water (0.15$/m$^3$) from groundwater contaminated with arsenic, while manpower, maintenance and pre-treatment only add up to 29%. Reduction in the membrane and pre-treatment costs is the main issues for further improvement. It should be noted that the costs for interest rate, land, and other peripheral facilities were not taken into consideration, and this may affect slightly the total cost. The membrane cost is rather optimistic at this stage since the cost for the NF membrane is just marginally higher than the market price of the ultrafiltration membrane ($35-50$). However, the price of the membrane and system depreciation could be reduced by constant improvement and increase in the market capacity.
The total cost for producing drinking water is 0.15 $/m³.

4. Conclusions

The performance of the SPEEK coated composite NF membranes for arsenic removal from drinking water were evaluated. The membranes showed a high rejection (above 95%) of As(V) with a water permeability about 11 L/(m²·h·bar). At higher pH of 9, high trans-membrane pressure (8 bar) and low feed concentration (360 µg/L), the membrane arsenic rejections were high (99.61%). The rejection properties of the membranes toward As in the presence of interfering ions were studied. Results showed that dielectric exclusion could rationally explain the rejection deviation from Donnan exclusion effect, where the presence of interfering ions and the valence of the ions played the major role. Finally, a cost estimation show that the treatment cost using the proposed SPEEK coated hollow fiber membrane for a plant of 1000 m³/h is about 0.15 US$/m³. This result indicates that the
SPEEK composite NF membranes can be a viable candidate for the arsenic removal from ground water.

Acknowledgments

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Reference