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Towards the potential of absorbing pervaporation based on ionic liquids for gas mixture separation

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ABSTRACT

A separation of a CH_4/CO_2 mixture was performed via absorbing pervaporation using ionic liquids as absorbent, using membrane gas separation as a comparator. Three factors were determined: the individual gas permeability through a poly(dimethyl-siloxane) membrane; the influence of the ionic liquid 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ([bmim][Tf_2N]); and the stage-cut value on separation factor. Both experiments were carried out at three different flux ratios. The separation factor was determined with different stage-cut values for both absorbing pervaporation and membrane gas separation. The results show a directly proportional dependence of the separation factor from stage cut. Due to higher CO_2 solubility in [bmim][Tf_2N] in comparison with CH_4, the ionic liquid separation factor using absorbing pervaporation is higher than for the comparable membrane gas separation. The superior performance of absorbing pervaporation vs. membrane gas separation in CH_4/CO_2 separation applications was observed.

Keywords: Polydimethylsiloxane; Ionic liquid absorbing pervaporation; Ionic liquids; Mixture separation; Membrane; Gas; Carbon dioxide; Methane

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1. Introduction

The separation of CO_2 from natural gas and biogas (i.e., CH_4/CO_2 separation) has received significant attention due to the growing importance of natural gas as an energy resource [1] and biogas as one of the most important renewable energy sources, due to the low environmental impact and high energy conversion efficiency during the production [2–5]. However, CO_2 is one of the most serious impurities in natural gas regardless of the type of gas reservoir. It is the source of many operational problems such as pipeline corrosion, gas hydrate formation, pressure drop in transmission, and gas heating value reduction. However, high content of CO_2 in natural and biogases is not conducive to its utilization in applications such as stoves fuel, vehicles, and fuel cells [6]. Therefore, removal of CO_2 from CH_4 sources plays an important role [7,8].

The conventional techniques such as amine scrubbing, cryogenic separation, physical and chemical adsorptions, and pressure swing adsorption have been successfully used for CH_4/CO_2 separation, through which the CH_4 purity can reach 95.98% [6,9,10]. Despite this, these techniques have

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significant drawbacks, (i.e., high operating pressure, low operating temperature, corrosion risks, and/or high energy costs) [3,7]. Therefore, a process that improves the efficiency of current separation techniques, or the development of a novel separation, would be of great value to the field.

Compared with energy-intensive CO_2, separation methods such as amine scrubbing, membrane-based separations are generally regarded as being more environmentally benign, having a smaller footprint, and reducing capital and operating costs. To be competitive with conventional separation processes, membranes must be high in productivity (permeability) and efficiency (selectivity). Obtaining polymeric membranes with high permeability and high selectivity is difficult due to the inherent trade-off in these two criteria [1]: the selectivity and permeability of membranes can be visualized using a Robeson plot, which shows membranes with higher permeability generally have lower selectivity and vice versa [11]. To improve the efficiency of separation, the membrane methods are used in a combination with well-known methods of separation: absorption, rectification, etc. The research in combining the absorption and pervaporation methods for the extraction of valuable components from gas mixtures, realized in one devicem, is of interest. An ionic liquids as selective absorbents were chosen.

Particularly noteworthy are techniques combined with gas absorption, such as membrane contactors and pervaporation. The membrane contactor can provide a calculable high specific surface area, independent controllable gas and liquid flow rates, and a linear scale-up design; while the gas absorption can give a high selectivity and a high mass transfer driving force [12]. Membrane gas absorbing contactors have been extensively studied involving CO_2 capture, H_2S and SO_2 removal, and volatile organic compounds (VOCs) recovery [12–14]. Membrane gas absorption is a promising, competitive alternative to conventional (e.g., packed tower, spray tower, or bubble columns) processes. Relevant investigations on membrane gas absorption have made significant progress [12–18].

This name of hybrid method that was proposed was called "absorbing pervaporation" [19]. This hybrid separation technique is a combination of gas absorption by liquid absorbent displaced on the membrane and further pervaporation (vaporization of gases at the downstream face on the membrane) [19–22]. Absorbing pervaporation technique using ionic liquids as an absorbent has the same advantages. Additionally, this process can be performed out without any phase transformation, in a one-volume mass-exchange apparatus and with an ionic liquid-polymer system that provides high selectivity due to high CO_2 solubility in the ionic liquid [19–22]. Furthermore, absorbing pervaporation apparatus does not require any heat supply/removal and has a scalable design that demonstrates its superior efficiency when compared with other membrane separation applications [20].

In spite of the low CO_2 permeability (<10 Barrers) and reasonable ideal CO_2/CH_4 selectivity (ca. 30–60), many membrane-based industrial CO_2/CH_4 separation processes use cellulose acetate-based materials [23,24]. The material advantages of these membranes, in particular their low cost, processability, and chemical resistance (which removes the need for pre-treatment of the gas stream), have ensured their continued industrial use [24]. Competing membrane technologies, including those under development are poly(imide), poly(fluorocarbon), and amine-based facilitated transport membranes, along with carbon molecular sieve membranes [11,24,25].

Thermally rearranged (TR) polymers are an emerging class of materials that display excellent CO_2/CH_4 selectivity properties (ca. 60) with high CO_2 permeabilities (ca. 100 Barrers) [26,27]. However, TR polymers require a thermal activation at ca. 400°C, which limits the opportunity to process these materials on organic supports or using organic "gutter layers" (which are thermally unstable at 400°C). Activated TR polymers are insoluble and inherently brittle, posing a difficult problem for preparing and processing membranes from these materials [11,26,27].

Zeolites are a class of porous, crystalline silicate-based frameworks with pore sizes matched to the size of light gas molecules [28–30]. Many zeolites have Al atoms isomorphously substituted for Si atoms and are thus charged materials with net anionic frameworks and mobile cations in the pores. As a result of molecular size matching with light gas molecules of interest, zeolite membranes can display high CO_2/CH_4 separation selectivities and CO_2 permeabilities due to a combination of preferential adsorption/desorption and molecular sieving [28–30]. Unfortunately, processing of these polycrystalline materials into thin, defect-free membrane configurations is technically challenging and currently prohibitively expensive [29–31] (limiting their widespread implantation).

Among the membrane materials that various research groups have screened for use with poly(dimethyl-siloxane) (PDMS) was shown as an attractive candidate. PDMS, as a reserve-selective, rubbery polymer material, favors permeation of gases with higher condensabilities, suggesting that the permeation rate of CO_2 through such a membrane exceeds that of less condensable, light compounds such as CH_4 [32,33]. Thus, PDMS is characterized with a remarkable permeability for CO_2 and a moderate CH_4/CO_2 selectivity [34,35].

Recently, room-temperature ionic liquids (RTILs) have been used [36–38]. RTILs owe their unexpected popularity to their remarkable properties. They are neat salts that are liquids at temperatures ≤100°C, and have a unique combination of material properties that include negligible volatility, high thermal stability, no flammability, good ion conductivity, and high intrinsic solubility of CO_2 compared with other light gases [36]. Since their discovery, ionic liquids have piqued the interest of many researchers, resulting in an expansion of the many chemical technologies field, and as well as analytical chemistry [39], biochemistry [40], catalysis [41–43], electrochemistry [37,44], separation technology [38,45–47], fluid engineering [48], and others [49–51]. Blanchard et al. [51] were the first to observe that significant amounts of CO_2 could be dissolved in imidazolium-based ionic liquids to facilitate the extraction of dissolved carbon dioxide, without contaminating from the ionic liquid, due to its insolubility in CO_2. It is known that the solubility of CO_2 increases in the following order of the anions: $[NO_3] < [SCN] < [MeSO_4] < [BF_4] < [DCA] < [PF_6] < [Tf_2N] < [Methide] < [C_7F_{15}CO_2]$ [52]. The paired $[Tf_2N]$ anion with different cations demonstrates the following trend in CO_2 solubility: [omim] > [hmim] > [pmim] > [bmim] > [emim] [53–55].

These results have inspired the current study of absorbing pervaporation based on ionic liquid for CH_4/CO_2 separation, whereas the ionic liquid [bmim][Tf_2N] was chosen due to the high solubility of CO_2. A PDMS membrane was chosen for this experiment due to the high permeability values of this material.

2. Experimental technique

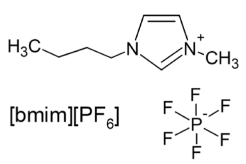
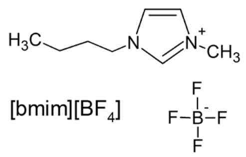
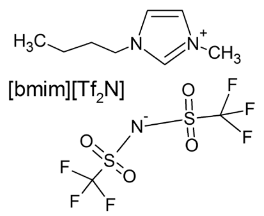
2.1. Materials

In this study, PDMS 5 μm thickness non-porous membrane on support purchased from Vladipor JSC (Vladimir, Russia) was used. To prepare the binary systems, the following materials were used high purity 99.9% wt. methane (Monitoring, Russia) and 99.999% wt. carbon dioxide (Monitoring, Russia). Ionic liquids [bmim][Tf_2N], [bmim][BF_4], and [bmim][PF_6] were purchased from Sigma-Aldrich Group (USA). The structure of the ionic liquids and their water content are shown in Table 1. All ILs were dried under vacuum for 24 h, at which point the water content was found using Karl–Fischer titration technique by Coulometer 831 KF (Metrohm, Switzerland) to be between 0.03% and 0.24% (w/w) (Table 1).

2.2. Preparation of binary gas mixture

The feed gas mixture CH_4/CO_2 was prepared in sealable gas container by static volumetric method. For CH_4/CO_2 mixture (1 ± 0.05 vol.% CO_2 content), CO_2 (99.999%) and CH_4 (99.9%) were used. CH_4 and CO_2 were filled in the preliminary vacuumed container to reach the appropriate ratios. The composition was analyzed by gas chromatography for confirmation of the calculated gas mixture ratio.

Table 1
Source and water content in conventional ionic liquid

Name and structure of IL	Source	Water content (ppm)
 [bmim][PF_6]	Sigma-Aldrich (USA)	900.8
 [bmim][BF_4]	Sigma-Aldrich (USA)	2366.3
 [bmim][Tf_2N]	Sigma-Aldrich (USA)	308.7

2.3. Apparatus and procedures

The experimental setup presented in Fig. 1 was designed for high precision membrane gas separation experiments. Setup included: 1 – a membrane module [56] made of stainless steel (316 SS), 2 – chemical resistant membrane vacuum pump (Ilmvac LVS 105 T-ef), 3 – reducers on CH_4/CO_2 mixture and carrier gas, 4 – membrane valves (Swagelok SS-DSS4) on gas and vacuum lines, 5 – pneumatic valves on feed and permeate side controlled by solenoid valves, 6 – manometers, 7 – pressure sensors (Wika pressure transmitter 0–16 bar on feed side and MKS Instruments Baratron pressure transducer 0-20 torr on permeate side), and 8 – flowmeters on feed and permeate outlets of membrane module. Setup connected to gas chromatograph (GC) "Tswet 800" (Tswet, Dzerzhinsk, Nizhny Novgorod region, Russia) and to personal computer (PC).

The preparation of binary gas mixture was carried out on this setup, which included two high-precision digital pressure gauges (CPG 1000, Wika, accuracy: ±0.05% FS positive pressure: ±0.25% FS vacuum/500 psi; and below) for low and high pressure, which is necessary for mixtures preparation with the desired concentration.

CH_4/CO_2 mixture determination was carried out by gas chromatography, using helium carrier gas (99.99999%, Monitoring, Russia), a thermal conductivity detector (TCD), and a Porapak™ Q packed column (70°C 60/80 mesh 4 m × 2 mm inner diameter stainless steel tube) with detection limits of 1×10^{-3} %mol. The analytical procedure is described in detail in previous publications [57–60].

2.4. Contact angle determination

The measurement of contact angle between the polymer and ionic liquid was provided using the drop shape method described in our previous works [61–63]. The droplet of ionic liquid (IL) was placed on the polymer surface, and an image of drop shape was obtained. The optical system apparatus consisted of a light source, an adjustable stage, and a USB optical microscope. The microscope (Chuo Seiki, TS-H) was fixed on an adjustable microscope mount. A digital image of the drop shape was made using CCD camera of microscope. The ImageJ® software with DropSnake plugin was used for the calculation of contact angle value.

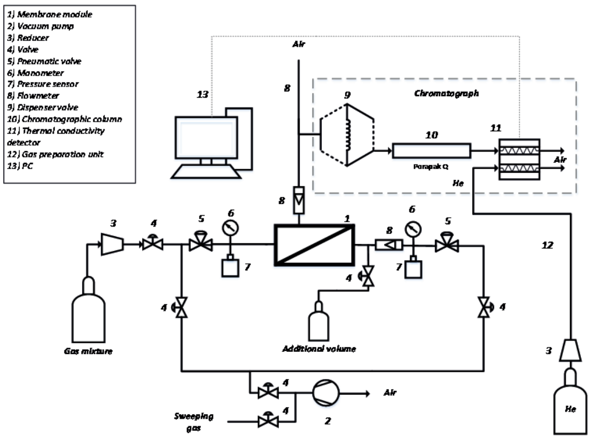


Fig. 1. The scheme of the gas separation membrane system.

2.5. Single gas permeation test

He, N_2, CO_2 and CH_4 single gas permeation test was performed for PDMS membrane and PDMS covered by 2 mm uniform layer of [bmim][Tf_2N] system with active area available for permeation 2.54 cm^2, according to a well-known time-lag method [64]. The feed pressure of single gases was set at 110 kPa by a reducer and recorded by pressure transmitter on the feed side. Pressure on the permeate side was provided by a turbo pump and was equal to 0.006 Pa; consequently, the transmembrane pressure difference was about 110 kPa. Before each measurement was performed, regeneration of the ionic liquid by heating to 70°C and system was evacuated for 24 h. Following this, gas was filled at 110 kPa pressure and restrained over 12 h for IL saturation. The single gas permeability through every sample was measured in triplicate.

2.6. Membrane gas separation test

PDMS membrane was placed on a porous stainless steel support and sealed in a stainless steel membrane module 1 using a fluoroplastic O-ring. The feed pressure of CH_4/CO_2 mixture was set at 110 kPa by reducer and monitored by feed side pressure sensor. Pressure on the permeate side was assured by vacuum pump and was equal to 2 kPa; consequently, the transmembrane pressure difference was about 100 kPa. The pump allowed the desired pressure on the permeate side (in the range of 0.4–100 kPa). Fluxes rate on outlets from feed and permeate side was recorded by flowmeters. Depleted feed flux on outlet of membrane module was analyzed by gas chromatograph. All the measurements were conducted at ambient temperature (23°C).

2.7. Ionic liquid absorption pervaporation test

PDMS film with effective area 15.2 cm^2 was covered by 3 mL of [bmim][Tf_2N] ionic liquid corresponded to approximately 2 mm height of uniform IL layer. The feed pressure of CH_4/CO_2 mixture was set at 110 kPa by reducer and monitored by feed side pressure sensor. Pressure on the permeate side was assured by vacuum pump and was equal to 0.4 kPa (due to lower flux rate through the PDMS film covered by ionic liquid), so the transmembrane pressure difference was about 110 kPa. Flux rates on outlets of membrane module were recorded by flowmeters; feed flux on outlet of membrane module was analyzed by gas chromatograph as in membrane gas separation test described above. All the measurements were conducted at ambient temperature (23°C).

2.8. Theoretical calculation

Individual gases permeability tests were carried out, and permeability coefficient (P, mol m m^{-2} s^{-1} Pa^{-1}), diffusion coefficient (D, m^2 s^{-1}), and sorption coefficient (S, mol m^{-3} Pa^{-1}) were calculated.

Permeability coefficient P was calculated according to:

$$P = \frac{Vp_2T_0}{V_m p_0 T}\frac{l}{S\tau(p_1 - p_2)} \qquad (1)$$

where V is downstream volume (mL); V_m, molar volume (mL mol^{-1}); p_2, permeate pressure for each individual experiment (Pa); p_1, feed pressure (Pa); p_0, atmospheric pressure (Pa); T, temperature (K); T_0, normal temperature (K); S, membrane effective area (m_2); τ, time of experiment (s); and l, membrane thickness (m).

To determine diffusion coefficient, the time-lag method was used, and it was calculated according to:

$$D = \frac{l^2}{6\theta_t} \qquad (2)$$

where θ_t is defined as time lag, s.

Sorption coefficient S was calculated through:

$$S = \frac{P}{D} \qquad (3)$$

Ideal selectivity of PDMS membrane was calculated as ratio of individual gases permeability coefficients through:

$$\alpha = \frac{P_A}{P_B} \qquad (4)$$

where P_A and P_B are permeability coefficients of A and B gas, respectively.

Membrane gas separation and ionic liquid absorption pervaporation tests were carried out and separation factor F as function of stage cut θ was determined and compared.

To determine separation factor, the gas chromatography method was used, and it was calculated according to [56]:

$$F = \frac{C_{\text{in}}}{C_{\text{out}}} \qquad (5)$$

where C_{in} is CO_2 content in CH_4/CO_2 mixture in feed flow, and C_{out} in retentate flow.

Stage cut, the parameter defined as the fractional amount of the total feed entering a membrane module that passes through the membrane as permeate, is determined as:

$$\theta_{\text{st}} = \frac{J_{\text{permeate}}}{J_{\text{feed}}} \qquad (6)$$

where feed flow rate is J_{feed}, and permeate flow rate is J_{permeate} (mL min^{-1}).

3. Results and discussion

3.1. Ionic liquid and PDMS surface interaction

The hydrophobicity of the polymer used was investigated by contact angle measurements [61–63]. Polydimethylsiloxane was used as support for 1-butyl-3-methylimidazolium cation ([bmim]), paired with bis(trifluoromethylsulfonyl)imide ([Tf_2N]), tetrafluoroborate ([BF_4]), and hexafluorophosphate

([PF_6]). The measured contact angles between the various ionic liquids on poly(dimethylsiloaxne) support are shown in Table 2.

The contact angle describes the interactions between the support and liquid phase. As shown in Fig. 2, among the ILs tested the wettability of PDMS surface was the highest in case of [bmim][Tf2N]. Thus, in addition to high CO_2 solubility, [bmim][Tf_2N] demonstrates the strongest interaction with PDMS surface.

3.2. Single gas permeation data

Permeability data of single gases: He, N_2, CO_2, and CH_4 through PDMS membrane and PDMS + IL membrane were determined from single gas permeation test and presented in Table 3. The lower helium and nitrogen permeability values compared with methane and carbon dioxide are explained in several works [50,52,65–67].

The diffusion and sorption coefficients were calculated from single gas permeation test and are shown in Table 4. The ideal selectivity for CO_2 systems was calculated and shown in Table 5.

Table 2
Contact angle between different ionic liquids and PDMS support

Ionic liquid	θ_{ca}
[bmim][Tf_2N]	58.4 ± 0.6
[bmim][BF_4]	90.0 ± 0.6
[bmim][PF_6]	69.3 ± 0.6

Table 3
Individual gases permeability through PDMS and PDMS + IL membranes with skin layer thickness 5 μm

Gas	p_{feed}, bar	P, Barrer	
		PDMS	PDMS + [bmim][Tf_2N]
He	1.1	420	0.9
N_2		230	0.3
CO_2		2,000	3.5
CH_4		800	0.09

Note: 1 Barrer = 3.346 × 10^{-16} mol m s^{-1} m^{-2} Pa^{-1}.

As seen from the results shown in Tables 3 and 5 and obtained in the experiment for measuring gas transport properties of PDMS membranes and systems PDMS + [bmim] [Tf_2N], a 2-mm layer of the ionic liquid applied to the polydimethylsiloxane film significantly increases the selectivity of the system for a pair of CO_2/CH_4 gas, but reduces the permeability value by about several orders of relatively "pure" PDMS. Thus, gas transport properties of the system can be changed by varying the thickness of the ionic liquid layer. Since the choice of material for use as a gas separation membrane is determined by the requirements for the efficiency and performance of the separation process, the promise of ionic liquids will be further investigated in future. To compare obtained results with the knowledge achieved by membraneologists since the late 1970s, it is convenient to use the Robeson plot (Fig. 3) [68]. It was shown that the PDMS membrane represents the area of high permeable membranes with lower selectivity (robbery polymers), and the use this membrane in the absorbing pervaporation changed the property to more selective, but with lower permeability coefficient as shown in Tables 3 and 5.

Table 4
Individual gases diffusion and sorption coefficients

	PDMS		PDMS + [bmim][Tf_2N]	
Gas	D × 10^{-12}, m^2 s^{-1}	S, mol m^{-3} Pa^{-1}	D × 10^{-14}, m^2 s^{-1}	S × 10^{-3}, mol m^{-3} Pa^{-1}
He	0.6	0.23	19.4	1.5
N_2	0.5	0.15	1.3	7
CO_2	2.2	0.12	7.5	15.5
CH_4	1.5	0.43	1.4	2.1

Table 5
Ideal selectivity for CO_2 systems

PDMS			PDMS + [bmim][Tf_2N]		
CO_2/He	CO_2/N_2	CO_2/CH_4	CO_2/He	CO_2/N_2	CO_2/CH_4
4.8	8.7	2.5	3.9	11.7	38.3

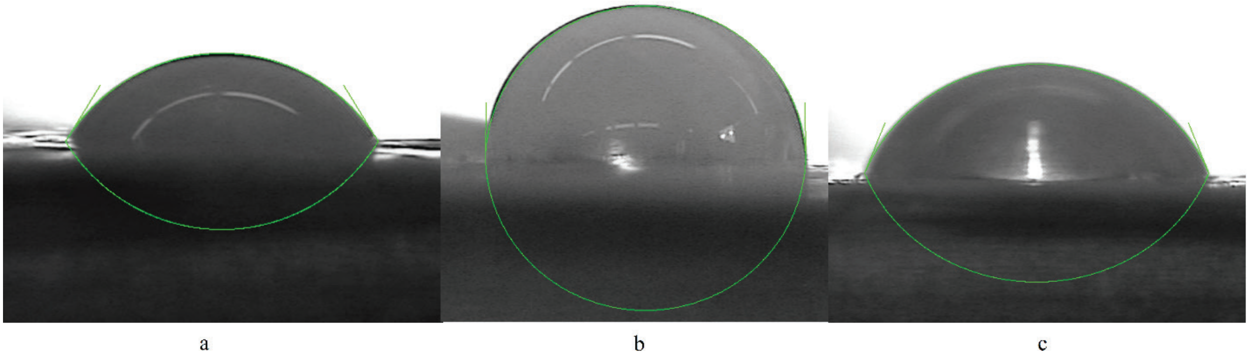


Fig. 2. Contact angle of (a) ([bmim][Tf_2N]); (b) ([bmim][BF_4]); and (c) ([bmim][PF_6]) on PDMS.

3.3. Membrane gas separation and ionic liquid absorption pervaporation

The main goal of this paper was to determine flux ratio influence on separation factors in membrane gas separation and ionic liquid absorbing pervaporation, and to compare these two techniques in CH_4/CO_2 separation efficiency.

Membrane gas separation of CH_4/CO_2 mixture was performed for three different feed flow rate values 740, 460, and 120 mL min^{-1}. Permeate flow rate was constant and equal to 6 mL min^{-1}. Stage-cut values were calculated according to Eq. (6) and equaled 0.008, 0.013, and 0.05, respectively. Ionic liquid absorbing pervaporation was performed for three different feed fluxes ratio as well: 500, 200, and 16 mL min^{-1}. Stage cut equals 0.002, 0.005, and 0.06. Experimental data is presented in Table 6. The dependences of the separation factor on stage-cut value are presented in Fig. 4. Experimental chromatograms are presented in Fig. 5.

As seen, the highest separation factor reached at the lowest feed flux values in both experiments, and ionic liquid absorption pervaporation shows significant increase in separation factor with stage-cut value increasing.

In comparison of these two experiments, absorbing pervaporation demonstrates a higher separation factor due to [bmim][Tf_2N] ionic liquid used. This can be explained by the selective solvation ability of the ionic liquid [bmim][Tf_2N]. It is widely accepted that the anion dominates the dissolution of CO_2, although the cation is believed to play a secondary role [69]. Anions containing fluorine have specific fluorine–CO_2 interactions, which increase solubility in the ionic liquid. The higher selectivity obtained for combined system of ionic

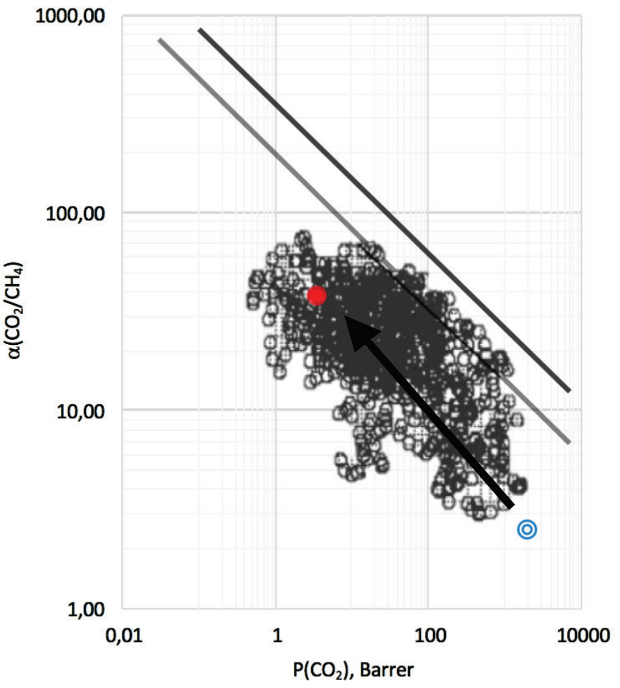


Fig. 3. The present (black line) and past (grey line) upper bound correlations for CO_2/CH_4 separation [73] and obtained data in the current work PDMS (blue dot) and PDMS + [bmim][Tf_2N] (red dot) (Table 3 and 5).

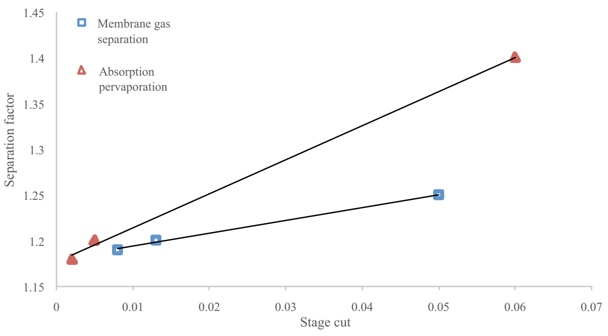


Fig. 4. Membrane gas separation and ionic liquid absorption pervaporation separation factor as function of stage-cut value.

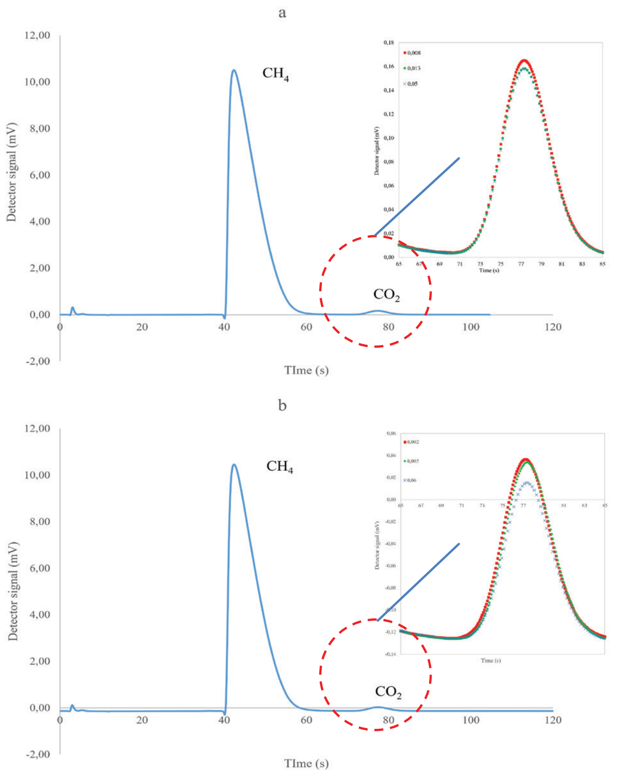


Fig. 5. Analysis results: (a) chromatogram of the permeate flow for membrane gas separation with CO_2 scaled-up pick and (b) chromatogram of the permeate flow for CH_4/CO_2 separation by absorbing pervaporation with CO_2 scaled-up pick.

Table 6
The separation factor of membrane gas separation and absorbing pervaporation dependence from the stage cut

Membrane gas separation		Absorption pervaporation	
θ_{st}	F	θ_{st}	F
0.05	1.25	0.06	1.40
0.013	1.20	0.005	1.2
0.008	1.19	0.002	1.18

liquid [bmim][Tf_2N]/PDMS compared with PDMS (Table 5) is realized due to the difference in CO_2 and CH_4 solubility by [bmim][Tf_2N]. Solubility in ionic liquids with [Tf_2N] anion decreases in the following order: $SO_2 > CO_2 > C_2H_4 > C_2H_6 > CH_4 > O_2 > N_2$. Similar gas solubility trends in [bmim][Tf_2N] ionic liquid were observed ($CO_2 > C_2H_4 > C_2H_6 > CH_4$) [70–72].

It is known that at high stage cut the separation ability in terms of partial pressure difference is reduced to maintain the material balance [73]. At low pressure ratio, the effect of the stage cut is the largest, and the lower the value of stage cut the larger the separation. Our experiment shows a reverse relationship due to limited solubility and the small size of the membrane module. As the permeate flow was constant and feed pressure changed slightly, the ionic liquid solubility and membrane permeability were constant; therefore, increasing feed flow did not lead to increased separation due to increased CO_2 content in the feed flow. It is also interesting to study the feasibility of unsteady-state operation of absorbing pervaporation process in further experiments [74].

4. Conclusions

In this work, the separation of CH_4/CO_2 gas mixture was investigated by the novel hybrid technique – absorbing pervaporation whereas the absorbent, the ionic liquid [bmim][Tf_2N], was used. This hybrid technique was compared with conventional membrane gas separation. It was shown that the ideal selectivity in hybrid system increases more than 15 times compared with membrane gas separation at the similar operation conditions.

Also, it was shown that separation factor for CH_4/CO_2 gas mixtures in the case of absorbing pervaporation increases faster than for membrane gas separation with the increasing of stage cut. And the ionic liquid absorbing pervaporation demonstrates higher separation factor than membrane gas separation with the similar stage-cut values. Moreover, the results show linear proportional dependence of stage cut on separation factor.

Acknowledgements

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Symbols and abbreviations

Q — Permeability, mol m^{-2} s^{-1} Pa^{-1}
V — Downstream volume, mL
V_m — Molar volume, mL mol^{-1}
p_2 — Permeate pressure, Pa
p_1 — Feed pressure, Pa
p_0 — Atmospheric pressure, Pa
T — Temperature, K
T_0 — Normal temperature, K
S — Membrane effective area, m^2
τ — Time of experiment, s
P — Permeability coefficient, mol m^{-1} s^{-1} Pa^{-1}
D — Diffusion coefficient, m^2 s^{-1}
l — Membrane thickness, m
$\theta\tau$ — Time lag, s
S — Sorption coefficient, mol m^{-3} Pa^{-1}
α — Ideal selectivity
F — Separation factor
θ_{st} — Stage cut
J — Flow rate, mL min^{-1}
C — Concentration, %
[omim] — 1-Octyl-3-methylimidazolium
[hmim] — 1-Hexyl-3-methylimidazolium
[pmim] — 1-Propyl-3-methylimidazolium
[bmim] — 1-Butyl-3-methylimidazolium
[emim] — 1-Ethyl-3-methyl-imidazolium
PDMS — Poly(dimethyl-siloxane)

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