Estimation of critical fluxes, thermal stabilities and failure criteria of cellulose-based membranes and modelling of salt diffusivity during pervaporative desalination

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Abstract

The consequences of highly saline freshwater on the ecosystem and humans are quite alarming and have gained little attention in recent times. Progressive advances in pervaporation have helped to unlock its potentials in the desalination of salty streams. In this study, desalination of lagoon-water using cellulose acetate membrane (CAM) and its copper-doped nanocomposite (CA-CuNP) membrane was investigated. A newly developed model was used in estimating salt diffusion coefficients in steady and unsteady state situations. At the experimental phase, permeate fluxes increased with temperature but dropped when the critical fluxes (5.11–6.01 L/m^{2}h and 5.29–7.56 L/m^{2}h) were exceeded for the CAM and CA-CuNP membranes respectively. At steady state, the critical permeate volumes for the pristine and nanocomposite membranes were 0.2273 and 0.1826 L with corresponding fluxes of 0.034 and 0.031 L/m^{2}h after 10 and 9 h, respectively. The estimated steady and unsteady diffusivities for the membranes are: 1.46 * 10^{-4}–8.43 * 10^{-3} m^2/h (4.06 * 10^{-7}–2.34 * 10^{-6} m^2/s) and 2.44 * 10^{-4}–0.17 * 10^{-4} (6.78 * 10^{-8}–4.72 * 10^{-9} m^2/s), respectively. The nanocomposite membrane gave slightly higher salt rejection with fluxes mimicking the power law model. Thermal resistance of the pristine membrane improved from 219.36 to 221.18 °C after doping it with copper nanoparticles. Furthermore, the estimated critical permeate fluxes are indicative of saturation conditions for the CAM and CA-CuMP membranes and hence are signals for membrane plugging which then implies that proactive measures can then be taken to abate such situations.

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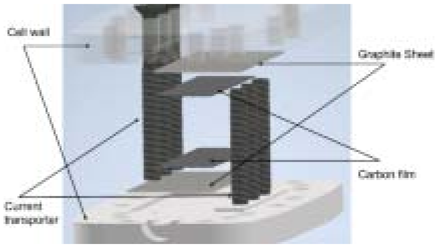

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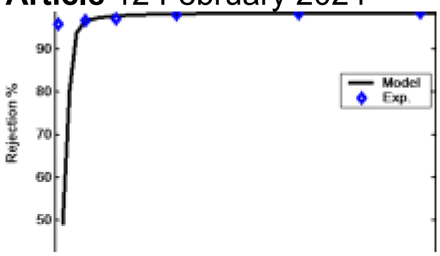

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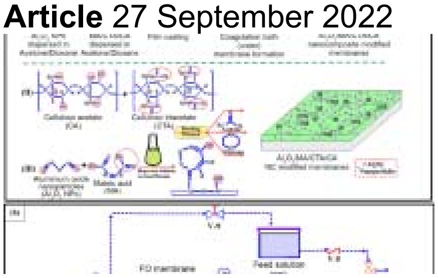

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Availability of data and materials

All relevant data generated from this research have been included in the submission.

References

1. Nielsen DL, Brock MA, Bees GN, Baldwin DS (2003) Effects of increasing salinity on freshwater ecosystems in Australia. Aust J Bot 51:655–665

   Article Google Scholar

2. Clout G (2008) Review of CSD-13 water and sanitation decisions. In: Statement of the United Nations Industrial Development Organization, UNIDO, New York City, U.S.A

3. Naim M, Elewa M, El-Shafei A, Moneer A (2015) Desalination of simulated seawater by purge-air pervaporation using an innovative fabricated membrane. Water Sci Technol 72(5):785–793. https://doi.org/10.2166/wst.2015.277

   Article **Google Scholar**

4. Dos Santos S, Adams EA, Neville G, Wada Y, De Sherbinin A, Mullin BE, Adamo SB (2017) Urban growth and water access in sub-saharan Africa: progress, challenges, and emerging research directions. Sci Total Environ 607–608:497–508. https://doi.org/10.1016/j.scitotenv.2017.06.157

   Article **Google Scholar**

5. Elimelech M, Phillip WA (2011) The future of seawater desalination: energy, technology, and the environment. Science 333(6043):712–717. https://doi.org/10.1126/science.1200488

   Article **Google Scholar**

6. Sharon H, Reddy KS (2015) A review of solar energy driven desalination technologies. Renew Sustain Energy Rev 41:1080–1118. https://doi.org/10.1016/J.Rser.2014.09.002

   Article **Google Scholar**

7. Zhou D, Zhu LFY, Zhu M, Xue L (2015) Development of lower cost seawater desalination processes using nanofiltration technologies—a review. Desalination 376:109–116. https://doi.org/10.1016/j.desal.2015.08.020

   Article **Google Scholar**

8. Wu D, Gao A, Zhao H, Feng H (2018) Pervaporative desalination of high-salinity water. Chem Eng Res Des 136:154–164. https://doi.org/10.1016/j.cherd.2018.05.010

   Article **Google Scholar**

9. Youseff PG, Al-Dadah RK, Mahmoud SM (2014) Comparative analysis of desalination technologies. Energy Procedia 61:2604–2607. https://doi.org/10.1016/j.egypro.2014.12.258

   Article **Google Scholar**

10. Shao P, Huang R (2007) Polymeric membrane pervaporation. J Membr Sci 287:162–179

    Article **Google Scholar**

11. Khayet MTM (2004) Pervaporation and vacuum membrane distillation processes: modeling and experiments. Am Inst Chem Eng J 50:1697–1712

Article Google Scholar

12. Semenova S, Ohya H, Soontarapa K (1997) Hydrophilic membranes for pervaporation: an analytical review desalination. Deaslination 110:251–286

Article Google Scholar

13. Alkhudhiri A, Darwish N, Hilal N (2012) Membrane distillation: a comprehensive review. Desalination 287(2012):2–18. https://doi.org/10.1016/j.desal.2011.08.027

Article Google Scholar

14. Camacho L, Dumée L, Zhang J, Li J, Duke M, Gomez J, Gray S (2013) Advances in membrane distillation for water desalination and purification applications. Water 5:94–196

Article Google Scholar

15. Drobek M, Yacou C, Motuzas J, Julbe A, Ding L, Diniz Da Costa J (2012) Long term pervaporation desalination of tubular mfi zeolite membranes. Membr Sci 415:816–823

Article Google Scholar

16. Kulkarni SS, Kittur AA, Aralaguppi MI, Kariduraganavar MY (2004) Synthesis and characterization of hybrid membranes using poly (vinyl alcohol) and tetraethylorthosilicate for the pervaporation separation of water–isopropanol mixtures. J Appl Polym Sci 94(3):1304–1315

Article Google Scholar

17. Jyoti G, Keshav A, Anandkumar A (2015) Review on pervaporation: theory, membrane performance, and application to intensification of esterification reaction. J Eng. https://doi.org/10.1155/2015/927068

Article Google Scholar

18. Abdallah H, El-gendi A, Khedr M, El-Zanati E (2015) Hydrophobic polyethersulfone porous membranes for membrane distillation. Front Chem Sci Eng. https://doi.org/10.1007/s11705-015-1508-4

Article Google Scholar

19. Liang B, Zhana W, Qi G, Lina S, Nana Q, Liua Y, Cao B, Pana K (2013) High performance graphene oxide/polyacrylonitrile composite pervaporation membranes for desalination applications. J Mater Chem A. https://doi.org/10.1039/C4TA06573E

Article Google Scholar

20. Li P (2016) Pervaporation: an emerging technology for desalination. Polym Sci 2:1

Article Google Scholar

21. Tijing L, Woo Y, Choi J-S, Lee S, Kim S-H, Shon H (2015) Fouling and its control in membrane distillation—a review. J Membr Sci 475:215–244

Article Google Scholar

22. Adham S, Hussain A, Matar JM, Dores R, Janson A (2013) Application of membrane distillation for desalting brines from thermal desalination plants. Desalination 314:101–108

Article Google Scholar

23. Kaminski W, Marszalek J, Tomczak E (2018) Water desalination by pervaporation—comparison of energy consumption. Desalination 433:89–93

Article Google Scholar

24. Mendez DLM, Castel C, Lemaitre C, Favre E (2018) Membrane distillation (MD) processes for water desalination applications. Can dense self-standing membranes compete with microporous hydrophobic materials? Chem Eng Sci 188:84–96. https://doi.org/10.1016/j.ces.2018.05.025

Article Google Scholar

25. García-Payo M, Izquierdo-Gil M, Fernández-Pineda C (2000) Wetting study of hydrophobic membranes via liquid entry pressure measurements with aqueous alcohol solutions. J Colloid Interface Sci 23:420–431

Article Google Scholar

26. Siversten E, Holt T, Thelin WR (2018) Concentration and temperature effects on water and salt permeabilities in osmosis and implications in pressure-retarded osmosis. Membranes 8(39):1–13. https://doi.org/10.3390/membranes8030039

Article Google Scholar

27. Duong HC, Cooper P, Nelemans B, Cath TY, Nghiem LD (2015) Optimising thermal efficiency of direct contact membrane distillation by brine recycling for small-scale seawater desalination. Desalination 374:1–9. https://doi.org/10.1016/j.desal.2015.07.009

Article Google Scholar

28. Khan AA, Siyal MI, Lee CK, Park C, Kim JO (2018) Hybrid organic-inorganic functionalized polyethersulfone membrane for hyper-saline feed with humic acid in direct

contact membrane distillation. Sep Purif Technol 210:20–28. https://doi.org/10.1016/j.seppur.2018.07.087

Article Google Scholar

29. Choi Y, Naidua G, Nghiema LD, Leeb S, Vigneswarana S. Membrane distillation crystallization for brine mining and zero liquid discharge: opportunities, challenges, and recent progress. Environ Sci Water Res Technol. https://doi.org/10.1039/C9EW00157C

30. Alanezi AA, Abdallah H, El-Zanati E, Ahmad A, Sharif AO (2016) Performance investigation of o-ring vacuum membrane distillation module for water desalination. J Chem. https://doi.org/10.1155/2016/9378460

Article Google Scholar

31. Strathmann H (2001) Membrane separation processes: current relevance and future opportunities. AIChE J 47(5):1077–1087

Article Google Scholar

32. Ali A, Quist-Jensen CA, Macedonio F, Drioli E (2015) Application of membrane crystallization for minerals' recovery from produced water. Membranes 5:772–792

Article Google Scholar

33. Kim J, Kwon H, Lee S, Lee S, Hong S (2017) Membrane distillation (MD) integrated with crystallization (MDC) for shale gas produced water (SGPW) treatment. Desalination 403:172–178

Article Google Scholar

34. Ngo T-T-M, Nguyen T-D-N, Nguyen H-H, Hoang T-D-K, Bui X-T (2019) Review on membrane module configurations used for membrane distillation process. Geosci Eng LXV 1:1–10. https://doi.org/10.35180/gse-2019-0001

Article Google Scholar

35. Gravelle S, Yoshida H, Joly L, Ybert C, Bocquet L (2016) Carbon membranes for efficient water-ethanol separation, conductive materials. J Chem Phys 145(12):124708. https://doi.org/10.1063/1.4963098

Article Google Scholar

36. Xie Z, Hoang M, Duong T, Ng D, Dao B, Gray S (2011) Sol–gel derived poly (vinyl alcohol)/maleic acid/silica hybrid membrane for desalination by pervaporation. J Membr Sci 383:96–103

Article Google Scholar

37. Cassard HM, Park HG (2018) How to select the optimal membrane distillation system for industrial applications? J Membr Sci 565:402–410. https://doi.org/10.1016/j.memsci.2018.07.017

Article Google Scholar

38. Zhang W, Yu Z, Qian Q, Zhang Z, Wang X (2010) Improving the pervaporation performance of the glutaraldehyde cross-linked chitosan membrane by simultaneously changing its surface and bulk structure. J Membr Sci 348(1–2):213–223

Article Google Scholar

39. Pearce GK (2010) SWRO pre-treatment: markets and experience. Filtr Sep 47(4):30

Article Google Scholar

40. Khawaji AD, Kutubkhanah IK, Wie J (2008) Advances in seawater desalination technologies. Desalination 221:47

Article Google Scholar

41. Zhao C, Wu H, Li X, Pan F, Li Y, Zhao J, Jiang Z, Zhang P, Cao X, Wang B (2013) High performance composite membranes with a polycarbophil calcium transition layer for pervaporation dehydration of ethanol. J Membr Sci 429:409–417

Article Google Scholar

42. Gebru KA, Das C (2017) Removal of Pb (II) and Cu (II) ions from wastewater using composite electrospun cellulose acetate/titanium dioxide (TiO_2) adsorbent. J. Water Process. Eng. 6:1–13. https://doi.org/10.1016/j.jwpe.2016.11.008

Article Google Scholar

43. Basha KSA, Dolfe H, Åslin M, El-Gabry L (2011) Membrane distillation test for concentration of RO brine at Wessco, Jeddah. In: World Congress/Perth Convention and Exhibition Centre (PCEC), Perth, Western Australia September 4–9 (2011), REF: IDAWC/PER11–351

44. Cho CH, Oh KY, Kim SK, Yeo YG, Sharma P (2011) Pervaporative seawater desalination using NAA zeolite membrane: mechanisms of high water flux and high salt rejection. J Membr Sci 371:226–238. https://doi.org/10.1016/j.memsci.2011.01.049

Article Google Scholar

45. Palatý Z, Bendová H (2015) Determination of diffusivity from mass transfer measurements in a batch dialyzer: numerical analysis of pseudo-steady state approximation. Chem Papers 69(4):560–568. https://doi.org/10.1515/chempap-2015-0070

Article Google Scholar

46. Zhelem RI, Tokarchuk MV, Omelyan IP, Sovyak EM (1999) Calculation of distribution functions and diffusion coefficients for ions in the system "initial electrolyte solution—membrane. Condens Matter Phys 2(17):53–62

Article Google Scholar

47. Bodor S, Zook JM, Lindner E, Tóth K, Gyurcsányi RE (2008) Electrochemical methods for the determination of the diffusion coefficient of ionophores and ionophore–ion complexes in plasticized PVC membranes. Analyst 133:635–642

Article Google Scholar

48. Divine C (2004) Estimation of membrane diffusion coefficients and equilibration times for low-density polyethylene passive diffusion samplers. Environ Sci Technol 38:1849–1857

Article Google Scholar

49. Gallab AAS, Ali MEA, Shawky HA, Abdel-Mottale MSA (2017) Effect of different salts on mass transfer coefficient and inorganic fouling of TFC membranes. J Membr Sci Technol 7(2):1–9. https://doi.org/10.4172/2155-9589.1000175

Article Google Scholar

50. Pismenskaya N, Sarapulova V, Nevakshenova E, Kononenko N, Fomenko M, Nikonenko V (2019) Concentration dependencies of diffusion permeability of anion-exchange membranes in sodium hydrogen carbonate, monosodium phosphate, and potassium hydrogen tartrate solutions. Membranes 9(170):2–20. https://doi.org/10.3390/membranes9120170

Article Google Scholar

51. Liu QYT (2011) Preparation of Cu nanoparticles with ascorbic acid by aqueous solution reduction method. Trans Nonferrous Met Soc China 22:1–6

Article Google Scholar

52. Moghadassi A, Rajabi Z, Hosseini S, Mohammadi M (2013) Fabrication and modification of cellulose acetate based mixed matrix membrane: gas separation and physical properties. J Ind Eng Chem 20:1050–1060

Article Google Scholar

53. Sanni SE, Emetere ME, Odigure JO, Efeovbokhan VE, Agboola O, Sadiku ER (2017) Determination of optimum conditions for the production of activated carbon derived from

separate varieties of coconut shells. Int J Chem Eng. https://doi.org/10.1155/2017/2801359

Article **Google Scholar**

54. http://www.lbwater.org/sites/default/files/reports/desalination_test_plan.pdf. Accessed 2020.

55. Dudek G, Borys P (2019) A simple methodology to estimate the diffusion coefficient in pervaporation-based purification experiments. Polymers 11:343. https://doi.org/10.3390/polym11020343

Article **Google Scholar**

56. Qian X, Li N, Wang Q, Jia S (2018) Chitosan/graphene oxide mixed matrix membrane with enhanced water permeability for high-salinity water desalination by pervaporation. Desalination 438:83–96

Article **Google Scholar**

57. Mulder MHV, Smolders CA (1984) On the mechanism of separation of ethanol/water mixtures by pervaporation I. Calculations of concentration profiles. J Membr Sci 17:289–307

Article **Google Scholar**

58. Kefford BJ, Marchant R, Schäfer RB, Metzeling L, Dunlop JE, Choy SC, Goonan P (2011) The definition of species richness used by species sensitivity distributions approximates observed effects of salinity on stream macroinvertebrates. Environ Pollut 159:302–310. https://doi.org/10.1016/j.envpol.2010.08.025

Article **Google Scholar**

59. Kefford BJ, Dalton A, Palmer CG, Nugegoda D (2004) The salinity tolerance of eggs and hatchlings of selected aquatic macroinvertebrates in south-east Australia and South Africa. Hydrobiologia 517:179–192. https://doi.org/10.1023/B:HYDR.0000027346.06304.bc

Article **Google Scholar**

60. Mount DR, Gulley DD, Hockett JR, Garrison TD, Evans JM (1997) Statistical models to predict the toxicity of major ions to Ceriodaphnia dubia, Daphnia magna and Pimephales promelas (flathead minnows). Environ Toxicol Chem 16(1997):2009–2019. https://doi.org/10.1897/1551-5028(1997)0162009:SMTPTT.2.3.CO;2

Article **Google Scholar**

61. Soucek DJ, Mount DR, Dickinson A, Hockett JR (2018) Influence of dilution water ionic composition on acute major ion toxicity to the mayfly Neocloeon triangulifer. Environ Toxicol Chem 37:1330–1339. https://doi.org/10.1002/etc.4072

Article Google Scholar

62. Hassell KL, Kefford BJ, Nugegoda D (2006) Sub-lethal and chronic lethal salinity tolerance of three freshwater insects: Cloeon sp. and Centroptilum sp. (Ephemeroptera: Baetidae) and Chironomus sp. (Diptera: Chironomidae). J Exp Biol 209:4024–4032. https://doi.org/10.1242/jeb.02457

Article Google Scholar

63. Soucek DJ (2007) Sodium sulfate impacts feeding, specific dynamic action, and growth rate in the freshwater bivalve *Corbicula fluminea*. Aquat Toxicol 83:315–322. https://doi.org/10.1016/j.aquatox.2007.05.006

Article Google Scholar

64. Chinathamby K, Reina RDA, Bailey PCE, Lees BK (2006) Effects of salinity on the survival, growth and development of tadpoles of the brown tree frog, *Litoria ewingii*. Aust J Zool 54:97–105. https://doi.org/10.1071/ZO06006

Article Google Scholar

65. Herbert ER, Boon P, Burgin AJ, Neubauer SC, Franklin RB, Ardón M, Hopfensperger KN, Lamers LPM, Gell P (2015) A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. Ecosphere 6:1–43. https://doi.org/10.1890/ES14-00534.1

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Contributions

SES conceptualized this research idea, prepared the manuscript, developed the model for estimating solute diffusivity at steady and unsteady states, provided the required supervision during experimentation, and carried out the data analyses; MH was involved with experimentation and data curation; PA was involved with project administration, equipment acquisition and the experimental set-up; EO, AA and BO made useful observations and contributions during the laboratory work.

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Ethics declarations

Conflict of interest

The authors declare that there is no conflict of interest as regards this publication.

Additional information

Supplementary Information

Below is the link to the electronic supplementary material.

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