Scientia Iranica C (2020) 27(3), 1243–1252

Sharif University of Technology
Scientia Iranica
Transactions C: Chemistry and Chemical Engineering
http://scientiairanica.sharif.edu

Preparation of Pt-ZSM-5 zeolite membrane catalysts for the isomerization of linear alkane

B. Bayati[a,b], C. Algieri[c], A.A. Babaluo[a,d,*], M. Haghighi[d,e], A. Ghorbani[b], and E. Drioli[c]

a. *Nanostructure Materials Research Center (NMRC), Sahand University of Technology, Tabriz, P.O. Box 51335/1996, Iran.*
b. *Department of Chemical Engineering, Ilam University, Ilam, P.O. Box 69315/516, Iran.*
c. *Institute on Membrane Technology (ITM), Italian National Research Council (CNR), Via P. Bucci CUBO 17/C, 87030 Arcavacata di Rende (CS), Italy.*
d. *Department of Chemical Engineering, Sahand University of Technology, P.O. Box 51335/1996, Tabriz, Iran.*
e. *Reactor and Catalyst Research Center (RCRC), Sahand University of Technology, Tabriz, P.O. Box 51335/1996, Iran.*

Received 7 April 2019; received in revised form 19 July 2019; accepted 28 December 2019

KEYWORDS
Catalytic zeolite membrane;
Pt catalyst;
Pentane;
Isomerization.

Abstract. A ZSM-5 supported membrane was synthesized by the secondary growth method. The Pt-ZSM5 membrane was prepared by the impregnation method. This membrane was characterized by a single gas permeation step at room temperature. The isomerization of *n*-pentane was selected as a probe reaction for evaluating the catalytic performance of the membrane. In particular, the effects of the space velocity and the time on stream were considered. After the catalytic tests, the membrane was characterized by Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray spectroscopy (EDX), and X-Ray Diffraction (XRD). N_2 permeance for the membrane, after calcination, was equal to 2.9×10^{-7} mol/m^2.s.Pa, indicating the coverage of the larger support pores by the zeolite crystals. This result was also confirmed by the SEM investigation. In addition, XRD analysis showed that the ZSM-5 was the desired zeolite type. During the catalytic tests, the reduction of the nC_5 conversion and the increase of the iC_5 selectivity with Weight Hourly Space Velocity (WHSV) were observed. The nC_5 conversion decreased from 2.5 to less than 0.5, with an enhancement in WHSV, while the selectivity increased from 30 to over 70. On the other hand, its conversion on catalyst enhanced from 10% to approximately 38% with an increase in the reaction temperature from 250 to 450°C.

1. Introduction

The isomerization of catalytic linear alkanes to branched alkanes is an important industrial reaction due to the increasing demand for iso alkanes, which are used as a substitute for octane boosters instead of aromatic and oxygenate compounds that are subjected to stringent environmental limitations [1–4]. Gasoline is composed of a large number of linear-chain compounds with a low octane number. Nevertheless, these compounds may rise when gasoline is exposed to the isomerization reaction through which linear-chain molecules are transformed to branched molecules [5,6]. In isomerization reactions, a mixture of di-branched, mono-branched, and linear molecules is formed; therefore, the conversion of linear paraffins in the isomerization reaction is limited by the thermodynamic equilibrium [7,8]. The linear paraffins from the isomerization process effluent are separated and recycled at the entrance of the isomerization reactor. A Membrane Reactor (MR) consists of a combination of

---

*. *Corresponding author.*
E-mail address: a.babaluo@sut.ac.ir (A.A. Babaluo)

doi: 10.24200/sci.2019.52832.2905

the distribution process or membrane separation with a chemical reactor in one system. Chemical processes are easier to implement due to the integration of distribution/separation and reaction, producing much lower processing costs than the costs of applying more conventional processes [9,10]. There are many scientific reports on the synthesis, characterization, and development of catalysts for pentane isomerization. Aboul-Gheita et al. evaluated the effect of Pt concentrations on the SZ catalyst performance [11]. The Ir/Pt-HZSM5 zeolite catalyst was prepared by the saturation of iridium on Pt-HZSM5 zeolite. The effect of Si/Al ratio on *n*-pentane isomerization using Ir/Pt-HZSM5 was studied by Setiabudi et al. The Ir/Pt-HZSM5 zeolite catalyst showed the highest activity for the isomerization of *n*-pentane at an Si/Al ratio of 23 [12,13]. The *n*-pentane isomerization on the Zn/HZSM-5 zeolite catalyst was carried out by Setiabudi et al. Their results indicated the iC5 conversion associated with the promotive effect of H_2 as a carrier gas [13]. To the best knowledge of the current author, there is no existing report on pentane isomerization using catalytic MRs.

Zeolites characterized by a regular structure and thermal and chemical stability have shown a major potential for combined systems of separation/reaction as an MR [14–18]. These advantages support zeolite membranes as a new technique for organic synthesis and particular separation in the chemical industry [19–22]. The MFI-type zeolite (ZSM-5 and aluminum-freesilicalite-1) with a pore size of 0.58 nm can separate nC_5 (minimum kinetic diameter = 4.3Å) from 2-methyle pentane (minimum kinetic diameter = 5Å) selectively based on the difference in adsorption strength and size. Thus, MFI membrane is employed as a separator and, also, an MR for diverse reactions such as linear alkane (C5-C7) isomerization [13,23,24], providing better product selectivity. A study of alkane isomerization using the MFI membrane reactor was performed by Gora and Jansen [25]. They passed a feed (iso-hexane/*n*-hexane) on the outer side of a tubular membrane. The conversion of *n*-hexane to iso-hexane was achieved by the permeation of nC_6 through the membrane and in the catalyst phase.

In this study, a zeolite catalytic MR, for the first time, was used for the isomerization of nC_5. The prepared membrane was characterized by Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray spectroscopy (EDX), and X-Ray Diffraction (XRD) analyses. Moreover, the permeation property was also evaluated before and after the calcination step. Finally, the MR performance for nC_5 isomerization was studied as a function of space velocity and time on stream.

2. Experimental

2.1. Materials

The chemicals used for the membrane preparation include tetraethoxysilane (TEOS, ACROS) as a silica source, aluminumisopropoxide (AIP, Merck) as an aluminum source, tetrapropylammonium hydroxide ((TPAOH, 1 M aqueous solution, Merck) as an organic structure-directing agent (the template), and triethylenetetramine (Trien, Merck) as a chelating agent. All of the solutions were prepared by adding sodium hydroxide (Merck) and distilled water.

Membrane supports were made of porous α-Al_2O_3 asymmetric tubes (*IKTS, I.D. = 7* mm, *O.D. = 10* mm, *L = 100* mm, *dpore = 100* nm). The tubular support used for removing possible dust and oil materials inside the pores was cleaned with acetone by an ultrasonic cleaner for 1 hour. Afterward, the support was boiled in distilled water for 1 hour and, then, dried in a furnace at 120°C for 2 hours.

2.2. Membrane preparation

ZSM-5 zeolite membranes were synthesized by the secondary growth method. This method, separating the nucleation from crystal growth, allows optimizing each step independently. The method is carried out in two stages: seeding and growth. In this work, the membranes were seeded by means of the procedure used by Garofalo et al. [26]. After the seeding, the crystals were grown by transferring the synthesized solution into the inner support positioned in a Teflon-lined autoclave. The zeolite layer on the outer surface of the support was formed without wrapping it with Teflon tape. Finally, the hydrothermal treatment was carried out by putting the autoclave in a preheated furnace. The operating conditions used for the growth are reported in Table 1.

After performing the hydrothermal synthesis, the synthesized membranes were washed several times with distilled water and, then, dried at 100°C for 8 hours to remove the water adsorbed in the pores of zeolite. After the synthesis, the prepared membrane was calcined up to 753 K to remove the template. Calcination was

Table 1. Operating conditions used for the hydrothermal treatment [35].

Molar composition	2.7 TPAOH: 46 SiO_2:5 Na_2O: Al_2O_3: 1.3 Trien: 2500 H_2O
Solution aging	12 hours
Temperature	180°C
Time	24 hours

performed using a furnace at heating and cooling rates of 1 K/min.

2.3. Pt-ZSM-5 catalytic membrane layer

For obtaining the HZSM-5 membrane, Na^+ ions present in the zeolite layer were exchanged with ammonium in a 0.1 M NH_4Cl solution for 4 hours at 95°C. This procedure was repeated three times. Then, the cation-exchanged membrane was dried at 50°C and, then, heated up to 450°C for 3 hours [27]. Pt/zeolite catalyst layers were prepared by impregnation with an aqueous solution of hexachloroplatinic acid hydrate for 24 hours. The catalysts were dried after saturation and activated under H_2 atmosphere for 3 hours at 623 K.

2.4. Zeolite membranes characterization

Powder X-ray diffraction (XRD, D5000 Siemens, Germany) was performed on the material scratched off the membrane surface. The morphology of the zeolite membrane was observed by Scanning Electron Microscopy (SEMCamScan MV2300, Check Republic). The Energy Dispersive Spectroscopy (EDS) and element mapping were applied to analyze the dispersed elements of the membrane sample. Before performing MR experiments, C_5 isomer permeation properties including separation factor and permeance of the membrane were evaluated in a continuous flow system. The isomerization reaction of *n*-pentane was selected to evaluate the catalytic activity of the prepared zeolite membrane.

The total pressure on the permeate side was kept at 1 atm for binary permeation tests, and the used membrane pressure difference (Δp) was 0.1–1 bar. A nitrogen stream was applied to eliminate the permeating species by sweep. Both components can permeate the feed solution and, afterward, separation can be achieved due to differences in diffusion rates, sorption rates, and the molecule capability to block or inhibit the other from penetrating the pores. The experimental setup used for performing the separation tests and the catalytic reactions is shown in Figure 1. The catalytic zeolite membrane was placed in a membrane module and sealed by O-rings. This reactor was placed inside an electrical oven to control the reaction temperature. The gas feed was controlled by a mass flow controller. The injection of pentane into the MR was carried out by means of a syringe pump. The outlet flow of the pump was evaporated in the gaseous form by using thermal wires that are wrapped around the steel tubes connected to the membrane modulus. Hydrogen gas was applied as a reactant in the processes under research. Nitrogen gas was used as a sweep stream on the permeate side of the membrane module. A nitrogen stream was applied to eliminate the permeating compounds by the sweep side in the membrane separation tests. The flow rate of gases was controlled by mass flow controllers. Gas was injected into the zeolite catalyst membrane cell, and the permeate and retentate pressures were controlled by back pressure regulators. Moreover, the differential pressure on the zeolite membrane was controlled by differential pressure gauges. Both of the retentate and permeate were evaluated online using gas chromatograph of Teif Gostar Company with a capillary column and a flame ionization detector (Serial No.: p2085307, Cat. No. TR-110222, ID: 0.25, l: 25 m, TRB-1, Tecknokroma). The experiments were performed in H_2 at 250°C and at a constant H_2/HC molar ratio 4.8.

The selectivity (or separation factor) of the membrane is defined through the following equation:

$$\alpha = (yi/yj)/(xi/xj), \tag{1}$$

where yi, yj and xi, xj are the molar fractions of components i and j on the permeate (y) and the feed (x) sides, respectively.

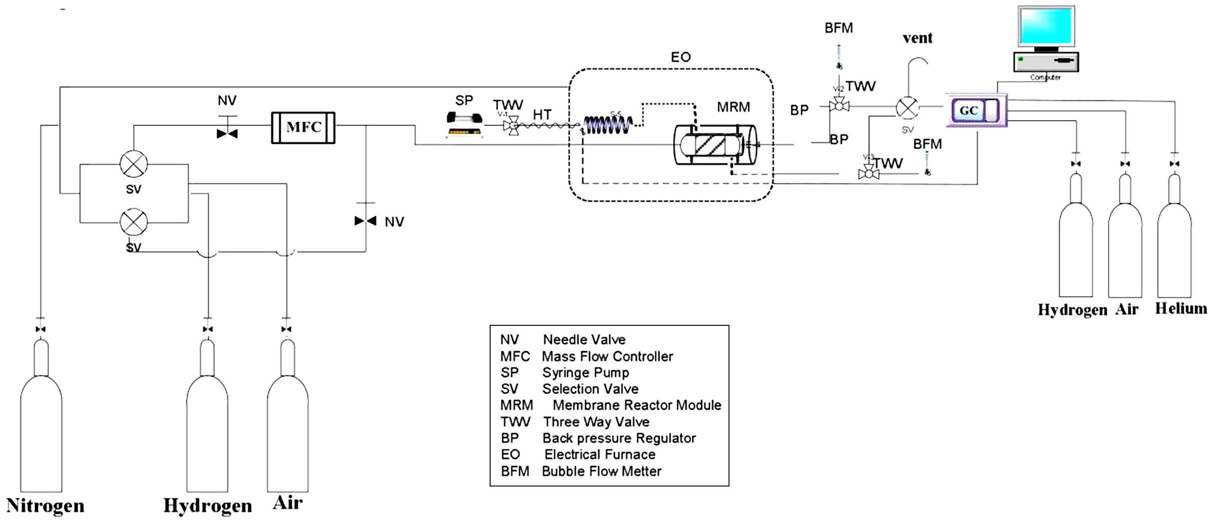


Figure 1. Scheme of the setup used for membranes characterization.

The total conversion of the n-pentane ($X_{n-pentane}$) is calculated as follows:

$$X_{n-pentane} = \frac{\sum A_i - A_{n-pentane}}{\sum A_i} \times 100, \qquad (2)$$

Further, the selectivity (S) is described for the reaction product, or the asset of products, through Eq. (3):

$$S_i = \frac{\sum A_i}{\sum A_i - A_{n-pentane}} \times 100, \qquad (3)$$

where A_i is the corrected chromatographic area for a particular compound, which is used to express the conversion and selectivity as molar percentages [28].

3. Results and discussion

Before calcination, the membrane was gas tight, indicating that the synthesized membrane was defect-free. After calcination, the single gas permeation test was performed at room temperature by using nitrogen as gas. The N_2 permeance was equal to 2.9×10^{-7} mol/m^2 s Pa and about 30×10^{-6} mol/m^2 s Pa for the bare support and the membrane, respectively. The lower membrane permeance with respect to the bare support indicates that, at least, the larger support pores are covered with the zeolitic layer.

Then, nC_5/2MB mixture (70/30) was separated using the synthesized Pt-ZSM-5 membrane. As shown in Figure 2, the selectivity decreased as the feed pressure increased. This phenomenon results from the growing number of transports through the non-zeolite pores with the feed pressure. This result confirms the presence of defects in the zeolite layer. The same results were found by a BZSM-5 zeolite membrane [29].

The isomerization of n-pentane was considered as a probe reaction to evaluate the catalytic activity of the prepared catalytic zeolite membrane. The catalytic test was performed at 250°C in accordance with the results obtained in the same process in previous works. Figure 3 shows the experimental results in terms of conversion and selectivity in the case of the isomerization of n-pentane as a function of the space velocity.

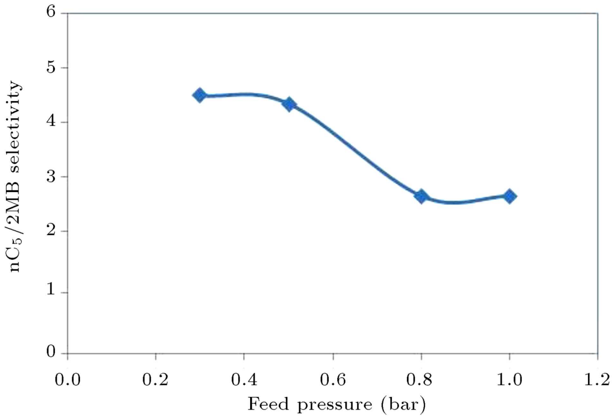


Figure 2. nC_5/2MB selectivity versus feed pressure (70/30 mixture, $T = 493$ K).

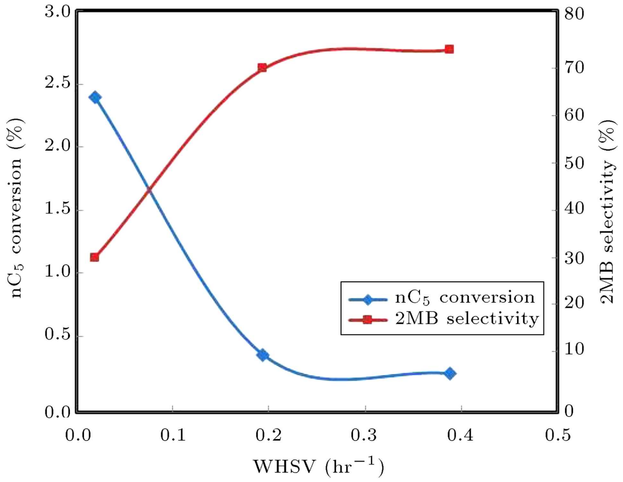


Figure 3. Effect of Weight Hourly Space Velocity (WHSV) on the pentane isomerization (conversion and selectivity); (sample: Pt-ZSM-5 membrane; molar ratio H_2/HC = 4.82; $T = 250$°C).

The experimental data, indicating an increase in the space velocity, were used to determine the decrease rate of the conversion and the increase rate of the selectivity. One way to account for this result is the fact that an increase in the space velocity causes a reduction in the contact between reagents and catalytic sites and, thus, the pentane conversion decreases. At the same time, an increase in the space velocity suppressed the side reaction of 2MB as the selectivity increased. In general, the nC_5 conversion reduced through the rising WHSV, and the reaction products shifted far away from the thermodynamic equilibrium and obtained a particular value regardless of nC_5 flow rate, while the selectivity of isomerization increased through the increasing WHSV. Given that the WHSV has a critical impact on reaction kinetics, high WHSV causes a reaction-rate-limited conversion and low WHSV leads to an equilibrium-limited conversion [30]. Figure 4 shows the conversion of n-pentane and selectivity as a function of the time on stream.

It is possible to observe the nC_5 conversion getting slower easily over time on stream, while the selectivity remains constant, probably because of coke deposition on acidic sites. In fact, different papers have reported that strong Lewis acidic sites in the absence of hydrogen become active sites for the formation of dehydrogenated carbonaceous species, turning into a precursor of coke on the surface of the catalyst [31,32]. The performances of both powdered Pt-ZSM-5 catalysts that were reduced at temperatures of 250 and 450°C are presented in Figure 5. The catalysts that were reduced at 450°C were more active in pentane iso-

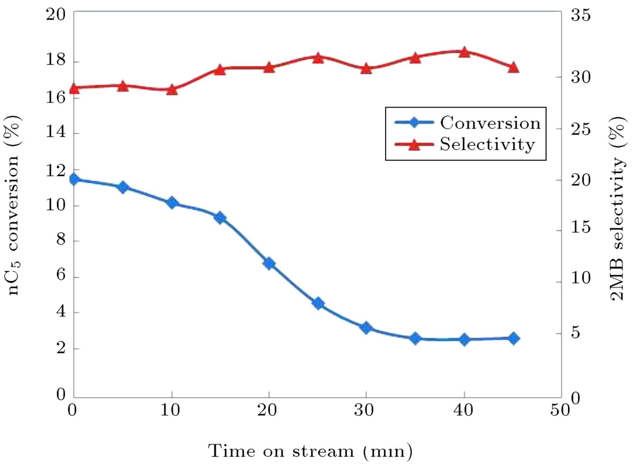


Figure 4. nC_5 conversion and 2MB selectivity versus time on stream (sample: Pt-ZSM-5 membrane; molar ratio of H_2:HC = 1.6; WHSV = 0.026 h^{-1}; $T = 250°C$).

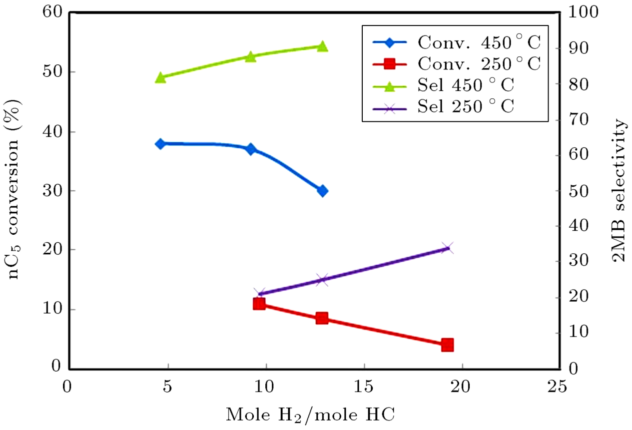
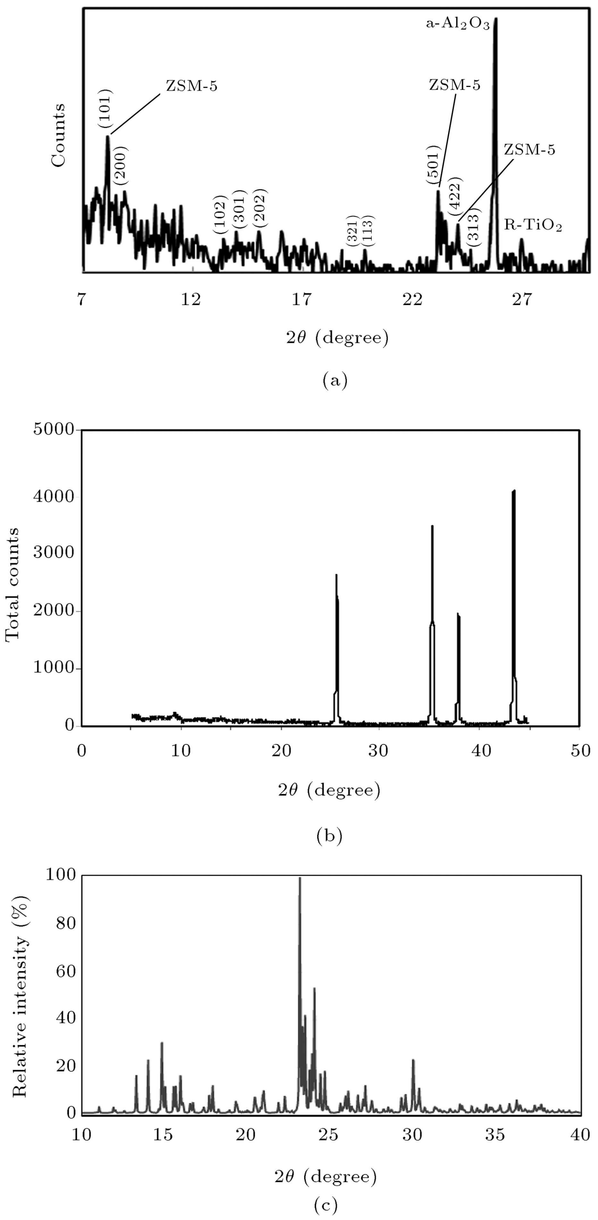


Figure 5. Effect of reduction temperature of catalytic activity of Pt-ZSM-5 zeolite powder at 250°C.

merization than those reduced at 250°C. The pentane conversion on the Pt-ZSM-5 catalyst increased from 10% to about 38% due to an increase in the reaction temperature from 250°C to 450°C. In addition, the reaction selectivity for catalysts reduced at 450°C was more than that reduced at 250°C. Therefore, it is expected that the reduction of the catalytic layer at 450°C may increase the conversion and selectivity of pentane isomerization.

After performing the catalytic experiments, the zeolite layers grown on the alumina supports were analyzed by XRD, SEM, and EDX. The XRD patterns of α-Al_2O_3 tubular support (Figure 6(b)) and ZSM5 powder (Figure 6(c)) were compared with those recorded for powder scratched on the surface of the membrane. The characteristic peaks of ZSM5 zeolite and alumina can be observed in the composite membrane spectrum (Figure 6(a)). In Figure 6(a), the peaks at 7–9° and 22.5–24.5° correspond to the MFI-type zeolite, indicating the presence of the desired zeolite.



(a)

(b)

(c)

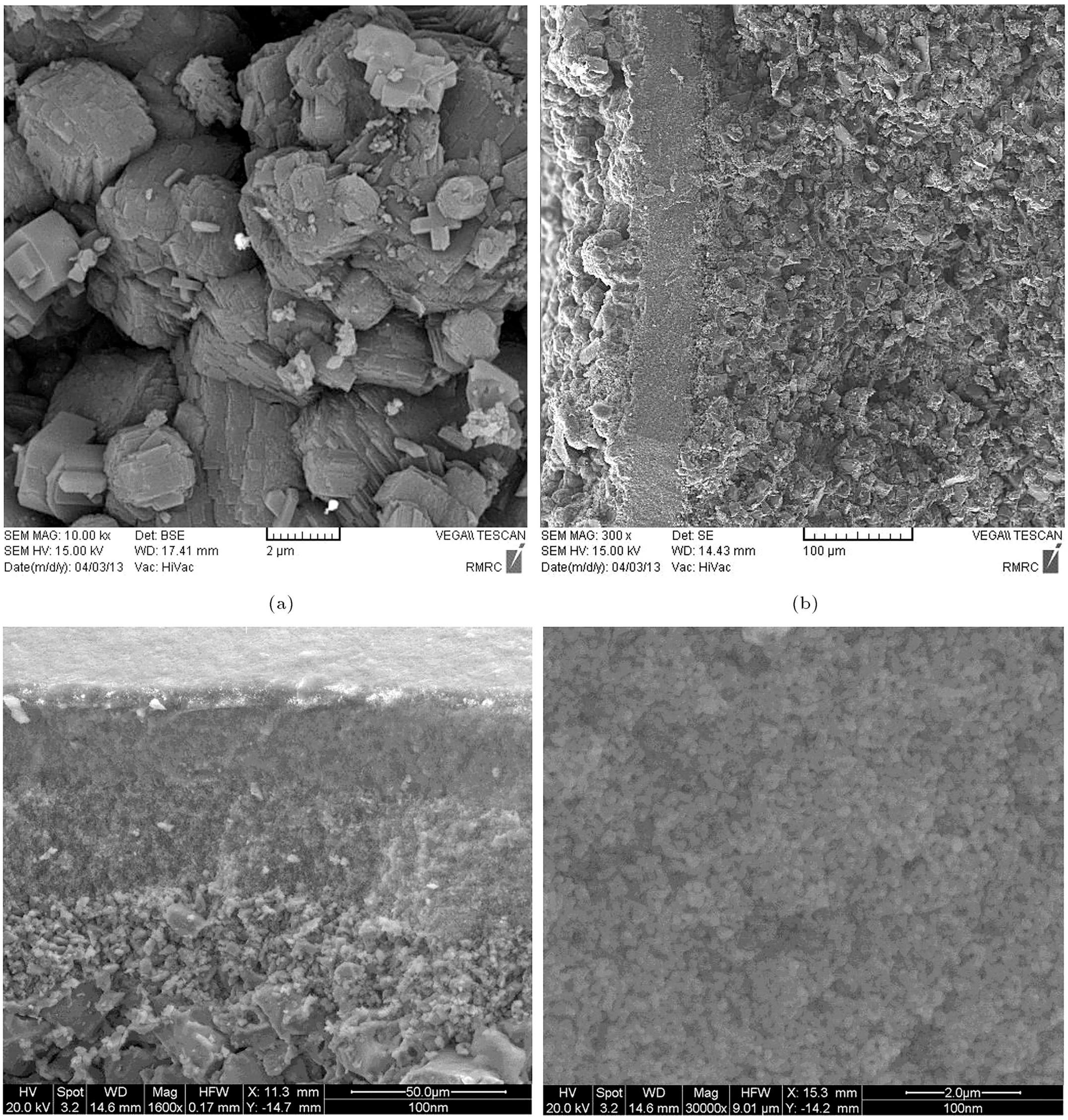
Figure 6. X-Ray Diffraction (XRD) spectra: (a) Powder scratched from membrane (b) α-Al_2O_3 support, and (c) ZSM5 powder [34].

Extra peaks correspond to the alumina support and R-TiO_2 (rutile phase) intermediate layer [20].

SEM micrographs of the membrane are shown in Figure 7. A mostly uniform and compact zeolite layer was present on the alumina support (see Figure 7(a)). In addition, the thickness of the zeolite layer on the support was about 50 mm, as shown in Figure 7(b). For comparison purposes, the image of bare support is also reported (Figure 7(c) and (d)).

EDX analyses were also carried out on the membrane cross-section of the ZSM5 layer. The presence of Si, Al, and Pt was detected (see Figure 8).

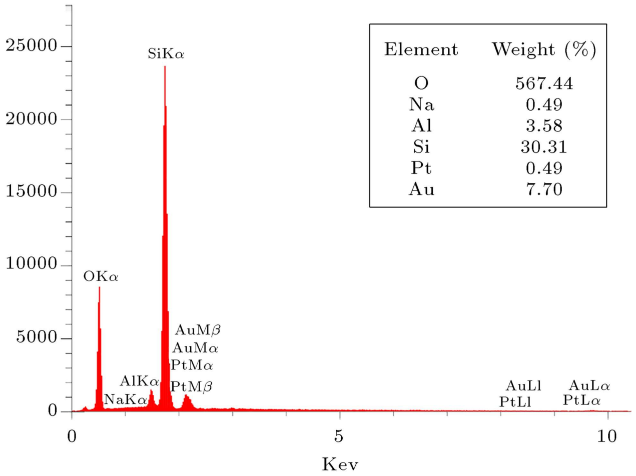
The elemental chemical mapping revealed that Si and Al were the major elements present along



(a) (b)

(c) (d)

Figure 7. Scanning Electron Microscopy (SEM) micrographs: (a) Cross-section, (b) top-view of the Pt-ZSM5 membrane, (c) cross-section, and (d) top-view of the bare support.



Element	Weight (%)
O	567.44
Na	0.49
Al	3.58
Si	30.31
Pt	0.49
Au	7.70

Figure 8. Energy Dispersive Spectroscopy (EDS) elemental analysis on the Pt-ZSM-5 membrane.

the thickness of the membrane. In addition, oxygen was also present outside the zeolite layer as a major component of the support (see Figure 9).

The results presented in this work demonstrate the possibility to perform the *n*-pentane isomerization by using zeolite membrane loaded with Pt. Usually, a zeolite catalytic membrane offers a good dispersion of catalytically active and nano-sized particles in a thin zeolite layer by improving the contact between the reactants and the catalytic site and reducing the by-pass problem [33]. However, to improve the performance of a process using catalytic zeolite membrane, it is very important to reduce the concentration of defects in the zeolite layer. In fact, it is well known that zeolite membrane functions very well in a process where liquid species are involved, while the limits are set when gas species are involved because of their small sizes;

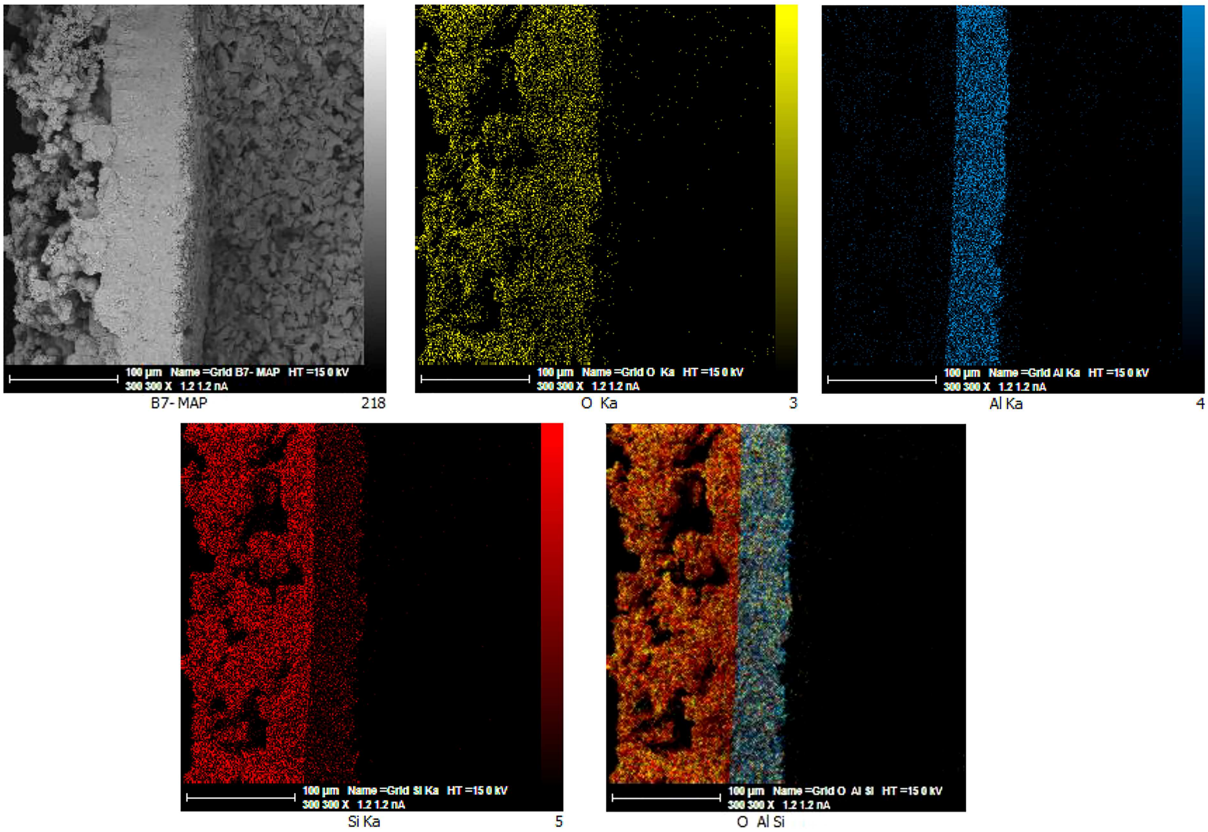


Figure 9. Energy Dispersive Spectroscopy (EDS) elemental mapping images of Pt-ZSM-5 membrane.

therefore, the necessity to have membrane defect-free should be considered [36].

4. Conclusion

ZSM5 supported membranes were synthesized by the secondary growth method. Pt-loaded zeolite membranes were prepared by the impregnation method. Scanning Electron Microscopy (SEM) analysis showed the formation of an almost uniform and compact layer on the alumina support. This result was also confirmed by the N_2 permeance of the membrane, measured after the calcination step. In addition, Energy Dispersive Spectroscopy (EDS) analysis confirmed the presence of Pt, Si, Al, and O in the zeolite layer. The catalytic tests showed the possibility to perform the nC_5 isomerization by using the Pt-ZSM5 membrane. Moreover, it was also observed that the nC_5 conversion decreased and the iC_5 selectivity increased with Weight Hourly Space Velocity (WHSV) due to the reduced contact time. It was also found that the nC_5 conversion decreased with time on stream, probably owing to the coke formation.

Nomenclature

EDS	Energy Dispersive Spectroscopy
MR	Membrane Reactor
SEM	Scanning Electron Microscope
WHSV	Weight Hourly Space Velocity
XRD	X-Ray Diffraction

List of symbols

A	[-] the chromatographic area
S	[dimensionless] selectivity
X	[dimensionless] the total conversion
x_i	[dimensionless] molar fractions of components i in the feed
y_i	[dimensionless] molar fractions of components i in permeate
α	[dimensionless] the separation factor

References

1. Al-Kandari, H., Al-Kandari, S., Al-Kharafi, F., and Katrib, A. "Molybdenum-based catalysts for upgrading light naphtha linear hydrocarbon compounds", *Energy & Fuels*, **23**(12), pp. 5737–5742 (2009).
2. Ramos, M.J., Gómez, J.P., Dorado, F., Sánchez, P., and Valverde, J.L. "Hydroisomerization of a refinery naphtha stream over agglomerated Pd zeolites", *Ind. Eng. Chem. Res.*, **44**(24), pp. 9050–9058 (2005).
3. Villegas, J.I., Kumar, N., Heikkilä, T., Lehto, V. P., Salmi, T., and Murzin, D.Y. "Isomerization of

n-butane to isobutane over Pt-modified Beta and ZSM-5 zeolite catalysts: Catalyst deactivation and regeneration", *Chem. Eng. J.*, **120**(1–2), pp. 83–89 (2006).

4. Dhar, A., Vekariya, R.L., and Sharma, P. "Kinetics and mechanistic study of n-alkane hydroisomerization reaction on Pt-doped γ-alumina catalyst", *Petroleum*, **3**(4), pp. 489–495 (2017).
5. Yoshioka, C.M.N., Garetto, T., and Cardoso, D. "n-hexane isomerization on Ni-Pt catalysts/supported on HUSY zeolite: The influence from a metal content", *Catal. Today*, **107–108**(0), pp. 693–698 (2005).
6. Noh, G., Shi, Z., Zones, S.I., and Iglesia, E. "Isomerization and β-scission reactions of alkanes on bifunctional metal-acid catalysts: Consequences of confinement and diffusional constraints on reactivity and selectivity", *J. Catal.*, **368**, pp. 389–410 (2018).
7. Baudot, A. and Bournay, L. "Intégration de membranes zéolithes MFI dans le procédé d'isomérisation des essences légères", *Oil Gas Sci. Technol. - Rev. IFP*, **64**(6), pp. 759–771 (2009).
8. Ejtemaei, M., Charchi Aghdam, N., Babaluo, A.A., Tavakoli, A., and Bayati, B. "n-pentane isomerization over Pt-Al promoted sulfated zirconia nanocatalyst", *Sci. Iran.*, **24**(3), pp. 1264–1271 (2017).
9. Daramola, M.O., Deng, Z., Pera-Titus, M., Giroir-Fendler, A., Miachon, S., Burger, A.J., Lorenzen, L., and Guo, Y. "Nanocomposite MFI-alumina membranes prepared via pore-pugging synthesis: Application as packed-bed membrane reactors for m-xylene isomerization over a Pt-HZSM-5 catalyst", *Catal. Today*, **156**(3–4), pp. 261–267 (2010).
10. Li, K., *Ceramic Membranes for Separation and Reaction*, Wiley (2007).
11. Aboul-Gheit, A.K., Gad, F.K., Abdel-Aleem, G.M., El-Desouki, D.S., Abdel-Hamid, S.M., Ghoneim, S.A., and Ibrahim, A.H. "Pt, Re and Pt-Re incorporation in sulfated zirconia as catalysts for n-pentane isomerization", *Egypt. J. Pet.*, **23**(3), pp. 303–314 (2014).
12. Setiabudi, H.D., Jalil, A.A., Triwahyono, S., Kamarudin, N.H.N., and Mukti, R.R. "IR study of iridium bonded to perturbed silanol groups of Pt-HZSM5 for n-pentane isomerization", *Appl. Catal., A*, **417–418**, pp. 190–199 (2012).
13. Setiabudi, H.D., Jalil, A.A., Triwahyono, S., Kamarudin, N.H.N., and Jusoh, R. "Ir/Pt-HZSM5 for n-pentane isomerization: Effect of Si/Al ratio and reaction optimization by response surface methodology", *Chem. Eng. J.*, **217**, pp. 300–309 (2013).
14. Deshayes, A.L., Miró, E.E., and Horowitz, G.I. "Xylene isomerization in a membrane reactor: Part II. Simulation of an industrial reactor", *Chem. Eng. J.*, **122**(3), pp. 149–157 (2006).
15. Zhang, C., Hong, Z., Chen, J., Gu, X., Jin, W., and Xu, N. "Catalytic MFI zeolite membranes supported on α-Al_2O_3 substrates for m-xylene isomerization", *J. Membr. Sci.*, **389**(0), pp. 451–458 (2012).
16. Anbia, M. and Aghaei, M. "Study of the effect of organic binders on 13X zeolite agglomeration and their CO_2 adsorption properties", *Sci. Iran.*, **26**(3), pp. 1497–1504 (2019).
17. Medrano, J.A., Garofalo, A., Donato, L., Basile, F., De Santo, M.P., Gallucci, F., Cofone, F., Ciuchi, F., and Algieri, C. "CO selective oxidation using catalytic zeolite membranes", *Chem. Eng. J.*, **351**, pp. 40–47 (2018).
18. Dong, X., Wang, H., Rui, Z., and Lin, Y.S. "Tubular dual-layer MFI zeolite membrane reactor for hydrogen production via the WGS reaction: Experimental and modeling studies", *Chem. Eng. J.*, **268**, pp. 219–229 (2015).
19. Sato, T., Kumagai, A., and Itoh, N. "A catalytic ZSM-5 membrane sandwiched with silicalite-1 layers for highly selective toluene disproportionation", *Sep. Purif. Technol.*, **73**(1), pp. 32–37 (2010).
20. Ejtemaei, M., Charchi Aghdam, N., Babaluo, A., Tavakoli, A., and Bayati, B. "Isomerization of C5 isomers in the BZSM-5 membrane reactor packed with Pt/SZ nanocatalyst", *Chem. Eng. Process.*, **130**, pp. 185–191 (2018).
21. Charchi Aghdam, N., Ejtemaei, M., Babaluo, A.A., Tavakoli, A., Bayati, B., and Bayat, Y. "Enhanced i-C5 production by isomerization of C5 isomers in BZSM-5 membrane reactor packed with Pt/ZSM-5 nanocatalyst", *Chem. Eng. J.*, **305**, pp. 2–11 (2016).
22. Algieri, C., Comite, A., and Capannelli, G. "6 - Zeolite membrane reactors", *Handbook of Membrane Reactors*, A. Basile, Ed., Woodhead Publ., pp. 245–270 (2013).
23. Song, Y.-Q., Feng, Y.-L., Liu, F., Kang, C.-L., Zhou, X. L., Xu, L.-Y., and Yu, G.-X. "Effect of variations in pore structure and acidity of alkali treated ZSM-5 on the isomerization performance", *J. Mol. Catal. A: Chem.*, **310**(1–2), pp. 130–137 (2009).
24. Kumar, N., Masloboischikova, O.V., Kustov, L.M., Heikkilä, T., Salmi, T., and Murzin, D.Y. "Synthesis of Pt modified ZSM-5 and beta zeolite catalysts: Influence of ultrasonic irradiation and preparation methods on physico-chemical and catalytic properties in pentane isomerization", *Ultrason. Sonochem.*, **14**(2), pp. 122–130 (2007).
25. Gora, L. and Jansen, J.C. "Hydroisomerization of C6 with a zeolite membrane reactor", *Journal of Catalysis*, **230**(2), pp. 269–281 (2005).
26. Garofalo, A., Carnevale, M., Donato, L., Drioli, E., Alharbi, O., Aljlil, S., Criscuoli, A., and Algieri, C. "Scale-up of MFI zeolite membranes for desalination by vacuum membrane distillation", *Desalination,* **397**, pp. 205-212 (2016).
27. Wang, H. and Lin, Y.S. "Synthesis and modification of ZSM-5/silicalite bilayer membrane with improved hydrogen separation performance", *J. Membr. Sci.*, **396**(0), pp. 128–137 (2012).
28. López, C., Guillén, Y., García, L., Gómez, L., and Ramírez, Á. "n-pentane hydroisomerization on Pt

containing HZSM-5, HBEA and SAPO-11", *Catal Lett*, **122**(3–4), pp. 267–273 (2008).

29. Bayati, B., Belbasi, Z., Ejtemaei, M., Aghdam, N.C., Babaluo, A.A., Haghighi, M., and Drioli, E. "Separation of pentane isomers using MFI zeolite membrane", *Sep. Purif. Technol.*, **106**, pp. 56–62 (2013).
30. Zhang, Y., Wu, Z., Hong, Z., Gu, X., and Xu, N. "Hydrogen-selective zeolite membrane reactor for low temperature water gas shift reaction", *Chem. Eng. J.*, **197**, pp. 314–321 (2012).
31. Ye, G., Sun, Y., Guo, Z., Zhu, K., Liu, H., Zhou, X., and Coppens, M.O. "Effects of zeolite particle size and internal grain boundaries on Pt/Beta catalyzed isomerization of n-pentane", *J. Catal.*, **360**, pp. 152–159 (2018).
32. Setiabudi, H., Jalil, A., Triwahyono, S., Kamarudin, N., and Jusoh, R. "Ir/Pt-HZSM5 for n-pentane isomerization: Effect of Si/Al ratio and reaction optimization by response surface methodology", *Chem. Eng. J.*, **217**, pp. 300-309 (2013).
33. Medrano, J., Garofalo, A., Donato, L., Basile, F., De Santo, M., Gallucci, F., Cofone, F., Ciuchi, F., and Algieri, C. "CO selective oxidation using catalytic zeolite membranes", *Chem. Eng. J.*, **351**, pp. 40–47 (2018).
34. Kokotailo, G.T., Lawton, S.L., Olson, D.H., and Meier, W.M. "Structure of synthetic zeolite ZSM-5", *Nature*, **272**, pp. 437–438 (1978).
35. Karimi, R., Bayati, B., Aghdam, N.C., Ejtemaee, M., and Babaluo, A.A. "Studies of the effect of synthesis parameters on ZSM-5 nanocrystalline material during template-hydrothermal synthesis in the presence of chelating agent", *Powder Technol.*, **229**, pp. 229–236 (2012).
36. Bedard, R. and Liu, C. "Recent advances in zeolitic membranes", *Annu. Rev. Mater. Res.*, **48**(0), pp. 83–110 (2018).

Biographies

Behrouz Bayati received the PhD degree in Chemical Engineering from Sahand University of Technology, Iran in 2013. He is currently an Assistant Professor of Chemical Engineering at Ilam University, Ilam, Iran. His research interests are in the general area of membrane and membrane reactor process, zeolite membranes, and molecular simulation. He has published over 30 research articles on related subjects. In the last decade, he presented different specialized courses.

Catia Algieri is a researcher at Institute for Membrane Technology, National Research Council of Italy (ITM-CNR) since 2001. She collaborated on several international and national projects focused on membranes preparation and characterization for application in water treatment, catalytic reactions, and gas separations. She is the co-author of more than 45 peer-reviewed papers and one patent. She has also offered more than 70 oral presentations (also as invited lecture) in National and International Conferences. She has chaired several sessions at conferences. She is also an Associate Editor of the Euro-Mediterranean Journal for Environmental Integration by Springer-Nature.

Ali Akbar Babaluo graduated from high school in 1992 and continued his education in Chemical petrochemical Engineering at Sahand University of Technology (SUT), Tabriz, Iran. He received his PhD degree in 2004. Dr. Babaluo continued his education and research-based activities at SUT as an Assistant Professor. He is the author of more than 80 journal papers, 150 national and 22 international conference papers, and 16 national patents (2 patents have scientific certificate). Dr. Babaluo has also performed other different scientific activities including publishing a journal, creating a research center and an incubator, writing book and book chapter, working as an editorial board member of two research journals, and presenting scientific comments, corrections, and corrigendum on published articles. Now, he continue his viable activities at Sahand University of Technology as a Full Professor.

Mohammad Haghighi was born in Iran, in 1969. He received his BSc and MSc degrees both in Chemical Engineering from Shiraz University and Isfahan University of Technology in 1992 and 1995 respectively. After graduation, he joined the Sahand University of Technology (in Iran) where he worked as a lecturer as well as researcher until 2003. He also worked at the "Reactor and Catalysis Research Center" and "Environmental Engineering Research Center" at SUT during his working at this university. He was awarded a PhD scholarship from MSRT of Iran in 2003 and started his PhD program at the Reactor and Catalysis Research Center at Curtin University of Technology in Western Australia. He finished his PhD under supervision of Professor Dong-ke Zhang, FTSE, with the topic "Catalytic Partial Oxidation of Methane for Direct Conversion of Natural Gas to Methanol" at the Reactor and Catalysis Research Center at Curtin University of Technology in Western Australia in 2007. After that he was back to Sahand University of Technology and appointed as Vice Chancellor of Financial Affairs at Sahand University of Technology as well as Director of Reactor and Catalysis Research Center.

Asma Ghorbani received both her BSc and MSc degrees in Chemical Engineering from Ilam University, Ilam, Iran in 2016 and 2018, respectively. Her research interests are in the general area of separation science, especially membrane and membrane reactor process, zeolite membranes, and molecular simulation. She has published more than four research papers and one chapter book. She also did one oral presentation at an International conference.

Enrico Drioli is an Emeritus Professor at the School of Engineering of the University of Calabria. He is the Founding Director of the Institute on Membrane Technology, CNR, Italy. Since 2012, he has been a Distinguished Adjunct Professor at CEDT King Abdulaziz University, Jeddah, Saudi Arabia. Since 2010, he has been a WCU Distinguished Visiting Professor at Hanyang University, Seoul Korea. His research activities focus on membrane science and engineering, membranes in artificial organs, integrated membrane processes, membrane preparation and transport phenomena in membranes, membrane distillation and membrane contactors, and catalytic membrane and catalytic membrane reactors. He is the author of more than 800 scientific papers, 22 patents, and 24 books on membrane science and technology.