Journal Homepage: http://ijcpe.uobaghdad.edu.iq
Iraqi Journal of Chemical and Petroleum Engineering
Vol. 26 No. 4 (December 2025) 151 – 159
EISSN: 2618-0707, PISSN: 1997-4884

Enhancing nanofiltration desalination performance using air sparging technique

Faaiz Hussain Saleh [a], Ahmed Faiq Al-Alawy [a, *], Sara Al-Salihi [b]

a Department of Chemical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
b Department of Chemical, Biological and Bioengineering, North Carolina A&T State University, USA

Abstract

Concentration polarization is a critical problem for nanofiltration membranes, as it reduces permeate flux and increases operating costs. This study aims to assess the efficacy of air spraying technology as an innovative approach to enhance nanofiltration membrane performance, specifically in water treatment. The methodology focused on conducting comprehensive trials using simulated water and on implementing air-spraying technology at flow rates ranging from 1.5 to 4.5 liters per minute. The membrane's performance was tested under a range of conditions, including varied input concentrations (2,000 to 15,000 ppm), pressures (4 to 6 bar), water flow rates, and temperatures (20 and 32°C). The results showed that adding air efficiently reduces concentration polarization, thereby significantly increasing permeate flux and the effectiveness of sodium chloride rejection. At 2,000 ppm and 6 bar, the most significant flow was 168 liters/h, with a rejection ratio of 90.8%. The highest achievable flux was likewise reached at 32°C, with an excellent rejection ratio of 91.75%. The study, on the other hand, indicated that increasing the feed concentration worsened the permeability flux. This study demonstrates that air-spraying technology is an effective means of improving nanofiltration membrane performance.

Keywords: Air sparging; Nanofiltration membrane; Permeate flux; Concentration polarization; pressure; Feed concentration; Temperature.

Received on 07/07/2025, Received in Revised Form on 04/09/2025, Accepted on 04/09/2025, Published on 30/12/2025

https://doi.org/10.31699/IJCPE.2025.4.13

1- Introduction

A primary environmental and financial concern is the global problem of water salinity, especially in highly saline water. Numerous important sectors are adversely affected by high salinity. It jeopardizes food security in agriculture by degrading soil and lowering crop yields. Environmentally, freshwater aquifers can become contaminated by saltwater intrusion, which damages aquatic ecosystems and lowers biodiversity. Using extremely saline water in industry accelerates equipment corrosion and requires costly treatment, increasing production costs. Furthermore, long-term use of saline drinking water can harm a person's health by causing kidney and digestive issues. Approximately 1 billion people worldwide lack access to clean, efficient drinking water sources. This is due to the inadequate management of water sources in both urban and rural regions across many parts of the world.

Therefore, millions of individuals are exposed to hazardous levels of microbiological and chemical contaminants in their drinking water daily [1-3]. In recent years, scientists and engineers have recognized the need for renewed, cost-effective approaches to effective water decontamination due to the significant increase in water pollution levels [4, 5]. Several advanced technologies have been employed for treating liquid waste, including membrane filtration, adsorption techniques, and advanced oxidation processes [6, 7]. There has been growing use of membrane technology for water recycling and reuse, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). Various industries have adopted these membrane technologies owing to their efficiency, minimal environmental impact, high productivity, flexible configuration, and sustainability[4, 8]. Nanofiltration (NF) is a membrane-based technology that offers a promising approach to treating salinity in various water sources, including brackish water, seawater, and even some types of industrial wastewater. Its effectiveness stems from its semi- permeable membranes with pore sizes permeable membranes with pore sizes usually between 1 and 10 nanometers, which enables the divalent ions to be rejected selectively (e.g., calcium, magnesium, sulfate) and larger organic molecules, while permitting the passage of monovalent ions (e.g., sodium, chloride) and water [9-11].

Nanofiltration (NF) membranes serve as an efficient alternative for water treatment owing to their numerous benefits. These membranes operate at reduced operating pressures, thereby reducing energy usage and operational expenses. They also exhibit elevated flux, enhancing treatment efficiency. Furthermore, they provide exceptional retention for organic molecules and

*Corresponding Author: Email: Drahmed@coeng.uobaghdad.edu.iq

multivalent anion salts while allowing the transfer of monovalent ions. These attributes make them a cost-effective option, given their comparatively low investment costs relative to alternative technologies [12, 13]. Air sparging, in which an air stream is bubbled through a liquid to boost flux, increase selectivity, and reduce fouling, has been used in nanofiltration. Several studies have documented air sparging in various membrane configurations to enhance flow, increase permeation cycle, and adjust selectivity.

The hydrodynamics of the gas/liquid two-phase flow have been described, and turbulence near the membrane surface has resulted in flux enhancement and altered foulant patterns. It has been employed in numerous applications, including drinking water and biological treatment, macromolecule separation, and in different membrane geometries such as hollow fiber, flat sheet, and tubular membranes. Concentration polarization and membrane fouling during the process are among the most common problems in membrane separation processes, particularly with NF membranes, due to their diverse effects on flux. The accumulation of rejected solutes within a thin boundary layer adjacent to the membrane surface is known as concentration polarization [9, 12].

The dissolved particles are bound to the surface of the membrane by the forces of adhesion, which are in equilibrium with the shear stress to which they are subjected. The membrane material subsequently fouls, allowing it to enter the pores and eventually block them [14, 15]. Therefore, modifying the hydrodynamic conditions at the membrane surface to promote a more turbulent flow regime could improve the elimination effectiveness of these pollutants [16]. The implementation of air sparging during filtration may be a capable fouling control technique for UF membranes [17, 18]. Shear force can be induced on the feed side by air sparging on the membrane surface, which causes bubbles to rise along the membrane; in turn, this prevents deposition by enhancing the back transport of foulants from the membrane surface [19].

The flux of water and solutes through an NF membrane is characterized by the mass transfer coefficient multiplied by the driving force. The driving force is due to osmotic and applied pressure differentials that cause the water to flow through NF membranes. The water flux (J_w) equation is [20]:

$$J_w = K_w(\Delta p - \Delta\pi) \quad (1)$$

Where the constant of the permeability of water is K_w, Δp is the pressure difference, while $\Delta\pi$ is the gradient in osmotic pressure [20].

The solute flux is due to the concentration gradient that performs as the driving force, and the solute flux equation is [21]:

$$Js = K_s(Cf - Cp) \quad (2)$$

Where Js is the solute flux, Ks is the solute permeability constant, Cf is the concentration of feed, and Cp is the concentration of permeate.

The purpose of this study is to evaluate the effect of air sparging on the performance of a nanofiltration-based desalination process. This study also investigated the effects of different operating conditions and values on permeate flux and rejection. These operating conditions include temperature, water flow rate, pressure, and NaCl concentration, with and without air sparging.

2- Experimental work

The nanofiltration system (with and without air sparging) has been implemented using a spiral-wound polyamide thin-film composite (The right fit CSM: NE1812-C, Korea) with an effective area of 0.4 m^2. The simulated solution was prepared using NaCl (99.9%, Central Drug House (P) Ltd., India) and deionized water.

Fig. 1 shows a schematic representation of the NF equipment. A diaphragm pump (AQUA LOTUS: AQ-400GPD) pumped the feed from a tank to the NF membrane. Three pressure gauges measured the pressure of water and air entering and leaving the membrane. To prevent water from returning to the air, isolation valves for the air entrance and departure included one-way valves.

Both the permeate and concentrate streams are recirculated to the feed tank, maintaining a constant feed concentration throughout the operation. Meanwhile, air and water are simultaneously pumped into the membrane. The operating parameters were, feed concentrations between 2000 and 15000 ppm, pressures between 4-6 bar, air flow rates 1.5-4.5 L/min, a temperature of 32±1 and 20 ± 1^{o} C and a constant water flow rate of 1 L/min. Each experiment was run for 10 min. To evaluate permeate concentration, a conductivity meter (CRISON Basic 30, Spain) was used. The flux was obtained using the following equation [22]:

$$Jw = \frac{\Delta V}{Am\,\Delta t} \quad (3)$$

Where the water flow volume from the feed side to the permeate side is ΔV, the active area of the membrane is Am, and the time experiment is Δt. The equation of rejection is [7]:

$$\text{Rej} = 1 - \frac{C_P}{C_F} \quad (4)$$

3- Results and discussion

Experiments were conducted to examine the performance of a nanofiltration (NF) membrane with and without air. The results revealed that the presence of air considerably increases the membrane's permeate flux. This improvement addresses the impact of air bubbles, which cause turbulence at the membrane surface. This turbulence dislodges accumulated solute particles by a process known as "back-diffusion." The agitation also disrupts the boundary layer, minimizing the buildup of

dissolved materials and preventing pore blockage [23, 24, 25]. Consequently, the solute concentration at the membrane surface decreases, reducing concentration polarization and increasing permeate flux by a considerable amount without compromising membrane integrity [26, 27].

Table 1 demonstrates the effect of air sparging on flux. The data demonstrate that permeate flux is substantially affected by operating pressure, feed concentration, and air flow rate, with the addition of air continuously improving performance. In the pressure experiments, flux increased with pressure in both cases, from 33 to 70.5 L/m².h without air and from 69 to 127.5 L/m².h with air as the pressure climbed from 4 to 6 bar. Air addition showed the most significant relative improvement at lower pressures, with a flux increase of roughly 109% at 4 bar compared to 81% at 6 bar, demonstrating that air scouring is more effective when the pushing force from pressure is lower.

In the concentration experiments, flux declined dramatically as feed concentration increased, dropping from 70.5 to 8.25 L/m².h without air and from 127.5 to 12 L/m².h with air when concentration grew from 4000 ppm to 15,000 ppm. While air addition still enhanced flow under all conditions, the relative benefit declined at higher concentrations due to the more decisive influence of osmotic pressure and fouling. For air flow rate (Q_a), the results suggested an optimum at 1.3 L/min, when flux reached 63 L/m².h with air, compared to 58.5 L/m².h at 1 L/min and 55.5 L/m².h at 1.5 L/min. This shows that while moderate airflow helps mixing and surface cleaning, excessive airflow may cause instability or diminish effective contact with the membrane surface. Overall, air addition greatly enhances membrane performance, especially at lower pressures and concentrations, although its success depends on adjusting both pressure and air flow rate.

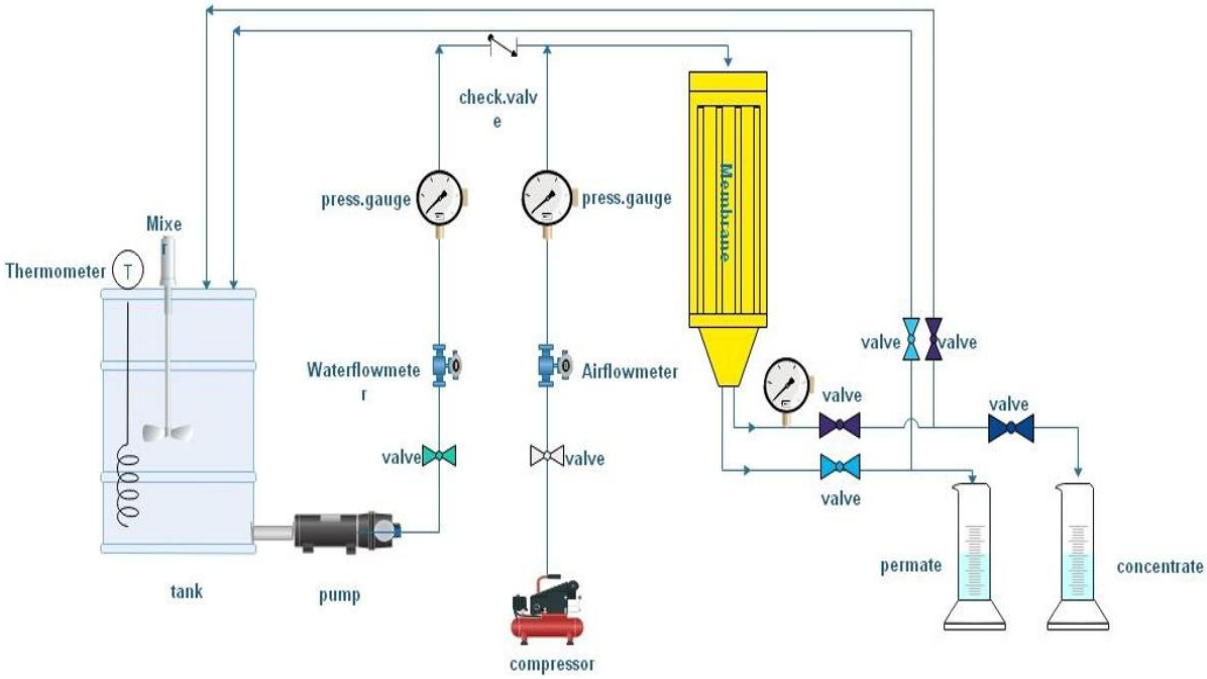

Fig. 1. Schematic diagram of a nanofiltration system with air sparing

Table 1. Values for fluxes at different applied pressures, initial concentrations and water flow rate (QA) for systems with and without air sparging

Pressure (bar)	4	5	6
flux without air (L/m². h)	33	51	70.5
flux with air (L/m². h)	69	97.5	127.5
Initial Conc. (ppm)	4000	10000	15000
flux without air (L/m². h)	70.5	15	8.25
flux with air (L/m². h)	127.5	25.5	12
water flow rate Q_A (L/min)	1	1.3	1.5
flux without air (L/m². h)	7.5	16.5	30
flux with air (L/m². h)	58.5	63	55.5

The impact of operating pressure on permeate flux is shown in Fig. 2. The results indicate that at an air flow rate of 2.5 L/min, the permeate flux increased from 78.78 to 169.69 L/m². hr. by increasing the pressure from 4 to 6 bar, after that the flux begins to decrease. The operating pressure directly influences the permeate flux in NF

systems. This behavior is consistent with that of Sentana and Al-Alawy [28, 29]. who demonstrate that higher permeate flux is typically achieved by applying high membrane pressure. Excessive pressure may compromise results, preventing one from fully reaping the benefits of the higher flow.

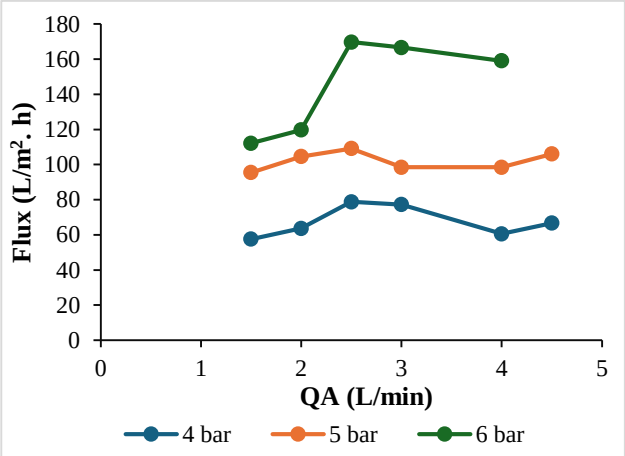

Fig. 2. Flow rates of air impact on the flux at various pressures and (C=2000 ppm, Q_{H2O}= 1 Liter/min, and Temp = 32℃)

The driving force for the process increases with increasing applied pressure, thereby enhancing the permeation rate. Pressure and permeation flux are linearly associated, suggesting that concentration polarization does not occur at the membrane surface [30]. Concentration polarization occurred at higher pressures, leading to a drop in permeation rate [31].

The rejection percentage of NaCl increased from 83.8% to 90.8% as pressure increased from 4 to 6 bar at a 2.5 L/min air flow rate. Subsequently, the pressure began to diminish, as illustrated in Fig. 3. A similar result was reported by Fadhil [32].

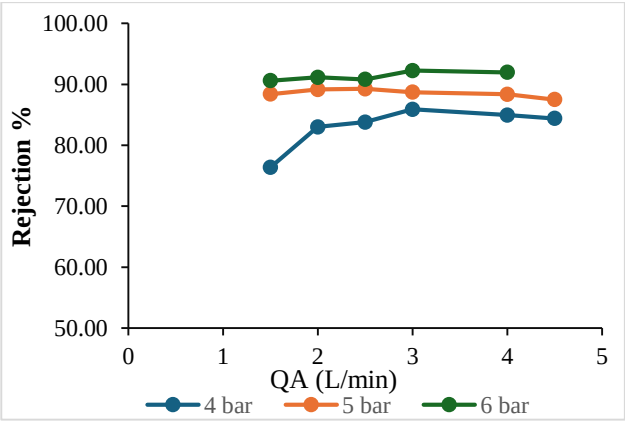

Fig. 3. Flow rates of air impact on the rejection at various pressures and (C=2000 ppm, Q_{H2O}= 1 Liter/min, and Temp. = 32℃)

The concentration polarization effect causes the rejection to rise first, reach a maximum, and subsequently decrease with increasing pressure; a correlation should be established between the applied pressure and the rejection percentage at a specific flow rate. Two phenomena would take place simultaneously if the applied pressure increased: more solute would be driven to the membrane surface, leading to concentration polarization, and solute rejection would decrease. Secondly, there will be an increase in solvent flow; however, steric and electrical considerations prevent the solute from traversing the membrane [32, 33].

Moreover, the effect of operating pressure on permeate flux and rejection has been studied at higher solute concentrations. Fig. 4 shows the influence of increasing pressure from 4 to 6 bar at 4000 ppm. The results demonstrate that the effect of increasing pressure at higher concentrations on the flux will be weaker, increasing from 69.69 to 128.78 L/m2.h.at 3.5 L/min, but these values are lower than the values obtained at 2000ppm. The rejection will increase from 77.68 to 87.175%, which is also lower than the values obtained at 2000 ppm. Due to the osmotic impact conveyed by the increased salt content, there is a noticeable decrease in flux [34]. This aligns with experiments conducted by Fadhil, Gherasim, and Otero-Fernández, which demonstrate that solute rejection decreases with concentration [32, 35, 36].

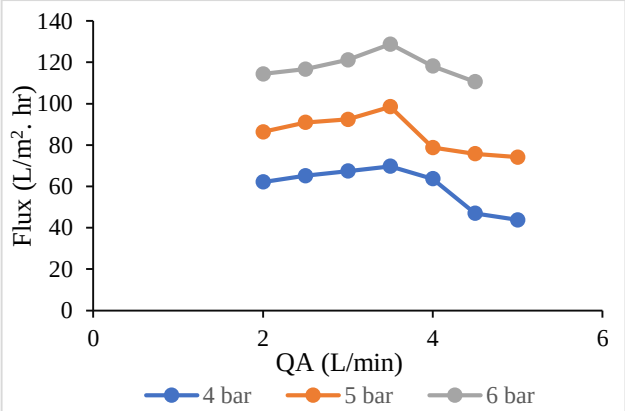

Fig. 4. Flow rates of air impact on the flux at various pressures and (C=4000 ppm, Q_{H2O}= 1 Liter/min, and Temp. = 32℃)

The concentration polarization effect is more pronounced at elevated feed concentrations due to the convective transport of both the solvent and the solute. The presence of salt induces a disparity in viscosity between the bulk solution and the membrane pore, elucidating the reduction in solute rejection and flux as salt concentration escalates. According to Fig. 5 [37, 38].

On the one hand, as a result of electrostatic attraction, which causes the adsorption of counter-ions in the membrane, an electric double layer forms when an excessive amount of salt ions builds up in or on membrane pores, thereby increasing the electroviscous effect and lowering permeate flow. On the other hand, a higher salt concentration increases the bulk viscosity, which in turn reduces back-diffusion of solute away from the membrane, making the CP layer more noticeable and decreasing permeate flow [39].

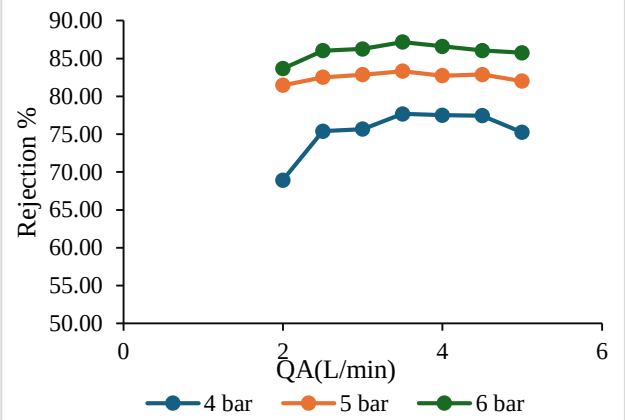

Fig. 5. Flow rates of air impact on the rejection at various pressures and (C=4000 ppm, Q_{H2O}= 1 Liter/min, and Temp. = 32℃)

Further experiments were conducted at C=10000 ppm and 15000 ppm to investigate the effects of solute concentrations above 4000 ppm on permeate flux and rejection. The results reveal that the flux dropped to 25.5 and 12 L/m2. h. and the rejection decreased to 66.7 % and 51% for solute concentrations of 10000 and 15000 ppm at 3 L/min air flow rate, respectively. The decrease in flow and rejection is mainly related to concentration polarization on the membrane surface. As the concentration of dissolved materials increases, these particles concentrate on the membrane surface more quickly than they can flow through or be removed, as demonstrated in Fig. 6 and Fig. 7.

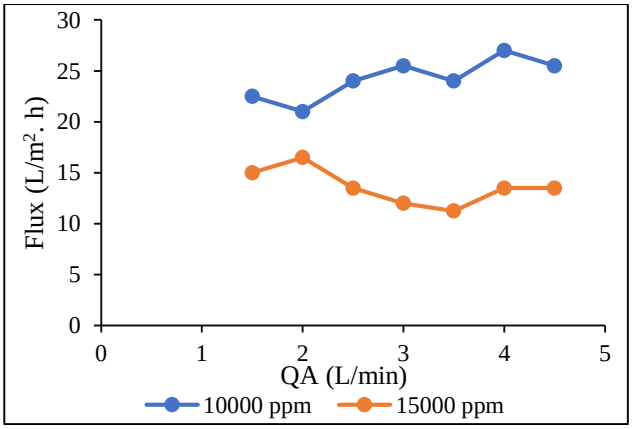

Fig. 6. Flow rates of air impact on the flux at various concentrations and (P= 6 bar, Q_{H2O}= 1 Liter/min, and Temp. = 32℃)

Fig. 8 and Fig. 9 show the effects of temperature on permeate flux and rejection. The results demonstrate that an increase in the feed temperature from 20 ℃ to 32 ℃ increases the flux from 76.5 to 147 (L/m^2. h) and rejection from 85.90 to 91.75%. increases the flux from 76.5 to 147 (L/m^2. h) and rejection from 85.90 to 91.75%. This is attributed to the increase in the active layer thickness as the solution temperature rises, leading to an increase in the membrane's pore size, most likely due to thermal expansion [40]. Additionally, it was thought that the increase in permeate flux was due to changes in the membrane and solution viscosities [41].

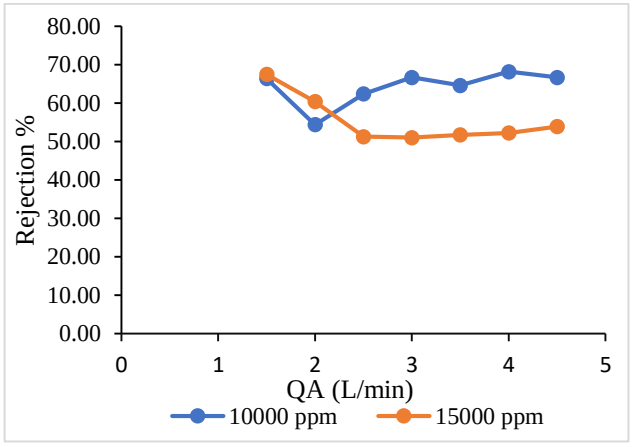

Fig. 7. Flow rates of air impact on the rejection at various concentrations (P 6 bar, QH2O 1 Liter/min, and Temp. = 32℃)

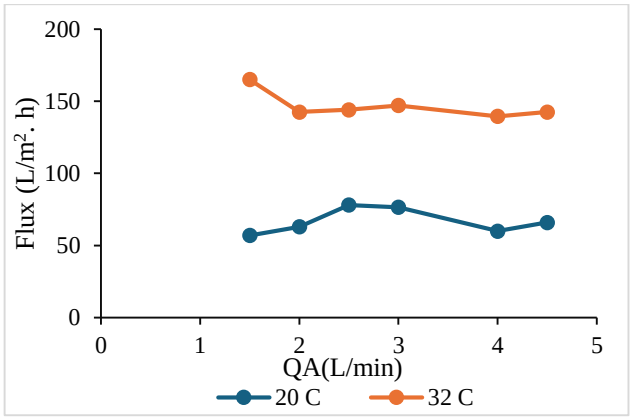

Fig. 8. Flow rates of air impact on the flux at various temperatures and (P= 6 bar, Q_{H2O}= 1 Liter/min, and C=2000 ppm)

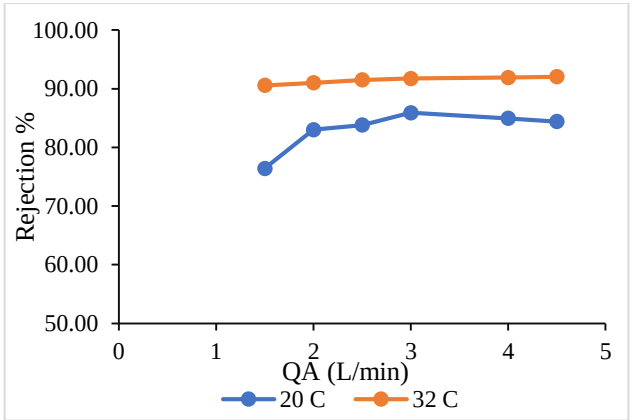

Fig. 9. Flow rates of air impact on the rejection at various temperatures and (P= 6 bar, Q_{H2O}= 1 Liter/min, and C=2000 ppm)

4- Conclusion

The technique of air sparging coupled with nanofiltration had a significant impact on desalination process performance compared to NF without sparging.

The results indicated an evident increase in permeate flux when using air. The flux increased by 109.09% and 80.85% without air sparging, and by 4% and 6% with air sparging at 4 and 6 bar, respectively. Also, at different concentrations of 4000 and 15000 ppm, the flux increased by 80.85% and 41.18%, respectively. Moreover, at solution flow rates of 1 and 1.5 L/min, the flux increased by 680% and 85%, respectively. Furthermore, pressure and temperature increase the permeate flux, while high feed concentrations decrease it. The maximum flux and the high rejection percentage were achieved at 2000 ppm and 6 bar, with a value of 168 L/m^2. hr., and of 90.8%, respectively.

References

[1] E. T. Sayed *et al.*, "Faradic capacitive deionization (FCDI) for desalination and ion removal from wastewater," *Chemosphere*, vol. 275, p. 130001, 2021, https://doi.org/10.1016/j.chemosphere.2021.130001

[2] S. S. Pawar, V. V, and T. Siya, "Nano Filtration Techniques in Waste Water Treatment," *International Journal for Research in Applied Science & Engineering Technology*, vol. 12, no. x oct. 2024, 2024, https://doi.org/10.22214/ijraset.2024.64592

[3] K. Wang *et al.*, "Tailored design of nanofiltration membranes for water treatment based on synthesis–property–performance relationships," *Chemical Society Reviews*, vol. 51, no. 2, pp. 672–719, 2022, https://doi.org/10.1039/D0CS01599G

[4] N. Shehata *et al.*, "Membrane-based water and wastewater treatment technologies: Issues, current trends, challenges, and role in achieving sustainable development goals, and circular economy," *Chemosphere*, vol. 320, p. 137993, Apr. 2023, Accessed: Feb. 06, 2025, https://doi.org/10.1016/J.CHEMOSPHERE.2023.137993

[5] S. El-Ghzizel, H. Zeggar, M. Tahaikt, F. Tiyal, A. Elmidaoui, and M. Taky, "Nanofiltration process combined with electrochemical disinfection for drinking water production: Feasibility study and optimization," *Journal of Water Process Engineering*, vol. 36, p. 101225, Aug. 2020, Accessed: Feb. 06, 2025, https://doi.org/10.1016/J.JWPE.2020.101225

[6] N. N. R. Ahmad, W. L. Ang, Y. H. Teow, A. W. Mohammad, and N. Hilal, "Nanofiltration membrane processes for water recycling, reuse and product recovery within various industries: A review," *Journal of Water Process Engineering*, vol. 45, p. 102478, 2022, https://doi.org/10.1016/j.jwpe.2021.102478

[7] M. H. Salih, A. M. Al-Yaqoobi, H. A. Hassan, and A. F. Al-Alawy, "Assessment of the Pressure Driven Membrane for the Potential Removal of Aniline from Wastewater," *Journal of Ecological Engineering*, vol. 24, no. 8, pp. 118–127, 2023, https://doi.org/10.12911/22998993/166283

[8] A. Golrokh Sani, H. Najafi, and S. S. Azimi, "CFD simulation of air-sparged slug flow in the flat-sheet membrane: A concentration polarization study," *Separation and Purification Technology*, vol. 270, Sep. 2021, https://doi.org/10.1016/j.seppur.2021.118816

[9] Y. H. Teow, J. Y. Sum, K. C. Ho, and A. W. Mohammad, "Principles of nanofiltration membrane processes," in *Osmosis Engineering*, Elsevier, 2021, pp. 53–95, https://doi.org/10.1016/B978-0-12-821016-1.00014-0

[10] N. S. Suhalim *et al.*, "Rejection Mechanism of Ionic Solute Removal by Nanofiltration Membranes: An Overview," *Nanomaterials*, vol. 12, no. 3, p. 437, 2022, https://doi.org/10.3390/nano12030437

[11] S. Han *et al.*, "Microporous organic nanotube assisted design of high performance nanofiltration membranes," *Nature Communications*, 2022, https://doi.org/10.1038/s41467-022-35681-9

[12] V. J. Y Du, B K Pramanik, Y Zhang, Ludovic Dumee, "Recent Advances in the Theory and Application of Nanofiltration: a Review," *Current Pollution*, no. 8, pp. 51–80, 2022, https://doi.org/10.1007/s40726-021-00208-1

[13] D. Yadav, S. Karki, and P. G. Ingole, "Current advances and opportunities in the development of nanofiltration (NF) membranes in the area of wastewater treatment, water desalination, biotechnological and pharmaceutical applications," *Journal of Environmental Chemical Engineering*, vol. 10, no. 4, p. 108109, Aug. 2022, Accessed: May 31, 2025, https://doi.org/10.1016/j.jece.2022.108109

[14] P. Sivaprakash and S. DasGupta, "Effect of air sparging on flux enhancement during tangential flow filtration of degreasing effluent," *Desalination and Water Treatment*, vol. 53, no. 1, pp. 73–83, Jan. 2015, http://dx.doi.org/10.1080/19443994.2013.839400

[15] F. H. Saleh and A. F. Al-Alawy, "Membrane, Air sparging as a strategy for optimizing reverse osmosis," *Journal of Ecological Engineering*, vol. 26, no. 3, pp. 99–107, 2025, https://doi.org/10.12911/22998993/199572%0A

[16] K. Natha and M. patel Tejal, "Mitigation of Flux Decline in the Cross-Flow Nanofiltration of Molasses Wastewater under the Effect of Gas Sparging," *Separation Science and Technology*, vol. 49, no. 10, pp. 1479–1489, 2014, https://doi.org/10.1080/01496395.2014.895766

[17] C. Wang, T. C. A. Ng, M. Ding, and H. Y. Ng, "Insights on fouling development and characteristics during different fouling stages between a novel vibrating MBR and an air-sparging MBR for domestic wastewater treatment," *Water Research*, vol. 212, p. 118098, 2022, https://doi.org/10.1016/j.watres.2022.118098

[18] Y. Liu *et al.*, "Advancements in nanofiltration fouling phenomenon: From water treatment to salt lakes environments," *Desalination*, p. 117649, 2024, https://doi.org/10.1016/j.desal.2024.117649

[19] S. B. Khan, S. Irfan, S. S. Lam, X. Sun, and S. Chen, "3D printed nanofiltration membrane technology for waste water distillation," *Journal of Water Process Engineering*, vol. 49, p. 102958, 2022, https://doi.org/10.1016/j.jwpe.2022.102958

[20] J. C. Crittenden, *Water treatment principles and design*. John Wiley, 2012.

[21] A. Chougradi, F. Zaviska, A. Abed, J. Harmand, J.-E. Jellal, and M. Heran, "Batch reverse osmosis desalination modeling under a time-dependent pressure profile," *Membranes (Basel).*, vol. 11, no. 3, p. 173, 2021, https://doi.org/10.3390/membranes11030173

[22] Z. Wang, D. Xia, B. Wang, H. Liu, and L. Zhu, "Highly permeable polyamide nanofiltration membrane incorporated with phosphorylated nanocellulose for enhanced desalination," *Journal of Membrane Science*, vol. 647, p. 120339, 2022, https://doi.org/10.1016/j.memsci.2022.120339

[23] H. Asefi, A. Alighardashi, M. Fazeli, and A. Fouladitajar, "CFD modeling and simulation of concentration polarization reduction by gas sparging cross-flow nanofiltration," *Journal of Environmental Chemical Engineering*, vol. 7, no. 5, Oct. 2019, https://doi.org/10.1016/j.jece.2019.103275

[24] A. Fouladitajar, F. Zokaee Ashtiani, H. Rezaei, A. Haghmoradi, and A. Kargari, "Gas sparging to enhance permeate flux and reduce fouling resistances in cross flow microfiltration," *Journal of Industrial and Engineering Chemistry*, vol. 20, no. 2, pp. 624–632, Mar. 2014, https://doi.org/10.1016/j.jiec.2013.05.025

[25] A. G. Boricha and Z. V. P. Murthy, "Preparation, characterization and performance of nanofiltration membranes for the treatment of electroplating industry effluent," *Separation and Purification Technology*, vol. 65, no. 3, pp. 282–289, 2009, https://doi.org/10.1016/j.seppur.2008.10.047

[26] C. I. Covaliu-Mierlă, O. Păunescu, and H. Iovu, "Recent Advances in Membranes Used for Nanofiltration to Remove Heavy Metals from Wastewater: A Review," *Membranes (Basel).*, vol. 13, no. 7, p. 643, 2023, https://doi.org/10.3390/membranes13070643

[27] M. C. Bhoumick, S. Roy, and S. Mitra, "Synergistic effect of air sparging in direct contact membrane distillation to control membrane fouling and enhancing flux," *Separation and Purification Technology*, vol. 272, p. 118681 Contents, 2021, https://doi.org/10.1016/j.seppur.2021.118681

[28] I. Sentana, M. Rodríguez, E. Sentana, and D. Prats, "Effect of pressure and pH over the removal of disinfection by-products using nanofi ltration membranes in discontinuous systems," *Desalination and Water Treatment*, vol. 23, no. 2010, pp. 3–12, 2010, https://doi.org/10.5004/dwt.2010.1343

[29] A. F. Al-Alawy and M. H. Salih, "Comparative Study between Nanofiltration and Reverse Osmosis Membranes for the Removal of Heavy Metals from Electroplating Wastewater," *Journal of Engineering*, vol. 23, no. 4, 2017, https://doi.org/10.31026/j.eng.2017.04.01

[30] J. M. Gozálvez-Zafrilla, B. Gómez-Martínez, and A. Santafé-Moros, "Evaluation of Nanofiltration Processes for Brackish Water Treatment Using the DSPM Model," *Computer Aided Chemical Engineering*, 2005, https://doi.org/10.1016/S1570-7946(05)80198-1

[31] H. N. Alavijeh, M. Sadeghi, and A. Ghahremanfard, "Experimental and economic evaluation of nitrate removal by a nanofiltration membrane," *Environmental Science and Pollution Research*, 2023. https://doi.org/10.1007/s11356-022-24972-9

[32] S. Fadhil, "Modeling of Nanofiltration of Low Concentration Pb(II) Aqueous Solutions Using a Coupled Concentration Polarization and Pore Flow Model," *Iranian Journal of Chemistry and Chemical Engineering*, vol. 16, no. 4, pp. 12–22, 2019.

[33] C. V. Gherasim, J. Cuhorka, and P. Mikulášek, "Analysis of lead(II) retention from single salt and binary aqueous solutions by a polyamide nanofiltration membrane: Experimental results and modelling," *Journal of Membrane Science*, vol. 436, pp. 132–144, Jun. 2013, Accessed: Jun. 01, 2025. https://doi.org/10.1016/J.MEMSCI.2013.02.033

[34] A. W. Mohammad, N. Hilal, H. Al-Zoubi, and N. A. Darwish, "Prediction of permeate fluxes and rejections of highly concentrated salts in nanofiltration membranes," *Journal of Membrane Science*, 2007. https://doi.org/10.1016/j.memsci.2006.11.035

[35] C.-V. Gherasim and P. Mikulášek, "Influence of operating variables on the removal of heavy metal ions from aqueous solutions by nanofiltratio," *Desalination*, vol. 343, no. 22, pp. 67–74, 2014, https://doi.org/10.1016/j.desal.2013.11.012

[36] A. Otero-Fernández *et al.*, "Reduction of Pb(II) in water to safe levels by a small tubular membrane nanofiltration plant," *Clean Technologies and Environmental Policy*, vol. 20, no. 2, pp. 329–343, 2017, https://doi.org/10.1007/s10098-017-1474-2

[37] W. R. Bowen and H. N. S. Yousef, "Effect of salts on water viscosity in narrow membrane pores W.," *Journal of Colloid and Interface Science*, vol. 264, no. 2, pp. 452–457, 2003, https://doi.org/10.1016/S0021-9797(03)00406-5

[38] J. Luo and Y. Wan, "Effects of pH and salt on nanofiltration-a critical review," *Journal of Membrane Science*, vol. 438, pp. 18–28, 2013, https://doi.org/10.1016/j.memsci.2013.03.029

[39] J. Luo, L. Ding, Y. Su, Y. Wan, and S. Wei, "Concentration polarization in concentrated saline solution during desalination of iron dextran by nanofiltration Luo," *Journal of Membrane Science*, vol. 363, no. 2–2, pp. 170–179, 2010, https://doi.org/10.1016/j.memsci.2010.07.033

[40] R. R. Sharma and S. Chellam, "Temperature and concentration effects on electrolyte transport across porous thin-film composite nanofiltration membranes: Pore transport mechanisms and energetics of permeation," *Journal of Colloid and Interface Science*, vol. 298, no. 1, pp. 327–340, 2006, https://doi.org/10.1016/j.jcis.2005.12.033

[41] K. S. Kim *et al.*, "The Effect of Feed Temperature On Permeate Flux During Membrane Separation," *Journal of the Korean Society for Marine Environment & Energy*, 2014, http://dx.doi.org/10.7846/JKOSMEE.2014.17.1.13

تحسين أداء تحلية المياه بتقنية النانوفلتر باستخدام تقنية ضخ الهواء

فائز حسين صالح [١]، أحمد فائق العلوي [١،*]، سارة الصالحي [٢]

١ قسم الهندسة الكيمياوية، كلية الهندسة، جامعة بغداد، بغداد، العراق
٢ قسم الهندسة الكيمياوية والبيولوجية والحيوية، جامعة ولاية كارولينا الشمالية للعلوم الزراعية والتقنية، الولايات المتحدة الأمريكية

الخلاصة

إن الاستقطاب التركيزي يُعد مشكلة كبيرة لأغشية النانوفلتر، إذ يقلل من كفاءة تدفق النفاذية ويزيد من تكاليف التشغيل. تهدف هذه الدراسة إلى تقييم فعالية تقنية ضخ الهواء كنهج مبتكر لتحسين أداء أغشية النانوفلتر، خصوصًا في سياق معالجة المياه. تركزت المنهجية على إجراء تجارب شاملة باستخدام مياه محاكاة وتطبيق تقنية ضخ الهواء بمعدلات تدفق تتراوح بين ١,٥ و ٤,٥ لتر في الدقيقة. تم اختبار أداء الغشاء في ظل مجموعة من الظروف المختلفة، والتي شملت تركيزات المدخلات المتغيرة (من ٢,٠٠٠ إلى ١٥,٠٠٠ جزء في المليون)، وضغوطًا متفاوتة (من ٤ إلى ٦ بار)، بالإضافة إلى معدلات تدفق المياه ودرجات الحرارة (٢٠ و٣٢ درجة مئوية).

أظهرت النتائج أن إضافة الهواء تقلل بفعالية من الاستقطاب التركيزي، مما يزيد بشكل كبير من تدفق النفاذية وكفاءة رفض كلوريد الصوديوم. عند تركيز ٢,٠٠٠ جزء في المليون وضغط ٦ بار، بلغ أعلى تدفق ١٦٨ لترًا/م²/ساعة، مع نسبة رفض بلغت ٩٠,٨%. كما تم تحقيق أعلى تدفق ممكن عند درجة حرارة ٣٢ درجة مئوية، مع نسبة رفض ممتازة بلغت ٩١,٧٥%. ومن ناحية أخرى، أشارت الدراسة إلى أن زيادة تركيز التغذية أدت إلى تدهور تدفق النفاذية. تثبت هذه الدراسة أن تقنية ضخ الهواء هي طريقة قوية لتحسين أداء أغشية النانوفلتر.

الكلمات الدالة: رش الهواء، غشاء الترشيح النانوي، تدفق النفاذية، استقطاب التركيز، الضغط، تركيز التغذية، درجة الحرارة.