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The effectiveness of imidazolium ionic liquid concentration by electrodialysis with heterogeneous and homogeneous ion-exchange membranes

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ABSTRACT

In this study, the applicability of electrodialysis for aprotic imidazolium ionic liquid concentration and recovery was investigated. The recovery of the ionic liquid 1-butyl-3-methylimidazolium chloride was examined, and its degree of concentration, current efficiency, as well as energy consumption was determined. The effects of the applied voltage, ionic liquid concentration, linear flow velocity, and the type of ion-exchange membrane on the ionic liquid recovery and concentration were examined. A 2.5-fold concentration of 1-butyl-3-methylimidazolium chloride with a recovery of 86.9% and current efficiency of 92.8% was achieved with heterogeneous membranes. It was also found that the surface morphology and wettability of the heterogeneous AM(H) – CM(H) membranes before and after electrodialysis were unchanged, in contrast to the homogeneous FAB-PK – FKB-PK membranes, where surface changes occurred.

Keywords: Ionic liquids; Electrodialysis; Ionic liquids recovery; Heterogeneous ion-exchange membranes; Homogeneous ion-exchange membranes

1. Introduction

Ionic liquids (ILs) are a group of compounds gaining an important role in the fields of chemistry, electrochemistry, and environmental protection. ILs are substances of ionic structure with a melting point below 100°C. Due to their chemical properties, ionic liquids are classed as so-called "green solvents" [1,2]. ILs can be classified into two main groups: protic and aprotic ionic liquids. Protic ionic liquids are prepared through proton transfer from a Brønsted acid to a Brønsted base. However, aprotic ionic liquids, due to their more convenient to produce structure, have had greater attention. The aprotic ionic liquids consist of organic cations (e.g., imidazolium cations) and simple inorganic anions (e.g., halides) [3]. Ionic liquids can be also classified based on the evaluation of their structure and properties: for example, as task-specific ionic liquids, chiral ionic liquids, bio-ionic liquids, poly-ionic liquids, energetic ionic liquids, neutral ionic liquids, and metallic ionic liquids [4]. Ionic liquids are attractive compounds because they possess several advantageous properties such as versatile solubility, non-volatility, high polarity, and physical and chemical stability [5]. Therefore ILs are used in a variety of industrial fields, for example, electrochemistry, solvents, catalysis, and analytical chemistry [6].

ILs are also used in the environmental protection field, including technologies related to lignocellulosic biomass treatment. According to the available literature, cellulose dissolves very well in imidazolium and ammonium ionic liquids. 1-Butyl-3-methylimidazolium chloride ([Bmim]Cl) is an example of an ionic liquid used as a green solvent. It can be used as a solvent for cellulose dissolution and regeneration as it has the ability to dissolve biopolymers [7].

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It is also known as an ionic liquid with high ionic conductivity, so it is commonly used as a charge carrier [8].

Due to the high cost of ILs, problems with their separation from post-reaction solutions, their unfavorable dilution to very low concentrations during individual stages of processing, and the impact of waste solutions containing ionic liquids on the natural environment, it is important to conduct research on the recovery of ILs from post-reaction solutions, such as those derived from lignocellulosic biomass treatment [9].

In the existing literature, the methods of recovery of ionic liquids from solutions include extraction, adsorption, distillation, crystallization, and membrane separation techniques [1–3].

One of the most common methods used for IL recovery is extraction. In this method, the difference in the solubility of the separated chemicals in two immiscible liquid phases is used. It is a simple method with simple apparatus. However, some technical skills and a pre-concentration step are required. It is also an expensive and inefficient method [1,10]. Another method known to be non-destructive, easy to operate, and robust is adsorption. However, further research on the ionic liquid adsorption mechanism and adsorbent recyclability still need to be carried out [11]. Distillation is also known as a rapid, simple, and robust method; however, its major disadvantage is high energy consumption [2,12]. Another method used for the purification of ionic liquids is crystallization. Crystallization can give ionic liquids of high purity; however, similarly to distillation, crystallization often exhibits high energy consumption costs [1–3,13]. Membrane separation methods exhibit low energy consumption and allow the recovery of ILs by making use of their selective permeability [14].

In recent years, the use of membrane processes (e.g., electrodialysis) for the recovery of ILs from waste aqueous solutions has become increasingly important [15]. Electrodialysis (ED) is mainly used for the desalination of sea and brackish water, the treatment of electroplating industrial wastewater, the recovery of useful raw materials from various effluents, and the treatment of solutions from the food and drug industry [16–20].

The available literature [15,21–26] presents some results on the electrodialytic recovery of ILs from industrial wastewater. Experimental results for the electrodialytic recovery of 1-allyl-3-methylimidazolium chloride ([Amim]Cl) after biomass pretreatment were reported by the study of Liang et al. [21]. It was noted that electrodialysis can be an efficient and quick method for ionic liquid recovery from aqueous solution, allowing for the recovery of [Amim]Cl with a 71% recovery ratio. Electrodialysis was also applied for the efficient recovery of 1-butyl-3-methylimidazolium hydrogensulfate ([Bmim]HSO_4). It was found that ED with [Bmim]HSO_4 as an electrode rinse solution increased the recovery of [Bmim]HSO_4 to up to 96% [22]. [Bmim]HSO_4 can be also recovered and regenerated by bipolar membrane electrodialysis (BMED). In the study of Liang et al. [23], it was stated that BMED gave $[\text{Bmim}]^+$ cation and SO_4^{2-} anion recovery with 96.2% and 96% efficiency, respectively. BMED-assisted ultrafiltration was applied to the recovery of triethylammonium hydrogen sulfate [TEA][HSO_4]. Ultrafiltration was used for the removal of dissolved lignin in the filtrate, which was then transferred to a BMED module as a feed solution [24]. Hybrid membrane-based technology was also used for ILs recovery from biomass pretreatment wastewater. Residual lignin was removed by ultrafiltration, and 1-butyl-3-methylimidazolium bromide ([Bmim]Br) was then recovered by electrodialysis [25]. The influence of the electrodialysis parameters on the effectiveness of [Bmim]Cl recovery was discussed by the study of Trinh et al. [15] and Wang et al. [26]. It was noted that ionic liquid recovery by electrodialysis should be further investigated. IL recovery is highly dependent on the initial concentration and voltage.

Due to the need for further research on the recovery of ILs, in this study, the possibility of aprotic [Bmim]Cl recovery and concentration in a laboratory-scale electrodialysis module was investigated. The influence of the ionic liquid concentration, the applied voltage, the linear flow velocity, and ion-exchange membrane type on the effectiveness of electrodialysis in [Bmim]Cl recovery was examined. Model dilute [Bmim]Cl solutions in a concentration range of 0.1–0.5 mol L^{-1} were used. Therefore, the ionic liquid recovery coefficient, the ionic liquid concentration degree, the electric current efficiency, as well as energy consumption were determined. Moreover, the influence of the examined ionic liquid on the ion-exchange membrane's surface morphology and wettability was discussed.

2. Materials and methods

2.1. Electrodialysis module and ion-exchange membranes

The experiments were carried out using an EDR-Z/10-0.8 module (MemBrain, Czech Republic) with an effective membrane area of 64 cm^2. The effective area of one membrane was 64 cm^2. There were five pairs of membranes in the ED stack. The ion-exchange membranes (IEMs) used in this investigation were heterogeneous AM(H) – CM(H) (Ralex, Czech Republic) and homogeneous FAB-PK 130 – FKB-PK 130 (Fumasep, Germany). The characteristics of the employed IEMs are shown in Table 1. The anode and cathode in the electrodialyzer were made of platinized titanium. A schematic diagram of the electrodialysis module is shown in Fig. 1. All the experiments were conducted periodically with process solution recirculation. Process solutions such as the diluate, concentrate, and electrode-rinse solution were recirculated by a peristaltic pump (Masterflex L/S, Cole-Parmer, United States). The process solution volumes were 100 mL for the diluate, 50 mL for the concentrate, and 100 mL for the electrode rinse solution. The experiments were performed until the diluate conductivity dropped to 0.5 mS cm^{-1}, which was monitored using a CPC-461 pH/conductivity meter (ELMETRON, Poland). During the course of the experiments, the electric current, and conductivities of the diluate and the concentrate were measured periodically every minute. The experiments were all performed at 25°C.

Before and after the electrodialysis experiments, the surface morphology of the tested membranes was investigated using a scanning electron microscope (Hitachi TM3000 TableTop TM Series, Japan), equipped with a backscattered electron (BSE) detector. The wettability of

Table 1
Summary of the technical data for the applied ion-exchange membranes

Membrane symbol	AM(H)	CM(H)	FAB PK-130	FKB PK-130
Type	Heterogeneous	Heterogeneous	Homogeneous	Homogeneous
Thickness, mm	0.75	0.65	0.11–0.14	0.11–0.14
Ion-exchange capacity, meq g^{-1}	1.8	2.2	0.7–1.0	0.8–1.0
Ionic permselectivity, %	>90	>90	93–98	96–99
Surface electric resistance, Ω cm^2	<8	<8	5–9	2.5–5

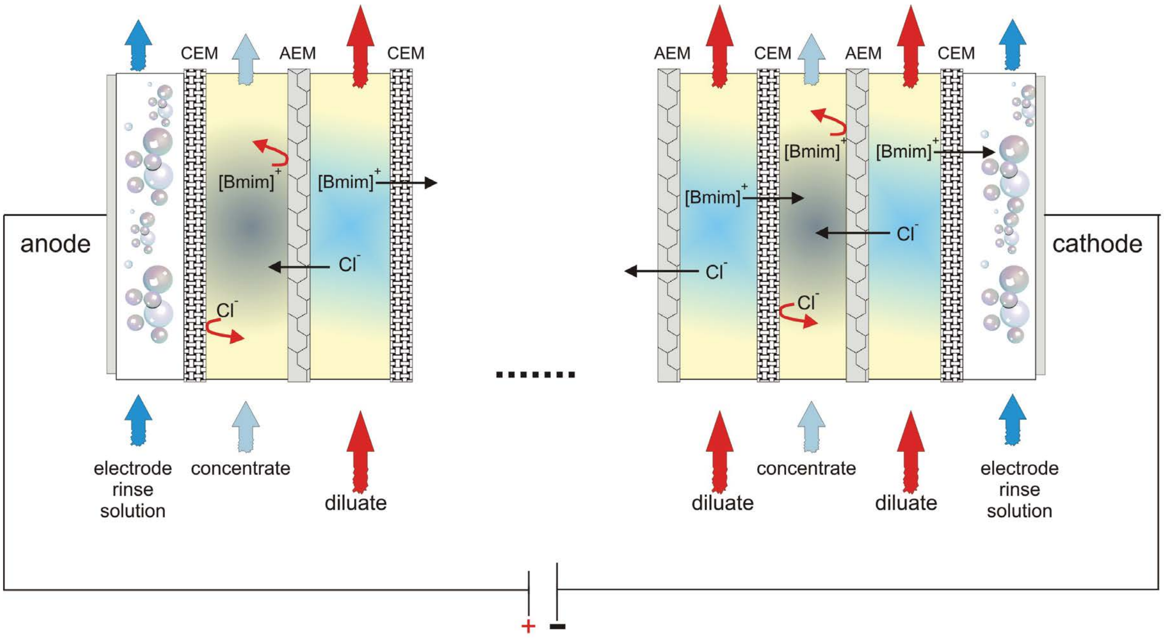

Fig. 1. Schematic representation of the electrodialysis module for ionic liquid recovery.

the membranes' surfaces was investigated using an optical contact angle measuring and contour analysis system (DataPhysics, OCA 15EC, Germany).

2.2. Experimental solutions

Experiments were conducted using model diluate, and concentrate solutions containing [Bmim]Cl (Sigma-Aldrich, USA). The particular solution compositions are presented in Table 2. Deionized water was prepared using a Millipore Elix 10 System.

2.3. Analytical methods

The concentrations of the [Bmim]Cl solutions were determined with a UV-Vis spectrophotometer (Varian Cary 50 Scan, Australia). The maximum absorption wavelength for the $[Bmim]^+$ cation was 211.40 nm.

2.4. Experiments

Experiments were conducted at a constant voltage. The effects of initial [Bmim]Cl concentration (0.1 to 0.5 mol L^{-1}), different applied voltages (5, 7.5, and 10 V), different linear flow velocities (1 to 3 cm s^{-1}) and the type of ion-exchange membrane (homogeneous or heterogeneous) were investigated. The experiments were performed until the diluate conductivity dropped to 0.5 mS cm^{-1}.

2.5. Data analysis

On the basis of the obtained results, the ionic liquid recovery ratio (R_{IL}), the ionic liquid concentration degree (R_{conc}), the electric current efficiency (CE_{IL}), as well as energy consumption (EC) were calculated as follows:

$$R_{IL} = \frac{m^{conc}_{IL,t}}{m^{dil}_{IL,0}} \cdot 100\% \qquad (1)$$

where $m^{dil}_{IL,0}$ is the initial mass (g) of the ionic liquid in the diluate solution before electrodialysis, and $m^{conc}_{IL,t}$ is the increase in the ionic liquid mass (g) in the concentrate solution after electrodialysis.

$$R_{conc} = \frac{C^{conc}_{IL,t}}{C^{dil}_{IL,0}} \cdot 100\% \qquad (2)$$

Table 2
Experimental conditions

Exp. no.	Initial diluate	Initial concentrate	Applied voltage, V
1.	100 mL of 0.103 M [Bmim]Cl	50 mL of 0.104 M [Bmim]Cl	10
2.	100 mL of 0.250 M [Bmim]Cl	50 mL of 0.250 M [Bmim]Cl	10
3.	100 mL of 0.511 M [Bmim]Cl	50 mL of 0.511 M [Bmim]Cl	10

where $C_{\mathrm{IL},0}^{\mathrm{dil}}$ is the initial concentration (mol L^{-1}) of the ionic liquid in the diluate solution before electrodialysis, and $C_{\mathrm{IL},t}^{\mathrm{conc}}$ is the final concentration (mol L^{-1}) of the ionic liquid in the concentrate solution after electrodialysis.

$$\mathrm{CE}_{\mathrm{IL}} = \frac{F \cdot z \cdot \dfrac{C_{\mathrm{IL},t}^{\mathrm{conc}}}{M_{\mathrm{IL}}} \cdot V_{\mathrm{conc},t}}{n \cdot \int_0^t I(t)dt} \cdot 100\% \quad (3)$$

where F is the Faraday constant (96,485 C mol^{-1}), z is the charge number of [Bmim]$^+$, $V_{\mathrm{conc},t}$ is the volume of the concentrate solution after electrodialysis (L), $C_{\mathrm{IL},t}^{\mathrm{conc}}$ is the concentration of the ionic liquid in the concentrate solution after electrodialysis (g L^{-1}), M_{IL} is the molar mass of [Bmim]Cl (g mol^{-1}), n is the number of membrane pairs, and I is the electric current (A).

$$\mathrm{EC} = \frac{U \cdot \int_0^t I(t)dt}{V_{\mathrm{dil},0}} \quad (4)$$

where EC is the energy consumption, U is the applied voltage (V), I is the electric current in (A), and $V_{\mathrm{dil},0}$ is the initial diluate volume (L).

3. Results and discussion

The objective of the present study was to investigate the effectiveness of the [Bmim]Cl recovery and concentration by the electrodialysis method. The effects of the initial ionic liquid concentration (0.1–0.5 mol L^{-1}), applied voltage drop (5–10 V), linear flow velocity (1–3 cm s^{-1}) and ion-exchange membrane surface morphology (heterogeneous/homogeneous) are described in the following sections.

3.1. Evaluation of the initial ionic liquid concentration effect

In this part of the study, the influence of the initial ionic liquid concentration in the diluate on the ED effectiveness is discussed. Experiments included three series of electrodialysis: with the different initial [Bmim]Cl concentrations in the diluate (0.1, 0.25, and 0.5 mol L^{-1}) at a constant potential of 10 V, a linear flow velocity of 2 cm s^{-1}, and heterogeneous Ralex ion-exchange membranes. As a concentrate, a [Bmim]Cl solution with the same ionic liquid concentration as in the diluate was used. The experimental conditions are shown in Table 2.

Ionic liquids are substances with an ionic structure, so in the ED process they can migrate across ion-exchange membranes under the applied electric field. As shown in Fig. 2, during the electrodialysis of [Bmim]Cl the diluate's conductivity decreased, while that of the concentrate increased. The diluate's conductivity initially decreased linearly, but by the end of the electrodialysis the conductivity changes were smaller and no longer had a linear character, due to a significant increase in the electrical resistance of the solutions in the desalination chambers. In addition, some effect of the initial ionic liquid concentration in the diluate on the ED performance was observed. It was shown that the electrodialytic desalination time increased with an increase in the initial diluate concentration. At higher feed concentrations the solution conductivity was higher, and a higher mass had to be transferred through the ion-exchange membranes.

In Fig. 3, the effects of feed concentration on ionic liquid distribution in the concentrate solution are presented. Upon completion of the experiment ionic liquid content in concentrate solution approached the value of 0.256, 0.572 and 0.903 mol L^{-1} for experiment no 1, 2 and 3 respectively. In Table 3 a summary of the effects of the initial ionic liquid concentration on the electrodialysis's effectiveness is presented. It was found that the electrodialysis of [Bmim]Cl gave effective ionic liquid recovery and concentration. It was observed that the ionic liquids were effectively removed from the diluate by the electrodialysis method with recovery rates of 86.9%, 89.4%, and 71.8% for 0.103, 0.250, and 0.511 M ionic liquid solutions, respectively. Moreover, it was noted that the ionic liquid concentration degree decreased with an

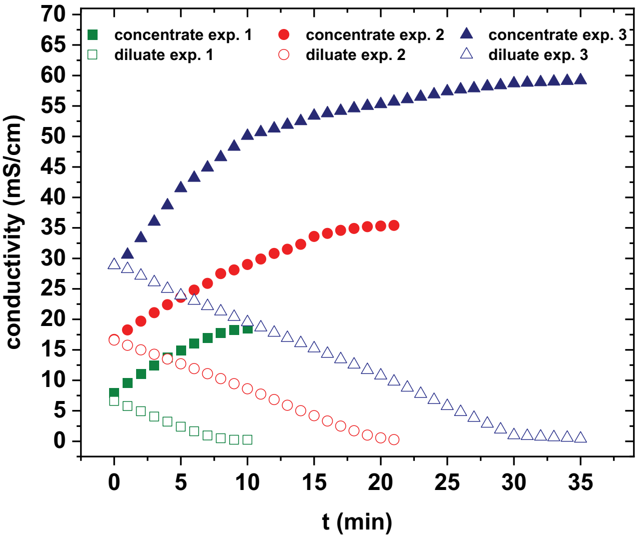

Fig. 2. Diluate and concentrate conductivity vs. time.

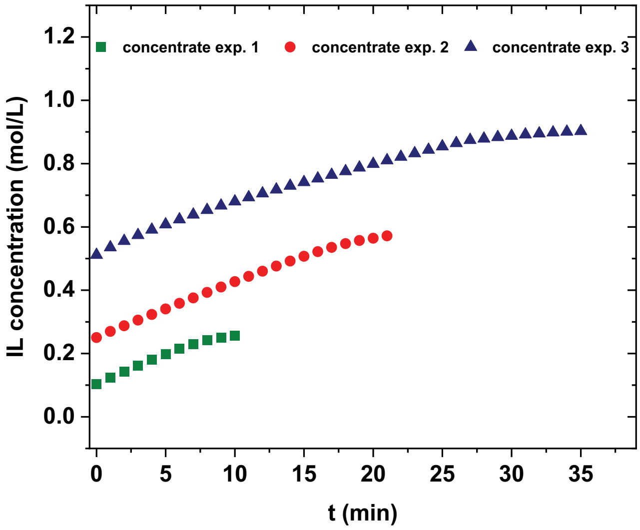

Fig. 3. Ionic liquid contents changes in the concentrate solution during the ionic liquid recovery effectiveness test.

increase in the initial ionic liquid concentration in the diluate due to the concentration gradient between diluate and concentrate during electrodialysis and electroosmotic water transport. The concentration degree could reach 2.5 for 0.1 M [Bmim]Cl (Fig. 3, Table 3).

The highest CE$_{IL}$ value was obtained for 0.1 M ionic liquid solution. It was found that the CE$_{IL}$ mostly depended on the initial ionic liquid concentration in the diluate. As shown in Table 3, the CE$_{IL}$ decreased with an increase in the initial ionic liquid concentration in the diluate. Due to the high concentration gradient, a large back diffusion of ions from the concentrate to the diluate compartment could occur. The lowest current efficiency (CE$_{IL}$) was observed at the highest initial ionic liquid diluate content (Table 3). Such behavior can also be attributed to the organic character of the ionic liquid compounds and their high molecular weight in the diluate, which may cause membrane fouling, thus hampering ion transport. In addition, charged organic species may migrate much more slowly across IEMs than simple ions or their hydrated forms, which seems to be supported by the decreased current efficiencies observed at higher ionic liquid concentrations.

Energy consumption (EC) also depended on the initial ionic liquid concentration in the diluate. As shown in Table 3, the EC increased with an increase in the initial ionic liquid concentration in the diluate, values of EC in a range of 5.2–27.5 kWh m^{-3} being found. The EC linearly increased when the initial ionic liquid content in diluate increased, due to the greater energy needed to transport ions across the ion-exchange membranes.

3.2. Evaluation of the applied voltage drop effect

The influence of the applied voltage drop on the effectiveness of ionic liquid recovery and concentration was evaluated by three electrodialysis experiments conducted with the same ionic liquid concentration (0.5 M [Bmim]Cl), and linear flow velocity (2 cm s^{-1}). The examined voltage drops were 5, 7.5, and 10 V. The experiments were conducted until the diluate's conductivity was lower than 0.5 mS cm^{-1}. The obtained results were evaluated by the IL recovery ratio, the ionic liquid concentration degree, the electric current efficiency, as well as energy consumption. The results are presented in Table 4.

Table 3
The influence of the initial ionic liquid concentration on the electrodialysis effectiveness factors (U = 10 V; w = 2 cm s^{-1})

Exp. no.	$C^{dil}_{IL,0}$, mol L^{-1}	R_{IL}, %	R_{conc}	CE$_{IL}$, %	EC, kWh m^{-3}
1.	0.103	86.9	2.5	92.8	5.2
2.	0.250	89.4	2.3	87.6	13.7
3.	0.511	71.8	1.8	71.7	27.5

As was suspected, the electrodialysis process time decreased with an increase in the applied voltage. When the applied voltage increased, the driving force for ion transport across the membranes also increased. Table 4 shows that the IL concentration degree depended on the applied electrical potential. The R_{conc} increased slightly with an increase in the applied voltage drop. Under the examined conditions the maximum value of R_{conc} was 1.8 for 10 V. It was also found that the applied voltage had some effects on the ionic liquid recovery and current efficiency. When the electric potential drop increased from 5 to 7.5 V, the ionic liquid recovery and current efficiency slightly increased to maximum values of 76.2% and 74.7%, respectively. In the case of 10 V, the ionic liquid recovery and current efficiency slightly decreased to 71.8% and 73.8%, respectively. As shown in Table 4, the energy consumption increased with the increasing applied potential drop.

3.3. Evaluation of the linear flow velocity effect

The electrodialysis efficiency depends not only on operational parameters such as electrical properties, but also on fluid dynamics. The influence of the linear flow velocity on the effectiveness of ionic liquid recovery was evaluated by three electrodialysis experiments conducted with the same IL concentration (0.5 M [Bmim]Cl) and voltage drop (10 V). The examined linear flow velocities were 1, 2, and 3 cm s^{-1}. Experiments were conducted until the diluate's conductivity was lower than 0.5 mS cm^{-1}. The influence of linear flow velocity on the electrodialysis performance is shown in Table 5. It was noted that the ionic liquid concentration degree did not greatly depend upon the linear flow velocity. In all cases, the concentration degree was slightly higher than two. Moreover, the energy consumption did not depend on the solution flow velocity. However, the IL recovery and electric current efficiency increased slightly with an increase in the linear flow velocity, as shown in Table 5. When the solution flow velocity increased from 1 to 2 cm s^{-1}, the ionic liquid recovery and current efficiency increased to maximum values of 86.9% and 92.8%, respectively. In the case of a 3 cm s^{-1} velocity, the ionic liquid recovery and current efficiency slightly decreased to 67.9% and 71.2%, respectively. This trend can be explained by the residence time of ions inside the compartments of the electrodialyzer. When the linear flow

Table 4
The influence of applied voltage drop on the electrodialysis effectiveness factors ($C^{\mathrm{dil}}_{\mathrm{IL},0}$ = 0.527 M [Bmim]Cl; w = 2 cm s^{-1})

Electric potential, V	n_F, mol	R_{IL}, %	R_{conc}	$\mathrm{CE}_{\mathrm{IL}}$, %	EC, kWh m^{-3}
5	0.0592	73.1	1.6	65.1	15.9
7.5	0.0538	76.2	1.7	74.7	21.6
10	0.0512	71.8	1.8	73.8	27.5

velocity is lower than 3 cm s^{-1} and higher than 1 cm s^{-1}, the ions have more time to be transferred through the ion-exchange membranes.

3.4. Evaluation of the membrane type effect

Due to a variety of membrane fabrication methods, ion-exchange membranes have different features and give different concentration efficiency values. Therefore, in this study, the influence of the type of ion-exchange membrane on the ionic liquid recovery and concentration efficiency was investigated. Heterogeneous AM(H) – CM(H) (Ralex, Czech Republic), and homogeneous FAB-PK 130 – FKB-PK 130 (Fumasep, Germany) ion-exchange membranes were used in this investigation. The influence of the membrane type on the effectiveness of ionic liquid recovery was evaluated by two electrodialysis experiments conducted with the same ionic liquid concentration (0.1 M [Bmim]Cl), voltage drop (10 V), and linear flow velocity (2 cm s^{-1}). The evaluation of membrane effects also included the surface morphology and an examination of wettability. The scanning electron micrographs and wettability of the pristine membranes and of the membranes after the experiments are presented in Figs. 4 and 5. The AM(H) – CM(H) Ralex membranes are an example of membranes with heterogeneous surface morphology. As shown in Fig. 4, the AM(H) – CM(H) membranes exhibited porous surfaces with the ion-exchange resin heterogeneously incorporated into the polymer membrane matrix, in contrast to the smooth homogeneous FAB-PK – FKB-PK membranes. Both the heterogeneous and homogeneous membranes were hydrophobic in nature. The influence of membrane type on the electrodialysis performance is shown in Table 6. It was found that the energy consumption did not particularly dependent upon the ion-exchange membrane type, with values of EC in a range of 5.2–5.3 kWh m^{-3} being found. However, the membrane-type had strong effects on the ionic liquid recovery, concentration degree, and current efficiency. It was noted that the heterogeneous AM(H) – CM(H) membranes allowed up to 86.9% ionic liquid recovery with a current efficiency equal to almost 93%. Moreover, the results in Table 6 showed that the [Bmim]Cl content in the concentrate after electrodialysis was 2.5 times higher than in the initial working solutions. Additionally, the electrodialysis effectiveness factors for the experiment with homogeneous FAB-PK 130 – FKB-PK 130 ion-exchange membranes (presented in Table 6) indicated lower values than for the heterogeneous membrane type. There was direct evidence that the type of membrane had an influence on the effectiveness of [Bmim]Cl

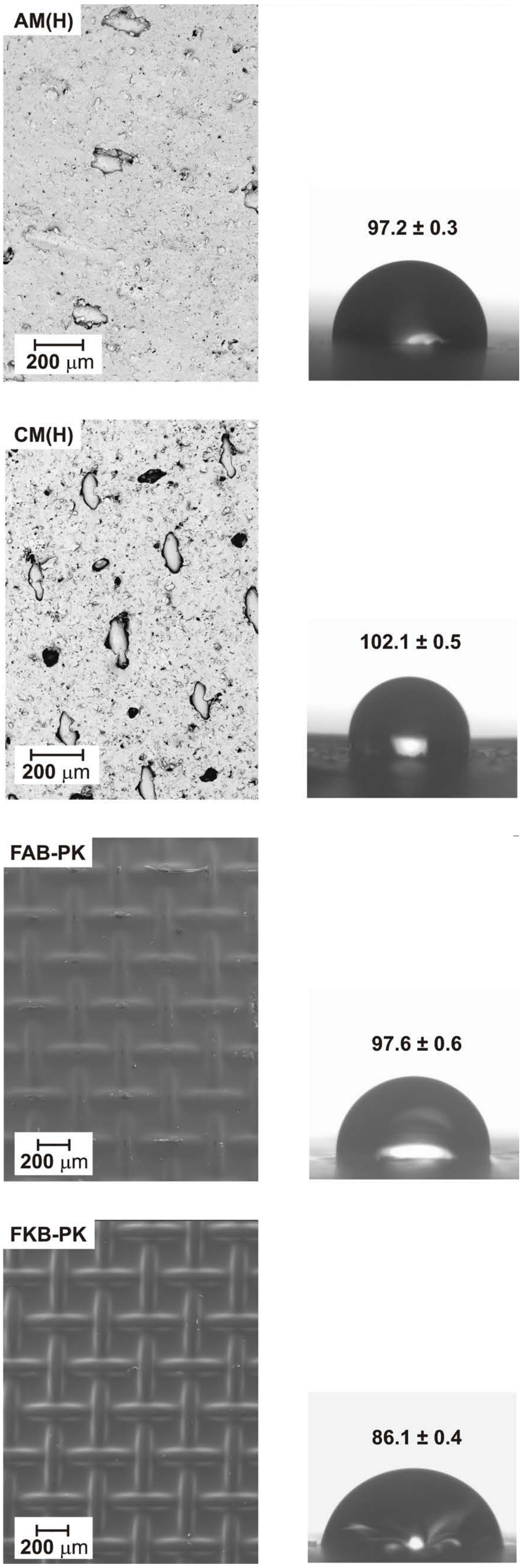

Fig. 4. Morphology and wettability of the tested membrane surface before the experiments.

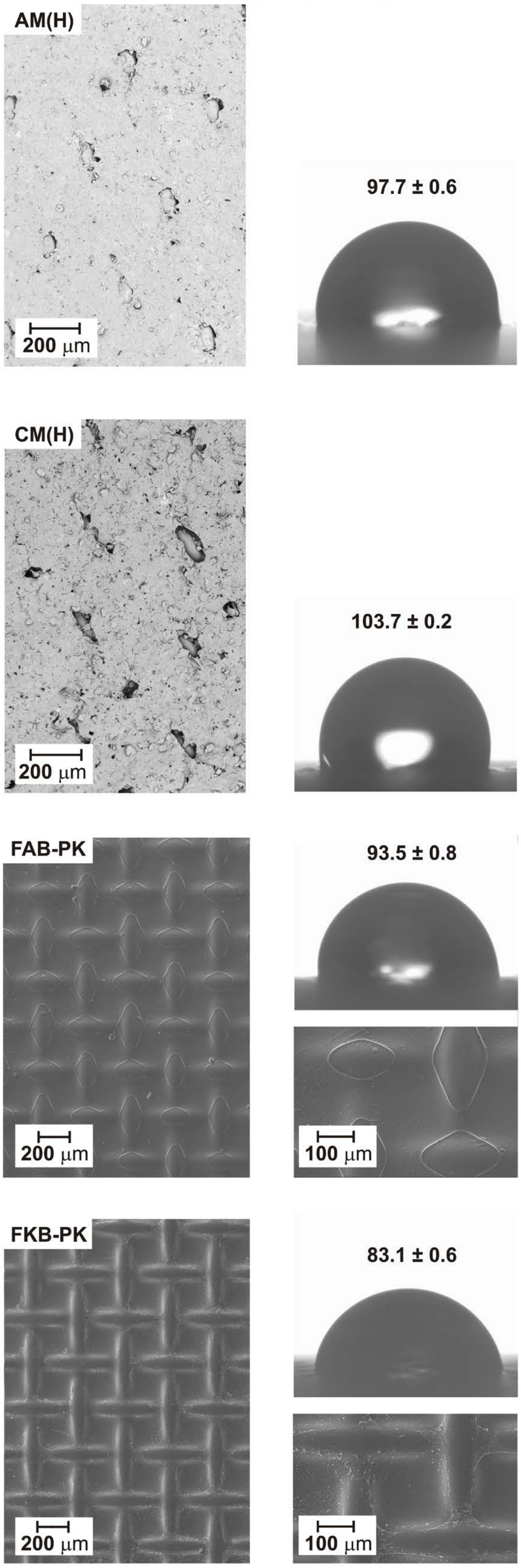

Fig. 5. Morphology and wettability of the tested membrane surface after the experiments

recovery. As shown in Table 1, the tested heterogeneous membranes had a higher ion-exchange capacity.

As shown in Fig. 4, the AM(H) – CM(H) membranes had an evident heterogeneous character, surface roughness, and pores, which probably improved ionic liquid transport across the membrane to the concentrate compartment. It should also be noted that the non-porous, homogeneous FAB-PK – FKB-PK membranes could restrict the transport of organic species. On the other hand, the ion flux across the membranes may also be reduced by membrane fouling. In Fig. 5 the morphology and wettability of the tested membrane surfaces after the experiments are presented. It can be noted that there was no great difference in the surface morphology and wettability of the heterogeneous AM(H) – CM(H) membranes before and after the experiments. However, in the case of the tested homogeneous FAB-PK – FKB-PK membranes, slight changes to the surface morphologies and wettability were observed. A thin, soft layer or particles on the FAB-PK – FKB-PK homogeneous membranes surfaces were noted; these are also presented under magnification in Fig. 5. The observed changes on the homogeneous membranes after electrodialysis probably affected the ion migration and increased the duration of the experiment, and therefore had some effects on the ED effectiveness factors presented in Table 6. Lindstrand et al. [27] it was stated that organic species present in feed solutions cause the fouling of IEMs and affect ion migration in an electric field. However, in this study, it could be clearly seen in both cases that the membrane polymer matrix was not degraded, and the ion-exchange membranes were stable for ionic liquid recovery by the electrodialysis method.

4. Conclusions

In this study, the possibility of ionic liquid recovery and concentration from aqueous solutions by ED was investigated. It was observed that [Bmim]Cl was removed from the diluate effectively by the proposed method. The obtained results proved the possibility of electrodialysis recovery of up to 86.9% of the [Bmim]Cl at a current efficiency as high as 92.8%. The electrodialysis process allows not only for ionic liquid recovery, but also for the concentration of the ionic liquid. In fact, the [Bmim]Cl content in the examined process increased 2.5 times in comparison to the ionic liquid concentration in the initial diluate compartment. It was shown that the ionic liquid concentration, applied voltage drop, linear flow velocity, and membrane type all had an influence on the ED ionic liquid recovery and concentration. The highest electrodialysis efficiency for [Bmim]Cl recovery and concentration was obtained at 2 V applied potential per one membrane pair, 2 cm s^{-1} linear flow velocity, using heterogeneous Ralex membranes and 0.1 M ionic liquid in the feed solution. On the basis of the obtained results, it can be concluded that the electrodialysis of [Bmim]Cl is more profitable for solutions with a lower initial ionic liquid concentration, because it enables a greater ionic liquid concentration degree and is also characterized by a lower energy consumption. However, ED can be also successfully used for [Bmim]Cl recovery from solutions with higher ionic liquid concentrations. It was also noted that the surface morphology and wettability of the heterogeneous

Table 5
The influence of linear flow velocity on the electrodialysis effectiveness factors ($C^{\text{dil}}_{\text{IL,0}}$ = 0.1 M [Bmim]Cl; U = 10 V)

Linear flow velocity, cm s^{-1}	n_F, mol	R_{IL}, %	R_{conc}	CE$_{\text{IL}}$, %	EC, kWh m^{-3}
1	0.0095	65.0	2.1	68.1	5.1
2	0.0096	86.9	2.5	92.8	5.2
3	0.0095	67.9	2.2	71.2	5.1

Table 6
The influence of membrane type on the electrodialysis effectiveness factors ($C^{\text{dil}}_{\text{IL,0}}$ = 0.1 M [Bmim]Cl; U = 10 V; w = 2 cm s^{-1})

Membrane type	R_{IL}, %	R_{conc}	CE$_{\text{IL}}$, %	EC, kWh m^{-3}
Heterogeneous AM(H) – CM(H)	86.9	2.5	92.8	5.2
Homogeneous FAB PK130 – FKB PK130	81.9	1.8	80.5	5.3

AM(H) – CM(H) membranes after electrodialysis were unchanged, in contrast to the homogeneous FAB-PK – FKB-PK membranes, where surface changes were noted.

Symbols

[Bmim]Cl — 1-butyl-3-methylimidazolium chloride
CE$_{\text{IL}}$ — Electric current efficiency, %
$C^{\text{conc}}_{\text{IL,0}}$ — Initial concentration of the ionic liquid in the concentrate solution before electrodialysis, mol L^{-1}
$C^{\text{conc}}_{\text{IL},t}$ — Final concentration of the ionic liquid in the concentrate solution after electrodialysis, mol L^{-1}
EC — Energy consumption, kWh m^{-3}
ED — Electrodialysis
F — Faraday constant 96,485 C mol^{-1}
I — Electric current, A
IEMs — Ion-exchange membranes
IL — Ionic liquid
M_{IL} — Molar mass of [Bmim]Cl, g mol^{-1}
$m^{\text{conc}}_{\text{IL},t}$ — Increase in the ionic liquid mass in the concentrate solution after electrodialysis, g
$m^{\text{dil}}_{\text{IL,0}}$ — Initial mass of the ionic liquid in the diluate solution before electrodialysis, g
n — Number of membrane pairs
n_F — Number of moles of elementary charge passed through the system, mol
R_{conc} — Concentration degree
R_{IL} — Ionic liquid recovery, %
t — Time, min
U — Applied voltage, V
$V_{\text{conc},t}$ — Volume of the concentrate solution after electrodialysis, L
$V_{\text{dil,0}}$ — Initial diluate volume, m^3
w — Linear flow velocity, cm s^{-1}
z — Charge number of [Bmim]$^+$

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Declaration of competing interest

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