



## Separation of CO<sub>2</sub>/CH<sub>4</sub> by blended Polysulfone/ABS-Silica Nanocomposite Membranes

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Article	Abstract (row height 0.8 cm)
Article history: Received: 2021/03/10 Received in revised form: 2021/06/14 Accepted: 2021/06/19  Keywords: Gas Separation, Nanocomposite Membrane, Blended polymer matrix, Silica, polysulfone	In the present study, Polysulfone/ABS-10% composite and Polysulfone/ABS-10%-silica nanocomposite membranes prepared for CO <sub>2</sub> separation from CH <sub>4</sub> . A dense blend polymeric membrane with two partially miscible polymers was made and nano-silica was added into it to improve gas transport properties. The membranes were prepared by solution casting method and characterized by Fourier transform infrared spectroscopy (FTIR), and Scanning electron microscopy (SEM). Transport characteristics of single gas for CO <sub>2</sub> and CH <sub>4</sub> were investigated by the single gas test. Feed pressure altered from 2 to 6 bars and temperature kept at 25 °C. The gas permeability of methane and carbon dioxide were evaluated as a function of silica concentration. Permeability results show that by adding silica nanoparticles into the PSF/ABS matrix, permeability of both CO <sub>2</sub> and CH <sub>4</sub> increased and loading up to 3 wt.% increased the selectivity of CO <sub>2</sub> /CH <sub>4</sub> from 9.13 to 24.48 Barrer at 2 bars.

### 1. Introduction (head 1)

Methane is the main compound of natural gas and carbon dioxide is a major greenhouse gas and impurity in natural gas, that its needs to be removed from this gas streams. Low manufacturing cost and processing ability are the most important characteristics of polymeric membranes that make them conqueror in the industry [1-5]. The measurement performance of gas separation membranes is characterized by permeability (P) and selectivity ( $\alpha$ ), and membrane performance affected by material and structure [6-7]. Using new manufacturing process, formulate, and material were some of the researchers proceeding to overcome the problem with a polymeric membrane, achieving higher selectivity with similar processing ability and more persistent in the presence of harsh and aggressive feed is the most important issues [5,8]. Adding inorganic fillers in an organic polymer matrix is one of the good manners that improve both permeability and selectivity of gasses. Some of the inorganic

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particles may improve physical, thermal, and mechanical properties of the membrane. The permeability throughput of membranes can be enhanced by adding inorganic materials like silica particles into the polymeric matrix [5, 9-10]. Glassy polymers because of high gas selectivity and good mechanical features are the most domain membrane in industry. Polysulfone is a useful polymer for gas separations and because its high selectivity, it was the high consumption polymeric membrane for many years [8, 11]. Gas separation membranes follow solution-diffusion transport and this kind of membranes have many problems to overcome the limitation of 'upper bound' mixed matrix membranes (MMMs) that can enhance transport characteristic of the membrane [12]. Generally, inorganic particle phase are dispersed in the polymer matrix and their properties will affect by nanoparticles type, nanoparticle size, particle agglomeration, polymer/nanoparticles interface morphology [13-14]. Good mechanical strength, thermal stability, and chemical inertia are the most important characteristic of nanoparticles. Nano silica has most of this characteristic [15]. Poor distribution of particles and compatibility of nanoparticles and polymer is the first challenge facing MMMs [1]. Some mixed matrix membranes have the potential to achieve higher selectivity, permeability, or both relative compatibility of filler and polymer lead to aggraving this goal [16]. Polymer blending is a good manner to having good properties of two polymers in one matrix. Two polymers may be miscible, partially miscible or immiscible [17]. The ABS material has rubbery and glassy matrix (styrene-co-acrylonitrile) segments. Because of its rubbery region and glassy matrix, it has high permeability and selectivity [18]. Ahn et al. [19] characterized PSF/silica MMMs and they found CH<sub>4</sub> permeability is over five times greater than for the pure PSf membrane. Rafiq et al. [10] developed the membranes by Polysulfone/polyimide (PSF/PI) with inorganic silica nanoparticles. The highest permselectivity of (CO<sub>2</sub>/CH<sub>4</sub>) = 61 observed for treated membrane at 2–10 bars. Ismail et al. [20] investigated Blend of PES/PI incorporating zeolite 4A particles. Dorosti et al. [21] studied on dense PSF/PI membranes with zeolite. Xing [22] worked on PVA/PEG blend membranes with zeolite 5A filled for CO<sub>2</sub>/CH<sub>4</sub> separation. In this research, the performance of PSF/ABS 10%–silica nanocomposite membranes in the permeation properties of CO<sub>2</sub>/CH<sub>4</sub> has been studied. All nanocomposite membranes were prepared using solution casting method.

## **2. Materials and methods**

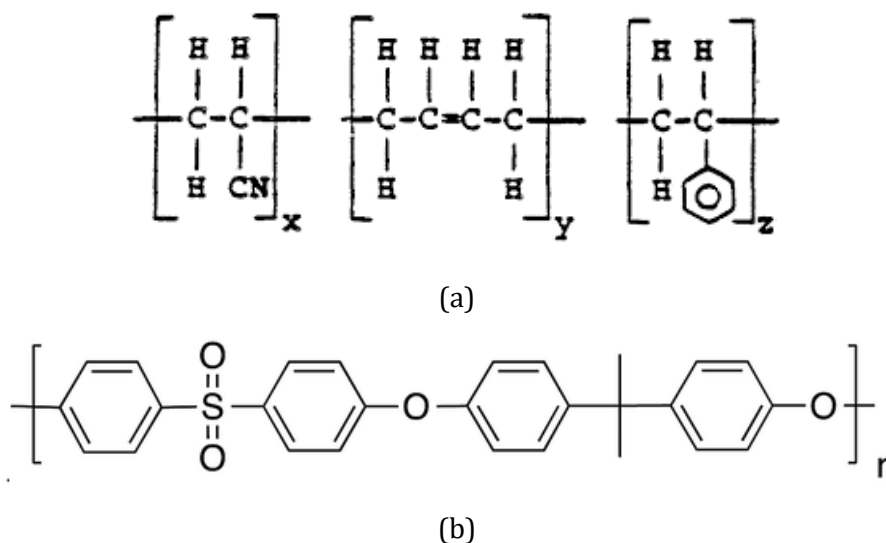
### **2.1. Materials**

Polysulfone (Ultrason S6010, T<sub>g</sub>189 °C) with reported density of 1.23 g/cm<sup>3</sup> was supplied by BASF Company, ABS-SD-0150 supplied by (T.P.C). The organic solvent Dichloromethane (DCM, 99%) was supplied by Merk. The nanoparticle of Silica was supplied from US Research Company. Silica nanoparticles have size about 5-10 nm. The CO<sub>2</sub> (purity 99.99%) that used for gas permeation test was purchased from Iran Azote Charger gas Company and CH<sub>4</sub> was purchased from Iran Arian Gas company. The chemical structures of PSF and ABS are shown in Fig. 1.

### **2.2. Polysulfone/ABS membrane preparation**

Samples with different blends of PSF/ABS containing 10, 15, 20, 25, and 30 wt% ABS were prepared by solution casting method, in order to compare their permeability results and choose the best membrane. For this purpose, a known weight of PSF powder was dissolved into the dichloromethane solvent and mixed using a magnetic stirrer for about 1 hours. In the next step, the needed weight amount of ABS was dissolved in the solution and dispersed by stirring. The polymers were dissolved and continue stirring at 27 °C for 2-3 hours then the solution placed in ultrasonic for 20 minutes to have the homogenous solution. The solution filtered with a 0.2µm filter to separate undissolved materials and impurities. The nanocomposite membrane films were cast on the clean glass plate. Finally, then the nanocomposite membranes were dried in a vacuum oven at 65°C for 10 hours to evaporate the solvent

completely. The mentioned technique was used for the preparation of five samples with various compositions.



**Figure 1.** Chemical Structure of (a) PSF and (b) ABS

### 2.3. Polysulfone/ABS silica nanocomposite membrane preparation

After comparison of the gas permeability results of prepared mixed matrix membrane, the suitable blend was chosen for nanocomposite preparation. In preparation of nanocomposite membrane at 10 %wt. ABS in PSF is selected because of the best performance result respect to the other blend composition. Then, the silica nanoparticles with different weight percentage added to the polymer solution (PSF/ABS-10%) and mixed well at 27 °C for 2-3 h then the solution placed in the ultrasonic bath for 20 minutes to remove the bubbles and homogenous solution completely. Then a nanocomposite membrane films were cast on the clean glass plate. Finally, the membranes were dried in a vacuum oven at 65 °C for 10 hours to evaporate the solvent completely.

### 2.4. Membrane characterization

The morphological characteristic of prepared membranes was analyzed by VEGA//TESCAN-LMU. The film was ruptured in the liquid nitrogen and then coated with gold. The distribution of silica nanoparticles in the prepared membranes was investigated too by scanning electron microscope. The FT-IR spectrum of the developed membranes was evaluated using Unicam galaxy series FT-IR 5000 spectrophotometer in the range of 400–4000  $\text{cm}^{-1}$ .

### 2.5. Gas permeation experiments

The permeation performance of synthesized membranes was evaluated by two parameters. One of those is the permeability and the other is selectivity. The permeability of all the fabricated polymeric blends and mixed matrix membranes for  $\text{CO}_2$  and  $\text{CH}_4$  were determined constant volume/variable pressure technique. Polysulfone/ABS-silica flat sheet nanocomposite membranes with an effective area of  $22.4\text{cm}^2$  were used for gas separation experiments. The feed pressure was varied from 2 to 10 bars and the temperature was kept at 25°C. The permeate side was kept at atmospheric pressure. The gas permeability of prepared membranes was calculated using the following equation [19, 23]:

$$P = \frac{273.15LV}{76p_0AT} \frac{dp(t)}{dt} \quad (1)$$

The permeability are reported in Barrer where 1 Barrer is  $10^{-10} \text{ cm}^3 \text{ (STP) cm/cm}^2 \text{ s cm Hg}$ , V is the volume of the downstream chamber( $\text{cm}^3$ ), A is the effective area of prepared membrane (cm), L is the membrane thickness (cm), T is the temperature (K),  $dp(t)/dt$  the steady state rate of pressure in the downstream chamber and  $p_0$  is the feed pressure with the same unit of p (t). The selectivity of membrane for gases can be calculated as:

$$\alpha_{AB} = \frac{P_A}{P_B} \quad (2)$$

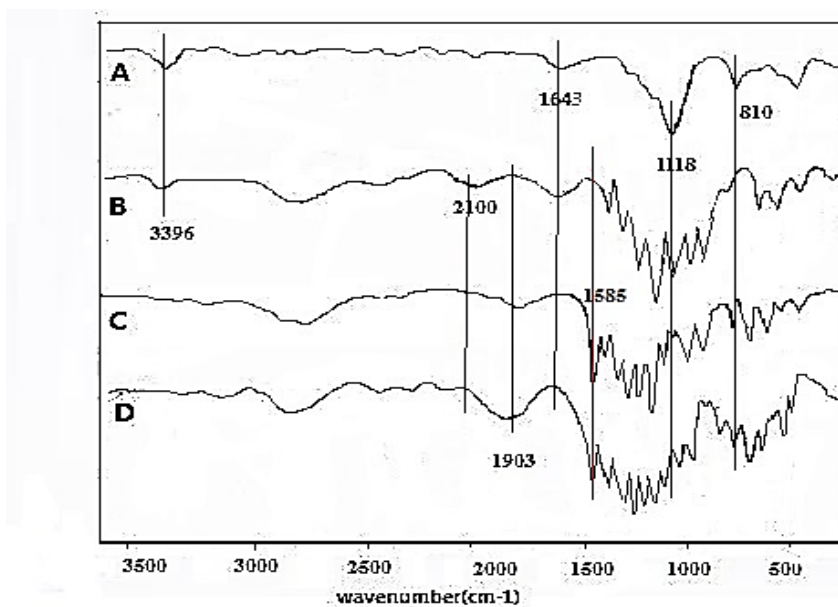
Where,  $P_A$  and  $P_B$  are pure gas permeability of gas A and gas B, respectively.

### 3. Results and discussion

#### 3.1. Membrane Characterization

##### 3.1.1. FTIR Spectroscopy

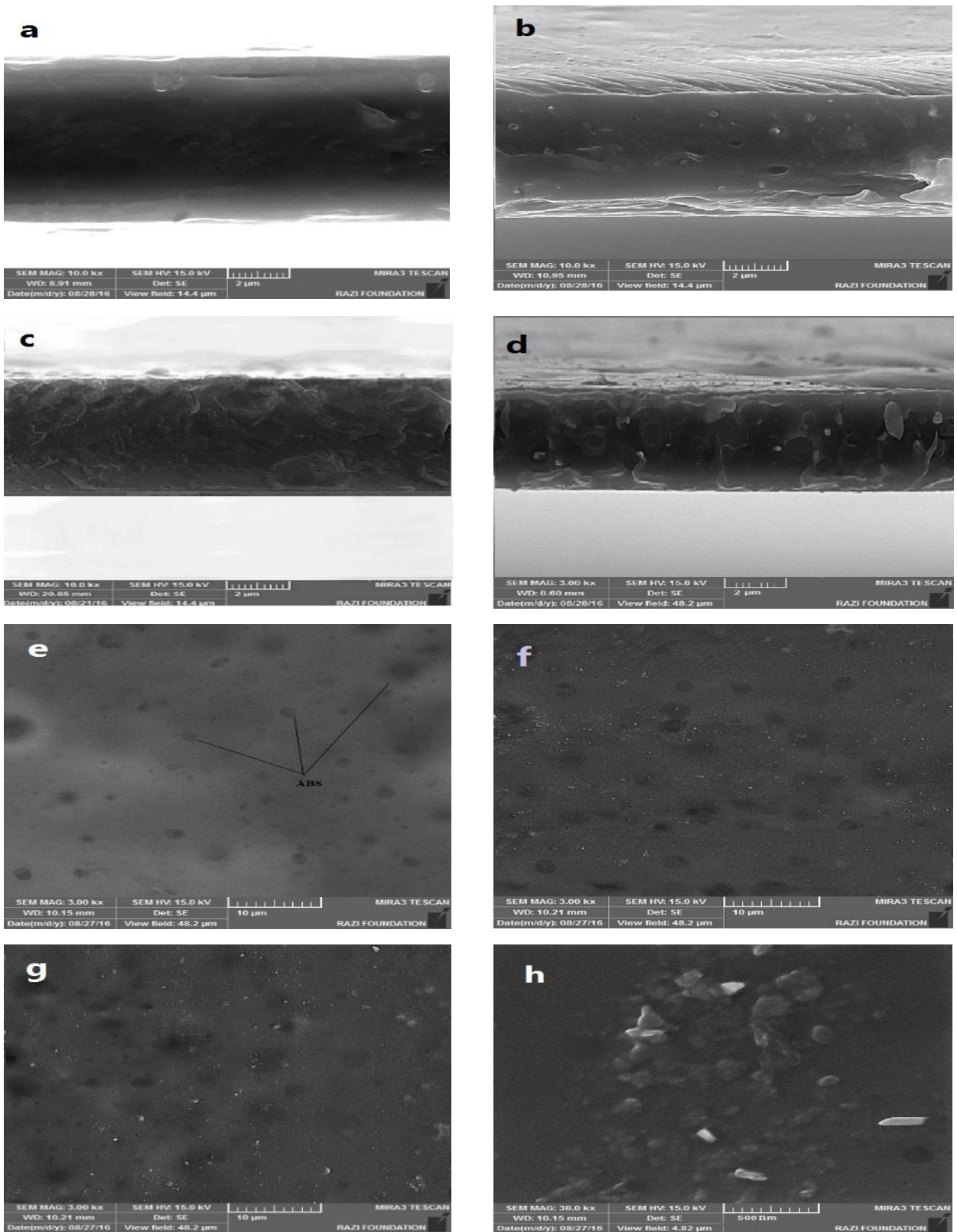
The FTIR spectra of the prepared membranes were showed in Fig. 2. The peak of  $3396 \text{ cm}^{-1}$  in curves A and B that relate to pure silica and PSF/ABS-silica respectively conform to the presence of Si-OH, so this peak describes the existence silica nanoparticle in the membrane matrix. The peaks related to Si-O-Si symmetry stretching occurred at  $810 \text{ cm}^{-1}$  and  $1118 \text{ cm}^{-1}$ . The presence of silica particles had shifted the peak  $1903 \text{ cm}^{-1}$  describes the existence of an interaction between polymer and silica. After adding silica particles in the membrane, the peak of  $1585 \text{ cm}^{-1}$  disappeared. There is no obvious changes in the intensity and weakness of peaks in curve relate to pure polysulfone in comparison to PSF-ABS blend (curves D and C). So the interaction between two polymers is enough to cause good distribution ABS in polysulfone matrix.



**Figure 2.** FTIR spectra of: (A) pure silica (B) PSF/ABS 3 wt% silica (C) PSF/ABS (D) pure PSF

##### 3.1.2. Scanning Electron Microscope

As above mentioned, the membrane structures were investigated by scanning electron microscopy (SEM). Images of the flat sheet nanocomposite membranes with various contents of nanosilica particles are shown in Fig.3. From the membrane's structure can be observed that polysulfone and ABS are partially miscible. The micro ABS phase is dispersed in the continuous polysulfone phase.



**Figure 3.** SEM images of: PSF/ABS (90/10), (a) cross section images of membrane without silica (b) cross section images of membrane with 1wt% silica (c) cross section images of membrane with 3 wt % silica (d) cross section images of membrane with 5wt% silica (e) surface image of membrane without silica (f) surface image of membrane with 3wt% (g) surface image of membrane with 5wt% silica (h) high magnification of membrane with 5wt% silica

According to the description of MMM, this blend matrix can be considered as MMM [16]. SEM images show that the obtained membrane without nanoparticle is dense and uniform in cross-section. As images with high magnification show compatibility between nanoparticles and polymers are acceptable and there is not rupture between the polymer and nanoparticles. Morphology diversity depended on the silica concentration. In the nanocomposite membrane with 3%wt. silica particles loading, SEM images revealed good adhesion between polymer and silica particles. As 5 wt% silica particles loading SEM results of MMMs exhibited more irregular with non-uniform structure in surface furthermore MMMs with 5%wt. silica loading showed more agglomeration in cross section. The particles in micron size appeared after adding 5%wt. nanoparticle that results from the agglomeration of nano silica particles. Due to the formation of aggregates, the membrane did not show homogeneity in comparison to other surfaces. The gas permeability of the membrane is not only dependent on the membrane structure and the gas properties but also, poor adhesion between inorganic particles and polymer chain could influence the permeability [13].

### 3.2. Gas permeation properties of prepared membranes

#### 3.2.1. Evaluation the effects of ABS the concentration on the gas permeability

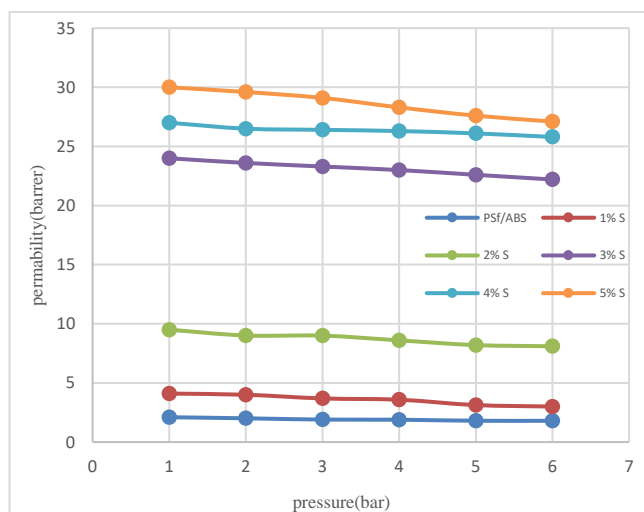
Membranes with a various weight percent of PSF and ABS content were investigated by CO<sub>2</sub> and CH<sub>4</sub> permeation test to delineate the effect of ABS content on the transport properties of the membranes. Table 1 shows that the blend membrane with a composition of 90/10 (PSF /ABS) has maximum selectivity and as ABS amount increases in blend membrane, the selectivity of gases decreases and on the other hand permeability of both CO<sub>2</sub> and CH<sub>4</sub> increased. As the results showed that mixed matrix membrane is able to offer higher permeability and acceptable selectivity in comparison to the pure membranes. So this blend (PSF /ABS-10%) was chosen to investigate the effect of adding silica nanoparticles on characteristics and transport properties of the blend of PSF/ABS membranes.

**Table 1:** Gas permeability (in Barrer) and ideal selectivity at 5 bars through the pure and blend membranes.

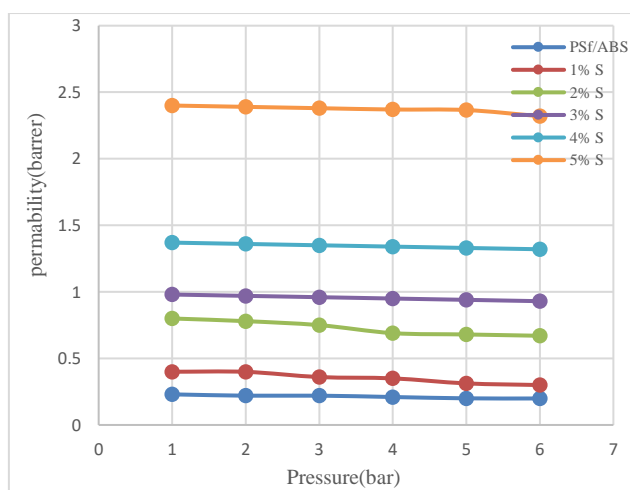
Membrane	P <sub>CO2</sub>	P <sub>CH4</sub>	$\alpha_{CO2/CH4}$
PSF	1.52	0.18	8.44
PSF/ABS(90/10)	1.89	0.21	9
PSF/ABS(80/20)	2.6	0.3	8.66
PSF/ABS(70/30)	2.9	0.36	8.05
ABS	3.78	0.378	7.14

#### 3.2.2. The effect of adding silica nanoparticles on the gas permeability

Mixed matrix membranes with blends of Polysulfone–ABS 10% filled with the different content of silica nanoparticles were fabricated (Table 2). The blend membranes with 10 %wt. ABS showed a CO<sub>2</sub> permeability of 1.89 Barrer and a CO<sub>2</sub>/CH<sub>4</sub> selectivity of 9 at 5 bar (Fig. 4). With the addition of 1 %wt. silica contents in membranes composition, the CO<sub>2</sub> permeability increased from 1.9 to 4.0 Barrer at 4 bars feed pressure, compared to unfilled membranes.



**Figure 4.** Permeability of pure CO<sub>2</sub> gas for PSF/ABS 10% membrane with different silica compositions against feed pressures



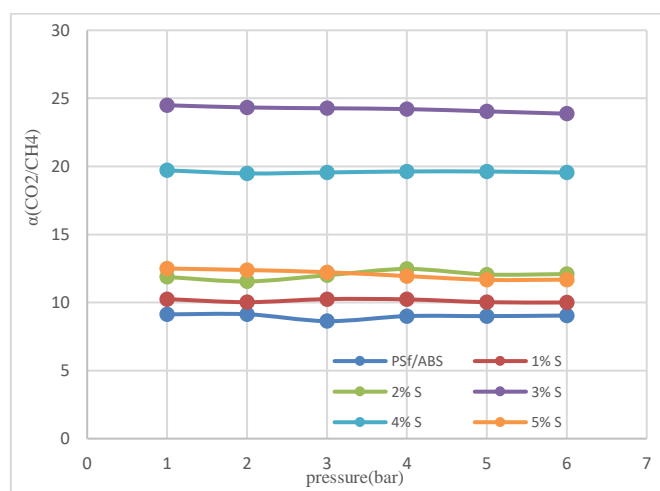
**Figure 5.** Permeability of pure CH<sub>4</sub> gases for PSF/ABS-20% membrane with different silica compositions against feed pressures

Because of the solution-diffusion mechanism of permeation in polymeric membrane OH groups of silica increase the CO<sub>2</sub> dissolving in the membrane. Furthermore adding silica nanoparticles increase molecular sieve property of membranes so smaller molecules can permeate more than larger one [24]. After adding silica nanoparticles permeability of two gases increase but an enhancement in the permeability of CO<sub>2</sub> was more than CH<sub>4</sub> (Fig. 6) because of molecular sieve property of composite membranes and larger molecular size of CH<sub>4</sub> in comparison to CO<sub>2</sub>. So according to this fact and results obtained from permeability test, it's obvious that the permeability of CO<sub>2</sub> is more than CH<sub>4</sub> because of its condensability and polar properties.

The permeability of CO<sub>2</sub> increases by adding more silica content until 30 Barrer for a membrane with 5 %wt. nano-silica. As silica contents increase CH<sub>4</sub> permeability (Fig. 5) enhanced similar to CO<sub>2</sub>. It was noticed that this is due to the fact that the silica particles caused disrupting in the polymer chain packing and increase the permeability of the membrane. So the structure will be disordered and free volume growth which caused increasing the gas permeability [22].

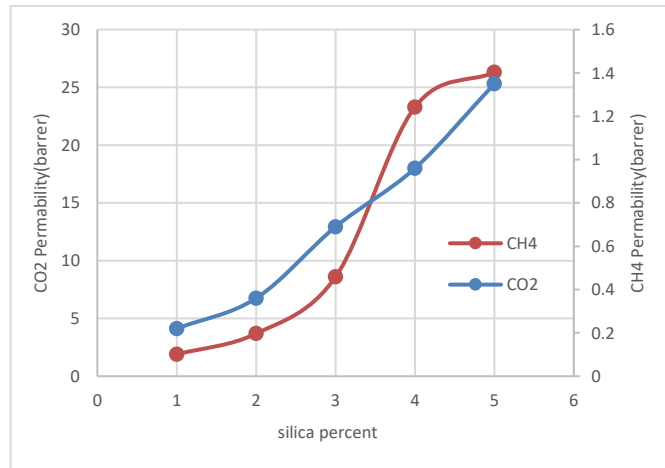
**Table 2.** The effect of the silica percentage on the gas permeability and selectivity of the nanocomposite membranes made of PSF/ABS-10% silica

Run	SilicaPercentage (wt.%)	Feed Pressure(bar)	Permeability(Barrer)		Selectivity $\alpha_{CO_2/CH_4}$
			$P_{CH_4}$	$P_{CO_2}$	
1	0	2	0.23	2.1	9.1304
2		3	0.22	2.01	9.1363
3		4	0.2201	1.9	8.63
4		5	0.21	1.89	9
5		6	0.199	1.79	9.04
6	1	2	0.4	4.1	10.25
7		3	0.399	4	10.02
8		4	0.36	4	10.25
9		5	0.35	3.58	10.022
10		6	0.31	3.13	10.02
11	2	2	0.3	3.00	10.00
12		3	0.8	9.5	11.87
13		4	0.78	9.01	11.55
14		5	0.75	9	12
15		6	0.69	8.6	12.46
16		2	0.68	8.2	12.05
17		3	0.67	8.1	12.08
18	3	2	0.98	24	24.48
19		3	0.97	23.6	24.32
20		4	0.96	24.27	23.3
21		5	0.95	23.00	24.21
22		6	0.94	22.6	24.04
23	4	2	1.37	27	19.70
24		3	1.36	26.5	19.48
25		4	1.35	26.4	19.55
26		5	1.34	26.3	19.625
27		6	1.33	26.1	19.626
28	5	2	2.4	30	12.5
29		3	2.39	29.6	12.38
30		4	2.38	29.1	12.22
31		5	2.36	27.6	11.94
32		6	2.32	27.1	11.68



**Figure 6** Effect of feed pressure on CO<sub>2</sub>/CH<sub>4</sub> selectivity for MMMs with different silica content at 27 °C





**Figure 7** Effect of loading percentage of silica on CO<sub>2</sub> permeability at 4 bars

Fig. 7 shows the permeability of CO<sub>2</sub> and CH<sub>4</sub> versus loading percentage of silica particles at 4 bars. The hydroxyl and other functional groups on the surface of these nano-materials may also interact with polar gases and thus improve the penetrant solubility in the resultant nanocomposite mixed matrix membranes [25]. Permeability results illustrate that the selectivity decrease after adding more than 3 wt.% nanoparticle, membrane selectivity increase with increasing nanoparticle till 3 %wt. (24.48 at 2 bars) but after that decreasing in selectivity was observed. In relation with SEM images, it is seen that with the highest silica loading of 5 %wt., silica particles aggregates increase. As noticed at higher silica contents disorder and free space increase and chain packing decrease so these changes caused enhancement in the gas permeation [10]. Formation of voids and an interfacial defect is a result of poor adhesion of polymers matrix and nanoparticles [26]. The predominant problem facing glassy polymers are used in the preparation of MMMs is adhesion between the polymer phase and particles, weak compatibility of polymer-filler caused the formation of voids and free space without selectivity [11]. The free volume that created by silica aggregations is disadvantages of incorporating nanoparticles in glassy polymers. More condensable gases show higher permeation in nonporous glassy polymer membrane [27]. Considering the SEM images with different magnification reveals the presence and distribution of silica particles in micron and nanometer as shown in Fig. 3, there are particles in micron size in the polymer matrix with 5 %wt. silica because of nano-silica particles agglomeration. As illustrated in FTIR spectra there is good interaction between polymer and silica particle but with adding more silica content and appearing more aggregation permeability will not be controllable. Increasing the feed pressure is the cause of decreasing both selectivity and permeability. It is because of permselectivity properties of PSF that dominate in the polymer matrix. As increasing the feed pressure permeation site saturate and permeability decrease.

#### 4. Conclusion

In this study, the transport of CO<sub>2</sub> and CH<sub>4</sub> in PSF/ABS blend membranes with different ratio of polymers at 27°C and 2–6 bar feed pressure were investigated. Gas transport property was measured using pure CO<sub>2</sub> and CH<sub>4</sub> gases and suitable content of ABS was used to investigating the effect of silica nanoparticles on transport properties of PSF/ABS blend. Adding silica nanoparticles into the PSF/ABS matrix increased both CO<sub>2</sub> and CH<sub>4</sub> permeation, and increasing of CO<sub>2</sub>/CH<sub>4</sub> selectivity as the silica loading increased to 3wt.% (24.48 at 2 bar) and decreasing after adding more than this content was probably due to the formation of agglomerates and poor adhesion of silica nanoparticles with polymer.

FTIR spectra confirm the desirable mixing of the silica in polymer and a weak compatibility between the two polymers. A comparison between polymer blend membranes shows that membranes with 90/10wt% ABS and 3 wt.% nanoparticles have higher selectivity, since that this result is highly dependent on manufacturing condition as a general conclusion it can say that blending of PSF/ABS polymers is effective in improving the permeation properties and economical point of view.

#### **Disclosure of potential conflicts of interest**

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**Conflict of Interest:** The authors declare that they have no conflict of interest.

#### **References**

- [1] Zhang Y., Sunarso J., Liu S., and Wang R., (2013) Current status and development of membranes for CO<sub>2</sub>/CH<sub>4</sub> separation: a review, *Int. J. Greenhouse gas control*, 12, 84-107.
- [2] Beyer A, Schomäcker R, Reichert K-H (2003) Synthesis and characterization of palladium containing membranes based upon poly acrylic acid. *Colloid Polym Sci* 281(9):862-868
- [3] Yoshida E (2015) Morphological changes in polymer giant vesicles by intercalation of a segment copolymer as a sterol model in plasma membrane. *Colloid Polym Sci* 293(6):1835-1840
- [4] Mizoguchi K, Terada K, Naito Y, Kamiya Y, Tsuchida S, Yano S (1997) Miscibility and gas permeability of poly(ethylene-co-5, 4 mol% 3,5,5-trimethylhexyl methacrylate) polydimethyl-siloxane blends. *Colloid Polym Sci* 275(Issue 1):86-90
- [5] Bet-moushoul E., Mansourpanah Y., FarhadiKh, Tabatabaei M., (2016) TiO<sub>2</sub> nanocomposite based polymeric membranes: A review on performance improvement for various applications in chemical engineering processes, *Chem. Eng. J.*, 283: 29-46.
- [6] Zhao D., RenJ., Wang Y., QiuY., Li H., HuaK., (2017) High CO<sub>2</sub> separation performance of Pebax®/CNTs/GTA mixed matrix membranes, *J. Membr. Sci.*, 521:104-113.
- [7] Salimi M., Pirouzfard V., Kianfar E. (2017) Enhanced gas transport properties in silica nanoparticle filler-polystyrene nanocomposite membranes, *Colloid Polym Sci* 295 (Issue 1):215-226.
- [8] Julian H. and Wenten I., (2012) Polysulfone membranes for CO<sub>2</sub>/CH<sub>4</sub> separation: State of the art, *IOSR J. Eng.*, 2 (3): 484-495.
- [9] Liang C.-Y., Uchytil P., Petrychkovych R., Lai Y.-C., Friess K., Sipek M., Reddy M. M., and Suen S.-Yi (2012) A comparison on gas separation between PES (polyethersulfone)/MMT (Na-montmorillonite) and PES/TiO<sub>2</sub> mixed matrix membranes. *Sep Purif Technol*, 92: 57-63.
- [10] Rafiq S., Man Z., Maulud A., Muhammad N., and Maitra S., (2012) Separation of CO<sub>2</sub> from CH<sub>4</sub> using polysulfone/polyimide silica nanocomposite membranes. *Sep Purif Technol*, 90:162-172.
- [11] Stern S. A., (1994) Polymers for gas separations: the next decade *J. Membr Sci*, 94(Issue 1) :1-65.
- [12] Ahn J., Chung W.-J., Pinnau I., Song J., Du N., Robertson G. P., Guive M. D. (2010) Gas transport behavior of mixed-matrix membranes composed of silica nanoparticles in a polymer of intrinsic microporosity (PIM-1). *J. Membr Sci*, 346: 280-287.

- [13] Wang M., Wang Z., Li N., Liao J., Zhao S., Wang J., Wang S. (2015) Relationship between polymer–filler interfaces in separation layers and gas transport properties of mixed matrix composite membrane. *J. Membr Sci*, 495:252-268.
- [14] Li X., Jiang Z., Wu Y., Zhang H., Cheng Y., Guo R., (2015) High-performance composite membranes incorporated with carboxylic acid nanogels for CO<sub>2</sub> separation. *J Membr Sci*, 495: 72-80.
- [15] Gorji B., Ghasri M. A., Fazaeli R., and Niksirat N. (2012) Synthesis and Characterizations of Silica Nanoparticles by a New Sol-Gel Method. *Iranian Journal of Applied Chemical Research*, 6(3):22-26.
- [16] Bastani D., Esmaeili N., and Asadollahi M., (2013) Polymeric mixed matrix membranes containing zeolites as a filler for gas separation applications: A review. *J. Ind. Eng. Chem. Res.* 19(2):375-393.
- [17] Rezakazemi M., Amooghin A.E., Montazer-Rahmati M. M., Ismail A. F., and Matsuura T., (2014) State-of-the-art membrane based CO<sub>2</sub> separation using mixed matrix membranes (MMMs): An overview on current status and future direction. *Prog. Polym. Sci.* 39: 817-86.
- [18] Marchese J., Garis E., Anson M., Ochoa N. A., and Pagliero C., (2003) *J Membr Sci.* 221, 185-197.
- [19] Ahn J., Chung W.-J., Pinnau I., and Guiver M. D., (2008) Polysulfone/silica nanoparticle mixed-matrix membranes for gas separation. *J Membr Sci.* 31:123-133.
- [20] Ismail A., Rahim R., and Rahman W., (2008) Characterization of polyethersulfone/Matrimid® 5218 miscible blend mixed matrix membranes for O<sub>2</sub>/N<sub>2</sub> gas separation. *Sep Purif Technol*, 63:200-206.
- [21] Dorosti F., Omidkhan M., Pedram M., and Moghadam F., (2011) Fabrication and characterization of polysulfone/polyimide–zeolite mixed matrix membrane for gas separation *Chem. Eng. J.*, 171:1469-1476.
- [22] H. W. Xing R, (2009) Synthesis and characterization of crosslinked polyvinylalcohol/polyethyleneglycol blend membranes for CO<sub>2</sub>/CH<sub>4</sub> separation, *J Taiwan Inst Chem Eng*, 40: 654-62.
- [23] Naghsh M., Sadeghi M., Moheb A., Chenar M. P., and Mohagheghian M., (2012) Separation of ethylene/ethane and propylene/propane by cellulose acetate–silica nanocomposite membranes. *J Membr Sci*, 423: 97-106.
- [24] Sadeghi M., Semsarzadeh M. A., Barikani M., and Chenar M. P., (2011) Gas separation properties of polyether-based polyurethane–silica nanocomposite membranes. *J Membr Sci*, 376: 188-195.
- [25] Aroon M. A., Ismail A. F., Matsuura T., and Montazer-Rahmati M. M., (2010) Performance studies of mixed matrix membranes for gas separation: a review. *Sep purif Technol*, 75: 229-242.
- [26] Goh P. S., Ismail A. F., Sanip S. M., Ng B. C., and Aziz M., (2011) Recent advances of inorganic fillers in mixed matrix membrane for gas separation. *Sep Purif Technol*, 81: 243-264.
- [27] Sadeghi M., Khanbabaei G., Dehaghani A. H. S., Sadeghi M., Aravand M. A., Akbarzade M., (2008) Gas permeation properties of ethylene vinyl acetate–silica nanocomposite membranes. *J Membr Sci*, 322:423-428.