ARTICLE | OPEN ACCESS

Indian journal of **Engineering**

Energy aspects and cost analysis in direct contact membrane distillation using commercial PTFE membranes

Quoc Linh Ve[1*], Minh Cuong Do[1], Thanh Cuong Nguyen[1], Quoc Huy Nguyen[1], Quang Lich Nguyen[2]

To Cite:
Ve QL, Do MC, Nguyen TC, Nguyen QH, Nguyen QL. Energy aspects and cost analysis in direct contact membrane distillation using commercial PTFE membranes. *Indian Journal of Engineering*, 2024, 21, e8ije1683
doi: https://doi.org/10.54905/disssi.v21i55.e8ije1683

Author Affiliation:
[1]Faculty of Engineering and Food Technology, University of Agriculture and Forestry, Hue University, Thua Thien Hue 530000, Vietnam
[2]School of Engineering and Technology, Hue University, Thua Thien Hue 530000, Vietnam

[*]**Corresponding Author**
Faculty of Engineering and Food Technology, University of Agriculture and Forestry, Hue University, Thua Thien Hue 530000, Vietnam
Email: vqlinh@hueuni.edu.vn; vequoclinh@huaf.edu.vn

Peer-Review History
Received: 01 May 2024
Reviewed & Revised: 04/May/2024 to 08/July/2024
Accepted: 11 July 2024
Published: 18 July 2024

Peer-Review Model
External peer-review was done through double-blind method.

Indian Journal of Engineering
pISSN 2319–7757; eISSN 2319–7765

DISCOVERY SCIENTIFIC SOCIETY

ABSTRACT

Energy aspects and cost analysis in DCMD using different commercial PTFE membranes are experimentally examined under the impact of operating conditions and membrane pore sizes. Regarding energy efficiency (EE), gain output ratio (GOR), and specific energy consumption (SEC), feed inlet temperature is the most influential factor in comparison to feed concentration and volume flow rate. Regarding the membrane pore size, the DCMD system using a larger pore of membrane had a lower cost per cubic meter of freshwater production than the system using a smaller pore of membrane.

Keywords: Direct contact membrane distillation, energy efficiency, gain output ratio, specific energy consumption, cost

1. INTRODUCTION

Membrane distillation (MD) is a potential technology because it can integrate low-grade heat sources or renewable energy into operation (Khayet, 2013; Baghbanzadeh et al., 2017). MD is more competitive than reverse osmosis (RO) which needs high energy requirements. Direct contact membrane distillation (DCMD) is a more attractive technology in terms of energy efficiency (Singh and Sirkar, 2012). The effect of experimental conditions such as feed inlet temperature, volume flowrates, and solution concentration on energy aspects is critically investigated (Singh and Sirkar, 2014; Dahiru and Atia, 2014; Levy and Earle, 1994; Manawi et al., 2014; Phattaranawik et al., 2001; Schofield et al., 1990; Taamneh and Bataineh, 2017). The energy requirements affected mainly the implementation feasibility of DCMD. It is the critical factor that impacts the freshwater production cost (Ali and Hassan-Ali, 2023). In comparison to RO, the permeate flux of DCMD is lower.

Therefore, the optimization of process parameters such as feed inlet temperature, feed concentration, volume flow rate, and thermal sources is involved. Solar photovoltaic thermal collectors are becoming increasingly common in desalination technologies (Maqbool et al., 2024; Al-Hrari et al., 2020; Anand et al., 2021; Choi et al., 2022). Thermal desalination techniques typically use between 40 to 80 kilowatt-hours per cubic meter for heating, along with 2.5 to 5 kilowatt-hours per cubic meter for auxiliary equipment. The average energy consumption of the widely used reverse osmosis (RO) desalination method is approximately 100 terawatt-hours per year, leading to emissions of 60 to 100 million metric tons of CO2 annually (Ahmed et al., 2019; Anand et al., 2021). Therefore, a robust solution is required to reduce both its energy consumption and the resulting emissions.

In addition, membrane configuration or membrane properties can contribute to a significant improvement in permeate flux (Al-Obaidani et al., 2008; Alkhudhiri et al., 2012). Furthermore, the membrane properties such as membrane thickness, membrane pore size, and membrane porosity also affected the permeate flux. The membrane thickness ranged from 50 to 180 μm (Phattaranawik et al., 2003; Termpiyakul et al., 2005). Additionally, a wider range of membrane thickness up to 1550 μm was also examined in other studies (Laganà et al., 2000). There are two opposite effects of membrane thickness relating to permeate flux issues. First, the membrane thickness should be minimized to reduce the resistance to the mass transfer; hence the permeate flux gets higher. However, the conductive heat loss across membranes rises in the case of thinner membranes. Therefore, the permeate flux drops because of the lower transmembrane temperature difference (Li et al., 2014).

In conclusion, the membrane thickness impacted permeate flux directly or indirectly. Another important factor influencing the permeate flux and energy efficiency is membrane materials and membrane pore size. The membrane materials and pore size affected the liquid entry pressure (LEP), and as a result, it influenced membrane penetration when the LEP was lower than the applied pressure (Sayed et al., 2024; Zare et al., 2024). Zare et al., (2024) create an affordable and highly hydrophobic ceramic membrane for use in DCMD applications. The contact angle and the LEP of the membrane were 1600 and 1.5 bar, respectively. According to the obtained findings, an average permeate flux of 3.15 kilograms per square meter per hour (kg/(m^2·h)) and a salt rejection rate (R%) of 99.62% were observed for the 3.5% sodium chloride (NaCl) solution (Zare et al., 2024). Furthermore, the membrane pore size is the crucial factor to determine the primary mass transfer mechanism through membrane pores.

According to Wang and Chung, (2015), the ideal MD membrane pore size should be in the range of (0.1 μm - 0.3 μm) to maximize freshwater production and energy efficiency because it reduces the temperature polarization effect and mass transfer resistance. If the surface tension of the solution is low, the role of membrane pore size is more important (Kimura et al., 1987). Generally, the previous studies' usual membrane pore sizes were from 0.2 μm to 0.45 μm to investigate the improvement in permeate flux and thermal efficiency (Courel et al., 2000; Durham and Nguyen, 1994; Kim et al., 2013). According to Li et al., (2014), both mass flux and thermal efficiency rose when the mean pore radius of the membrane increased, and the ideal values should be from 0.1 μm to 0.2 μm.

If the mean radius of membrane pores exceeds 0.2 μm, the growth of permeate flux and thermal efficiency is slow (Li et al., 2014). Furthermore, according to Ve et al., (2024a), the mass transfer mechanism should include the Poiseuille flow for the membrane having a pore diameter of 1 μm. This study aims to investigate the influence of operating conditions and pore size of commercial PTFE membranes on gain output ratio (GOR), energy efficiency (EE), and specific energy consumption (SEC). The cost analysis in terms of the unit cost for 1 m3 freshwater production is also calculated.

2. MATERIALS AND METHOD

Mass transfer in DCMD

The relationship between permeate flux and vapor pressure difference on the membrane surfaces in DCMD can be expressed in Equation (1) (Khayet et al., 2011; Lawson and Lloyd, 1997; Ve et al., 2021a; Ve et al., 2021b; Ve et al., 2019):

$$J_w = C_m \Delta p_{v,sw} = C_m \left(p_{v,swf} - p_{v,swp} \right) \quad (1)$$

Based on the experimental works from (Ve et al., 2024a; Ve et al., 2024b), the membrane permeability Cm should be calculated based on Ding's model in the case of (0.22 μm - 1 μm) PTFE membrane (Ding et al., 2003), as shown in Equation (2):

$$C_m = \frac{1}{RT_m \delta_m} \left[\left(\frac{3\tau}{2\varepsilon_m r} \left(\frac{\pi M}{8RT_m} \right)^{1/2} + \frac{p_a \tau}{\varepsilon_m PD} \right)^{-1} + 0.125 \frac{\varepsilon_m r^2 M P_m}{\tau \mu} \right] \quad (2)$$

Energy efficiency in DCMD configuration

In desalination plants, energy costs contribute to 30% - 50% of the cost of freshwater production (Al-Karaghouli and Kazmerski, 2013). In most studies, the energy aspects regarding EE, GOR, and SEC are commonly considered in the DCMD system (Khayet, 2013). As shown in Equation (3), the EE represents the proportion of heat utilized for evaporation compared to the overall heat transmission across the membrane:

$$EE = \frac{J_w A \Delta H_{v,w}}{\dot{Q}_m} \tag{3}$$

Where $\dot{Q}_m$ is equal to $\dot{Q}_P$ in the DCMD process at steady state conditions, as shown in Equation (4) (Gryta and Tomaszewska, 1998):

$$\dot{Q}_P = \dot{m}_p C_{p,p}\left(T_{po} - T_{pi}\right) \tag{4}$$

Generally, SEC represents the total required energy for producing 1 m3 of freshwater from saline water (Khayet et al., 2011). The SEC values are much higher for laboratory-scale DCMD than for larger pilot plants. The specific energy consumption can be evaluated (Elmarghany et al., 2019):

$$SEC = \left[\frac{\dot{Q}_m \times \varrho}{J_w \times A}\right] / 3600 \tag{5}$$

The GOR indicates how effectively the input energy generates freshwater within the DCMD module, as shown in Equation (6) (Khayet, 2013). For optimal performance in a DCMD configuration, the GOR value should be maximized.

$$GOR = \frac{J_w A \Delta H_{v,w}}{\dot{Q}_F} \tag{6}$$

$$\dot{Q}_F = \dot{m}_f C_{p,f}\left(T_{fi} - T_{fo}\right) \tag{7}$$

Experiment protocols

The DCMD system and two types of commercial PTFE membranes in this study were similar to previous studies (Ve et al., 2024a; Ve et al., 2024b). The feed inlet temperature, the feed and permeate volume flow rate, and feed concentration were in the range of (400C – 500C), (0.017L.s-1 – 0.03L.s-1), and (20000ppm - 40000ppm), respectively. The temperature on the permeate side remains constant at 200C. The feed and permeate solution were pumped counter-currently. The commercially available PTFE membranes come with pore dimensions of 0.22 μm and 1 μm and a membrane porosity of 75%. Figure 1 described the experimental setup.

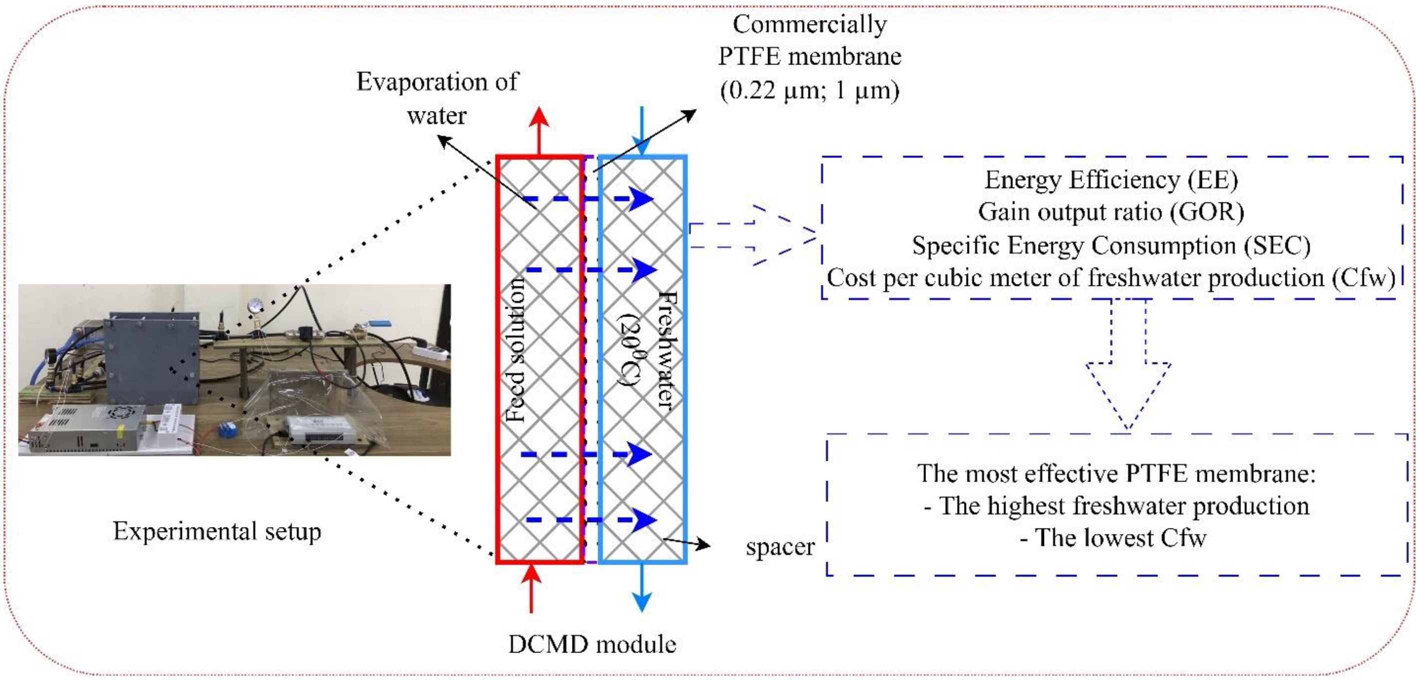
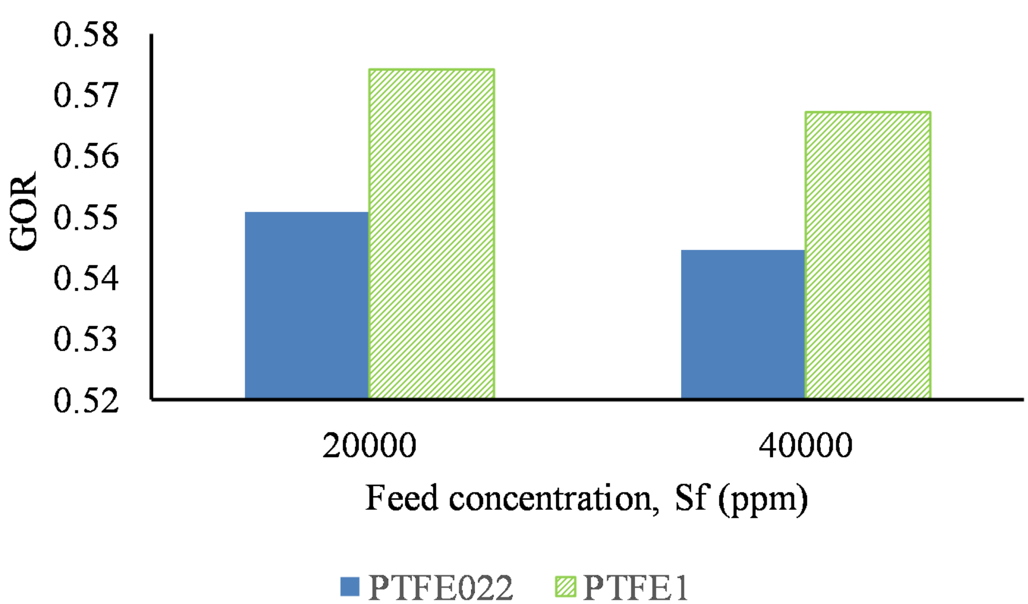


Figure 1 Experimental setup in DCMD configuration

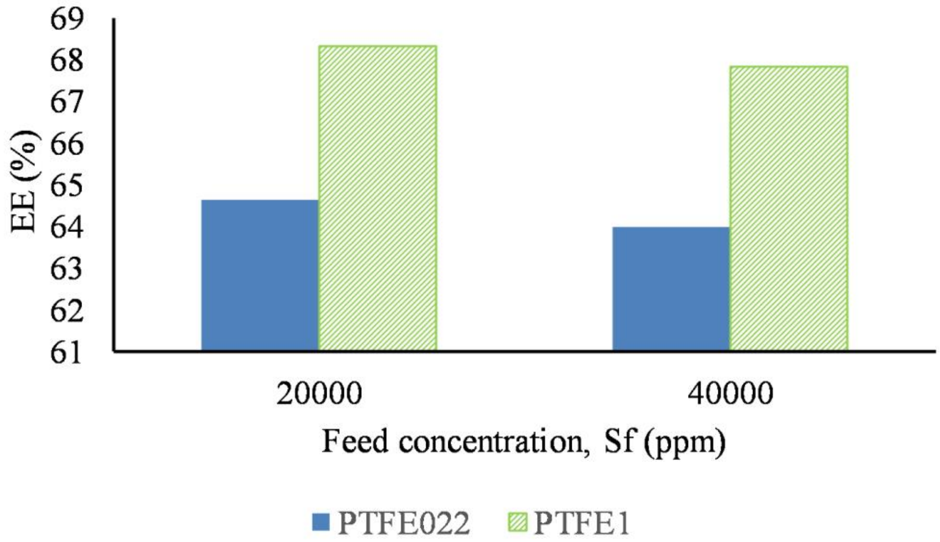
3. RESULTS AND DISCUSSIONS

Effect of feed concentration

Figure 1 revealed that the feed concentration fluctuation influenced the energy efficiency (EE) and gain output ratio (GOR) (Martínez and Rodríguez-Maroto, 2007; Ullah et al., 2018). However, there was an insignificant decrease in EE and GOR with nearly 1.2% when the feed concentration rose from 20000 ppm to 40000 ppm (Figure 2).



(a)



(b)

Figure 2 Effect of feed concentration on (a) GOR; (b) EE in DCMD configuration (Tf,in = 500C, Tp, in = 200C, Vf = Vp = 0.03 L.s-1)

Otherwise, there was a rise in the specific energy consumption (SEC) when the feed concentration rose (Figure 3). The slight reduction in permeate flux within the examined range of feed solution caused the aforementioned results. Furthermore, Ve et al., (2021a) provided a detailed explanation regarding the decrease in permeate flux.

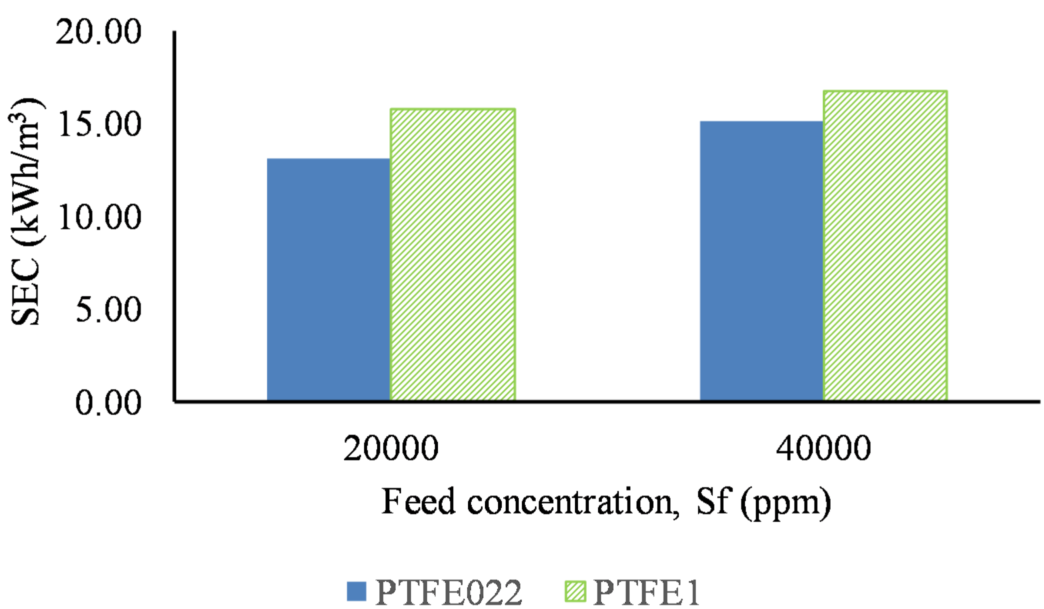


Figure 3 Effect of feed concentration on SEC in DCMD configuration (Tf, in = 500C, Tp, in = 200C, Vf = Vp = 0.03 L.s-1)

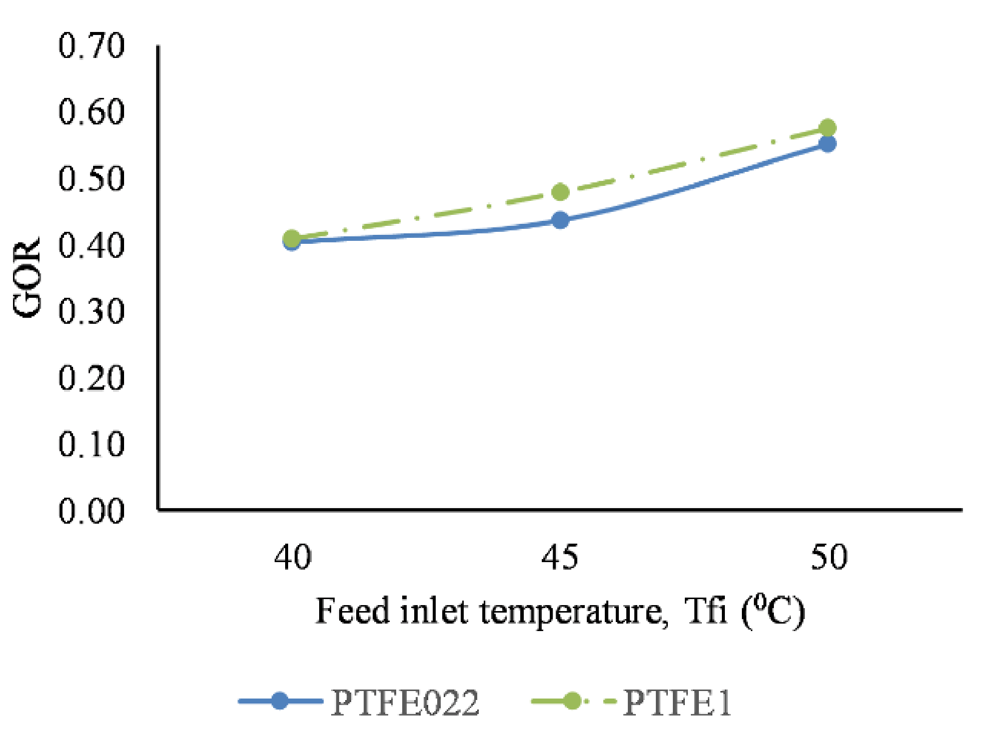
Figure 2 and Figure 3 showed that the difference in EE and GOR under the effect of different membrane pore sizes was insignificant. The DCMD configuration using the PTFE1 membrane had nearly 6% higher EE and GOR than the DCMD configuration using PTFE022. Furthermore, the DCMD system using the PTFE1 membrane consumed more energy by almost 20% and 11% compared to the DCMD system using the PTFE022 membrane when the feed solution was 20000 ppm and 40000 ppm, respectively.

Effect of feed inlet temperature

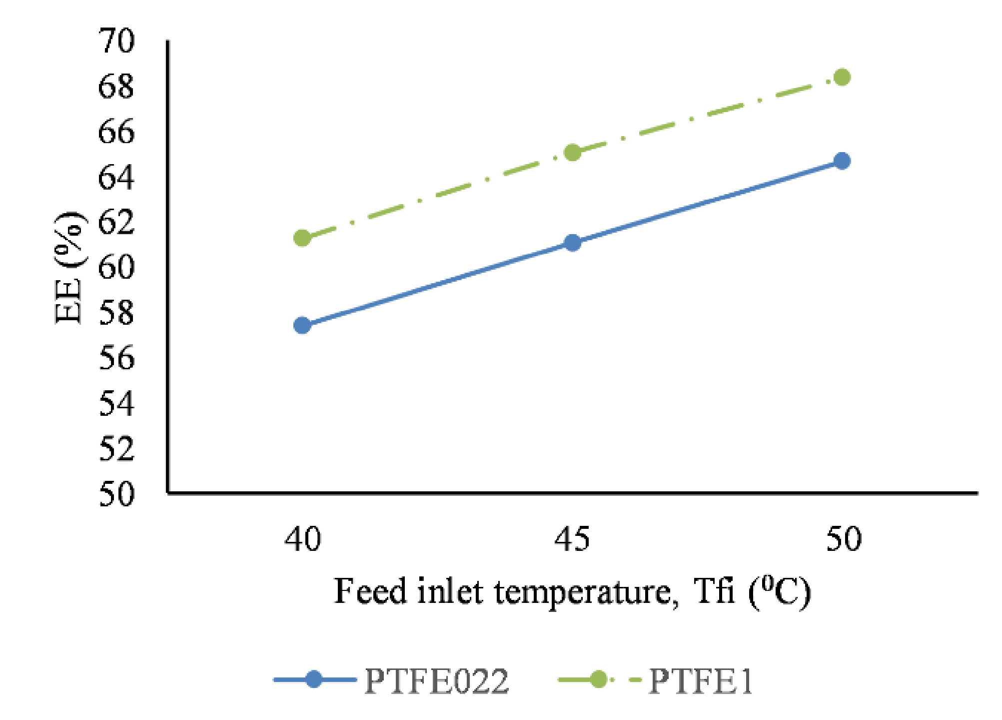
In the DCMD configuration, temperature was one of the critical factors contributing to the significant fluctuation of energy issues. Figure 4 shows that the GOR values rose significantly by up to 40% when the feed inlet temperature ranged between 40°C and 50°C for both DCMD configurations. Additionally, the improvement of EE was insignificant, with nearly 12.6%. According to the previous study (Deshmukh and Elimelech, 2017), the relationship between the partial vapor pressure difference and the temperature difference across the membrane increased as the average temperature at the membrane surface rose. Consequently, there was a considerable improvement in freshwater production. Moreover, latent heat accounted for (50% - 80%) of the total energy for vapor evaporation through the membrane, and the remaining heat was conductive heat loss. At higher feed inlet temperatures, the conductive heat loss was less significant, leading to higher energy efficiency (Khayet et al., 2011; Phattaranawik and Jiraratananon, 2001).

In contrast, the SEC decreased considerably when the feed inlet temperature rose. Figure 5 shows that the SEC decreased by nearly 47% as the feed inlet temperature rose from 400C to 500C. The significant rise in freshwater production was the main reason for that massive drop in SEC. In conclusion, the feed inlet temperature had a more significant impact on EE, GOR, and SEC compared to the feed concentration. To significantly enhance permeate flux and energy efficiency, the DCMD system should be operated at the highest feasible temperature.

Regarding the influence of membrane pore sizes, there was an insignificant discrepancy in EE and GOR, whereas the fluctuation of SEC was considerable. Figure 4 indicates that the DCMD configuration with the PTFE1 membrane had slightly higher EE and GOR compared to the configuration with the PTFE022 membrane. However, the DCMD configuration with the PTFE1 membrane consumed about 20.1% more energy than the configuration with the PTFE022 membrane to produce freshwater at a feed inlet temperature of 50°C, as shown in (Figure 5).



(a)



(b)

Figure 4 Effect of feed inlet temperature on (a) GOR; (b) EE in DCMD configuration (Tp,in = 200C, Sf = 20000 ppm, $\dot{V}_f = \dot{V}_p = 0.03 L.s^{-1}$)

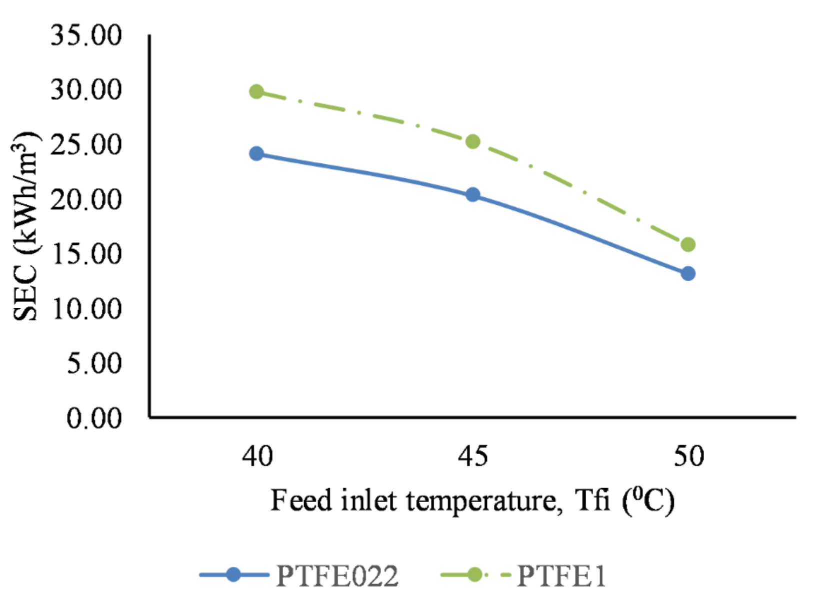
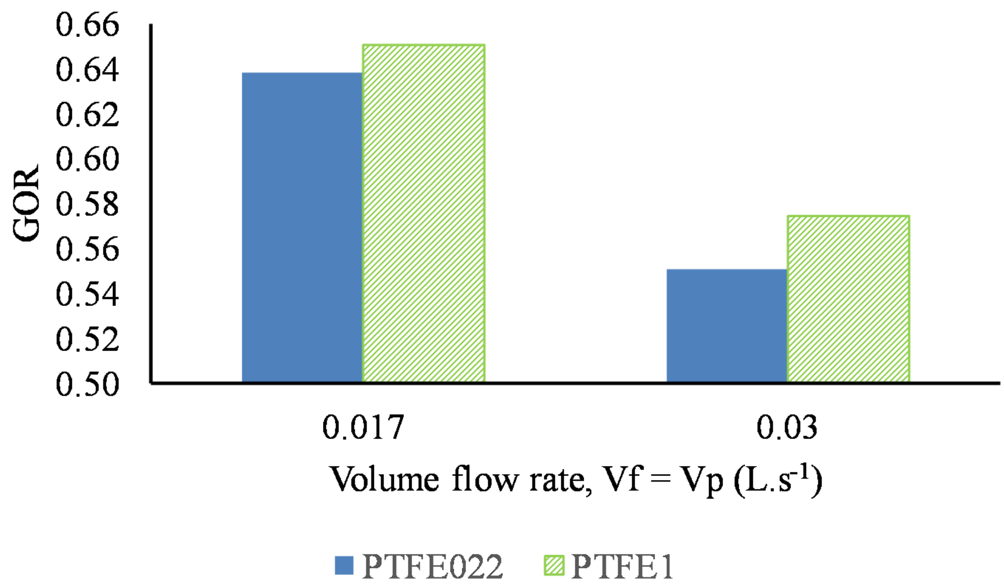


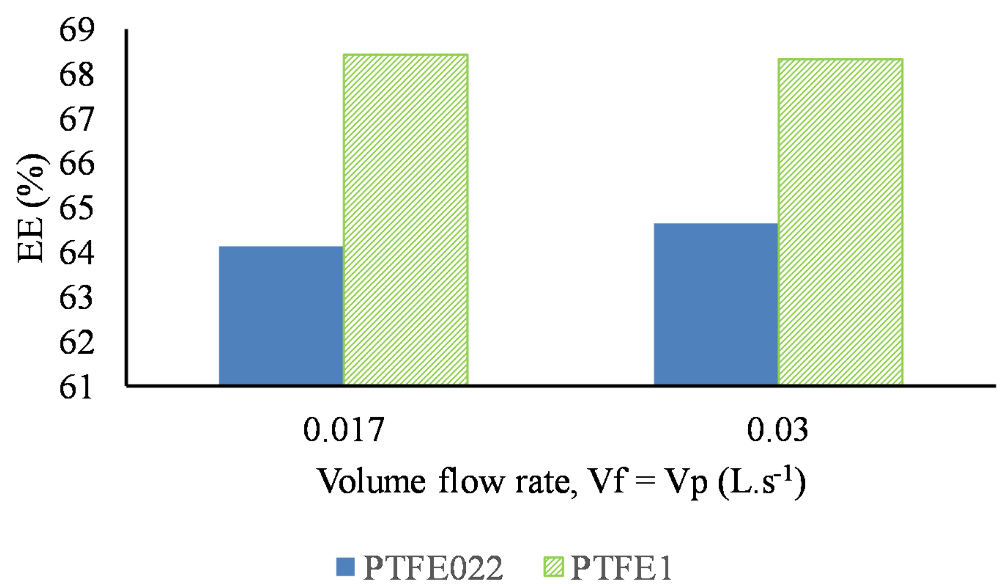
Figure 5 Effect of feed inlet temperature on SEC in DCMD configuration (Tp, in = 200C, Sf = 20000 ppm, $\dot{V}_f = \dot{V}_p = 0.03 L.s^{-1}$)

Effect of volume flow rate

As shown in Figure 6b, there was a slight rise in EE when the volume flow rate increased from 0.017 L.s-1 to 0.03 L.s-1. Additionally, Figure 6 revealed the same pattern happening in SEC with substantial growth. The SEC increased up to under 30% for both DCMD configurations using different PTFE membranes. Conversely, the GOR dropped by nearly 14% in both DCMD configurations as the volume flow rate rose, as illustrated in (Figure 6a). The fluctuation of EE, GOR, and SEC depended on the insignificant improvement of permeate flux, the considerable increase in heat transfer rate, and the pressure drop when the volume flow rate increased, as shown in Eqs. (4), (7).



(a)



(b)

Figure 6 The influence of volume flow rate on (a) GOR; (b) EE in DCMD configuration (Tf, in = 500C, Tp, in = 200C, Sf = 20000 ppm)

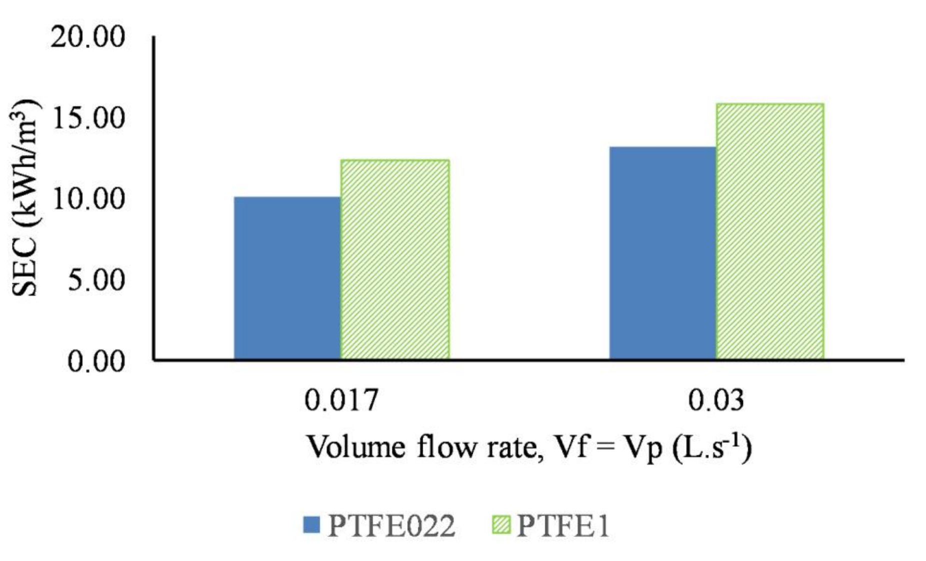


Figure 7 The influence of volume flow rate on SEC in DCMD configuration (Tf, in = 500C, Tp, in = 200C, Sf = 20000 ppm)

Figure 6 demonstrates that the difference in EE and GOR for DCMD configurations using different PTFE membranes was insignificant, with a variation of less than 7%. However, the SEC for the DCMD system using the PTFE1 membrane was 20.1% higher than that for the DCMD system using PTFE022, as shown in (Figure 7).

Cost analysis

To evaluate the costs associated with the DCMD system using various commercial PTFE membranes, this study implemented the method mentioned in previous studies (Ali and Hassan-Ali, 2023; Qasem and Zubair, 2019). Based on other studies noted in Table 1, certain assumptions were proposed to estimate the freshwater production cost.

Table 1 Cost calculation assumptions

Factor	**Value**	**Ref**
Unit cost of electricity (UCE)	0.08 $/kWh	(Ali and Hassan-Ali, 2023; Gilron et al., 2007)
Cost of labor (l)	0.1 $/m3	(Alazab et al., 2023; Ali and Hassan-Ali, 2023; Qasem and Zubair, 2019)
Cost of management (Cmg)	20% of labor cost	(Alazab et al., 2023; Ali and Hassan-Ali, 2023; Qasem and Zubair, 2019; Wang and Lior, 2011)
The cost of annual maintenance (CM)	1.5% of the capital investment cost	(Alazab et al., 2023; Qasem and Zubair, 2019)
Interest rate (i)	5%	(Ali and Hassan-Ali, 2023; Kabeel et al., 2013; Qasem and Zubair, 2019)
Life expectancy of the plant (y)	30 years	(Ali and Hassan-Ali, 2023; Qasem and Zubair, 2019)
Plant availability (f)	0.9	(Ali and Hassan-Ali, 2023; Qasem and Zubair, 2019)

In addition, Table 2 summarizes the total capital investment cost for the entire DCMD system. All capital expenditures were initially calculated in Vietnamese currency (VND) and subsequently converted into US dollars ($) using the exchange rate as of May 22, 2024.

Table 2 Total capital investment cost for DCMD

Item	Cost (VND)	Cost ($)
Commercially PTFE membrane	2.500.000	98.17
DI-2108 data taker	10.500.000	412.33
Chiller CW-5000	12.000.000	471.24
Heat exchanger	4.000.000	157.08
Water tanks	5.375.000	211.07
Sensors (temperature, volume flow rate)	7.100.000	278.81
Fitting/pipes/valves	5.120.000	201.06
Accessories	9.108.000	357.67
Total capital investment cost (Cci)	55.703.000	2187.43
Exchange rate: 1 USD = 25.465 VND (22/05/2024)		

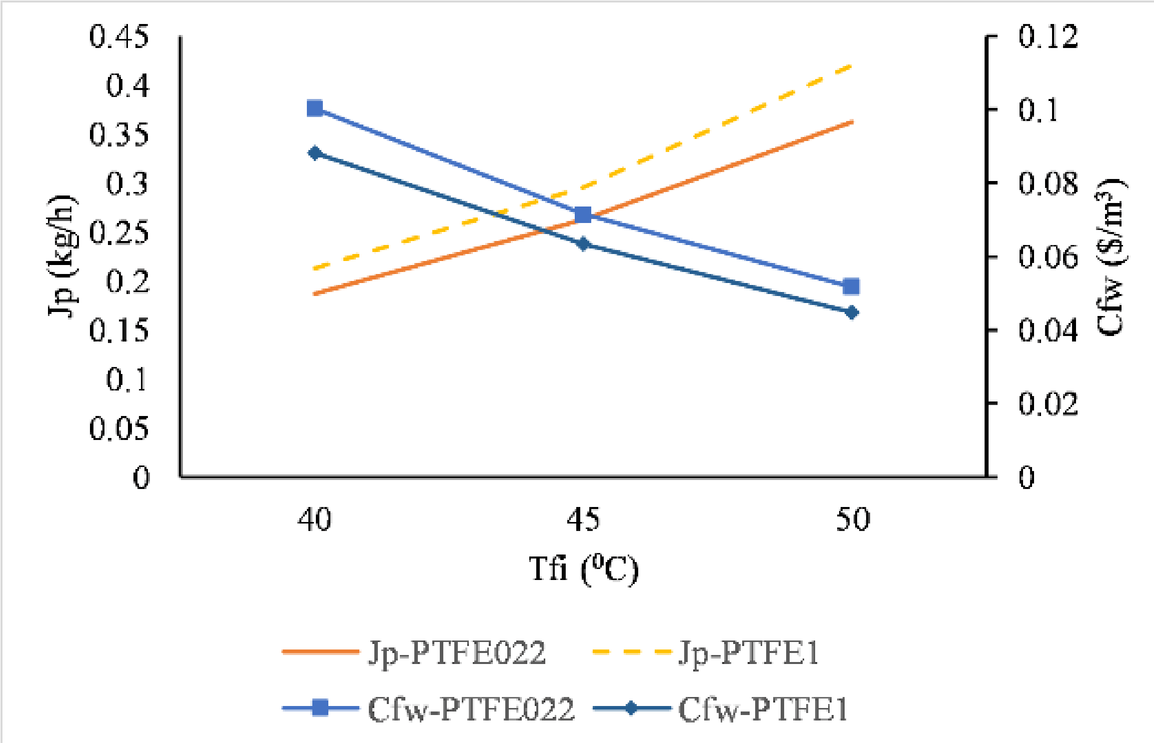
To assess the economic efficiency of the DCMD system, it is essential to analyse the cost per cubic meter of freshwater production (Cfw) over the assumed lifespan of the plant and the permeate flow rate (Jp). The process for calculating Cfw was detailed in Table 3, and Jp was determined using Eq. (16).

Table 3 Evaluation of the cost of producing fresh water (modified from (Ali & Hassan Ali, 2023; Qasem & Zubair, 2019))

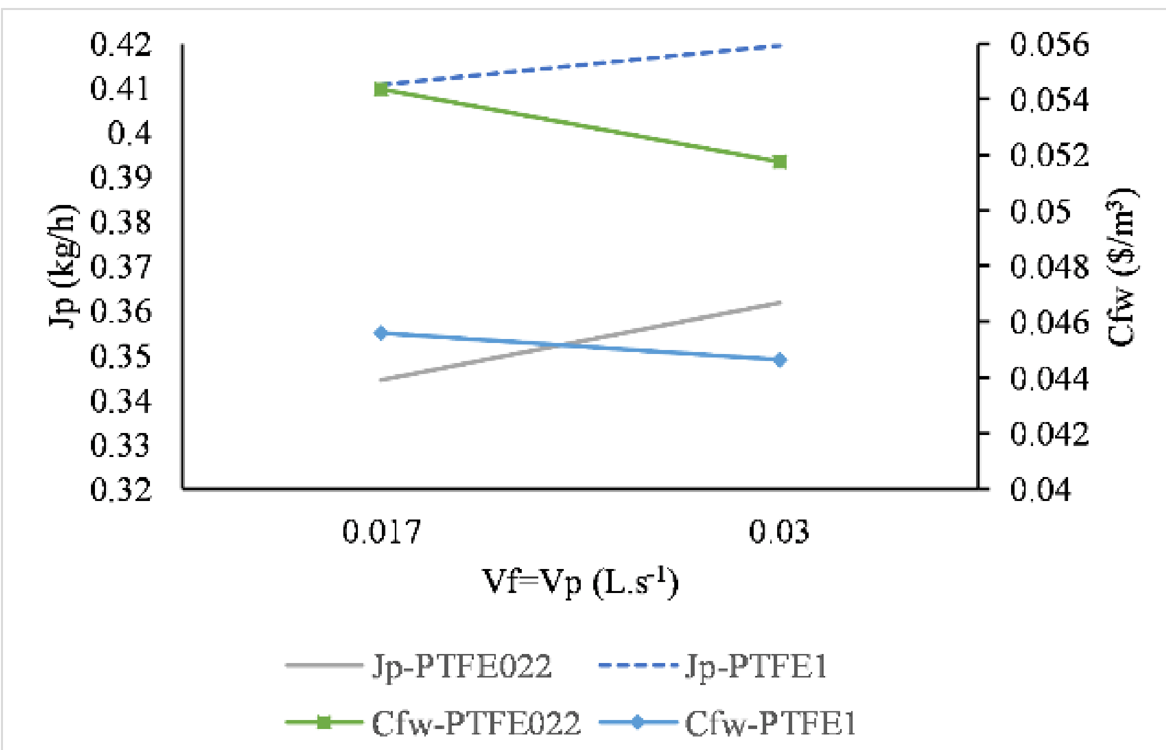
Factor	Equation	
Capital recovery ratio	$CRR=\frac{i(i+1)^{y}}{(1+1)^{y}-1}$	(8)
Annual capital cost ($/Year)	$C_A=C_{ci}\times CRR$	(9)
Annual power cost ($/Year)	$C_P=UCE\times\frac{e}{3600}\times f\times\dot{m}_{fw}\times3600\times24\times365$	(10)
Labor cost ($/Year)	$C_L=l\times\frac{\dot{m}_{fw}}{1000}\times f\times3600\times24\times365$	(11)
Maintenance cost ($/Year)	$C_M=C_A\times0.015$	(12)
Management cost ($/Year)	$C_{mg}=C_A\times0.2$	(13)
Total freshwater cost ($/Year)	$C_T=C_A+C_P+C_L+C_M+C_{mg}$	(14)
Cost of freshwater ($/m3)	$C_{fw}=\frac{C_T}{f\times\dot{m}_{fw}\times3600\times24\times365}$	(15)

$$J_p=J_{exp}\times A\times3600 \tag{16}$$

Figure 8 shows that the Cfw dropped when the feed inlet temperature and volume flow rate increased. The cost per cubic meter of freshwater production decreased remarkably by nearly 50% with increasing feed inlet temperature. However, there was a notable rise in Cfw when the volume flow rate increased. In contrast, as shown in Figure 9, when the feed concentration increased from 20000 ppm to 40000 ppm, the Cfw rose insignificantly by nearly 2%.



(a)



(b)

Figure 8 Effect of (a) feed inlet temperature; (b) volume flow rate on Jp and Cfw in DCMD configuration

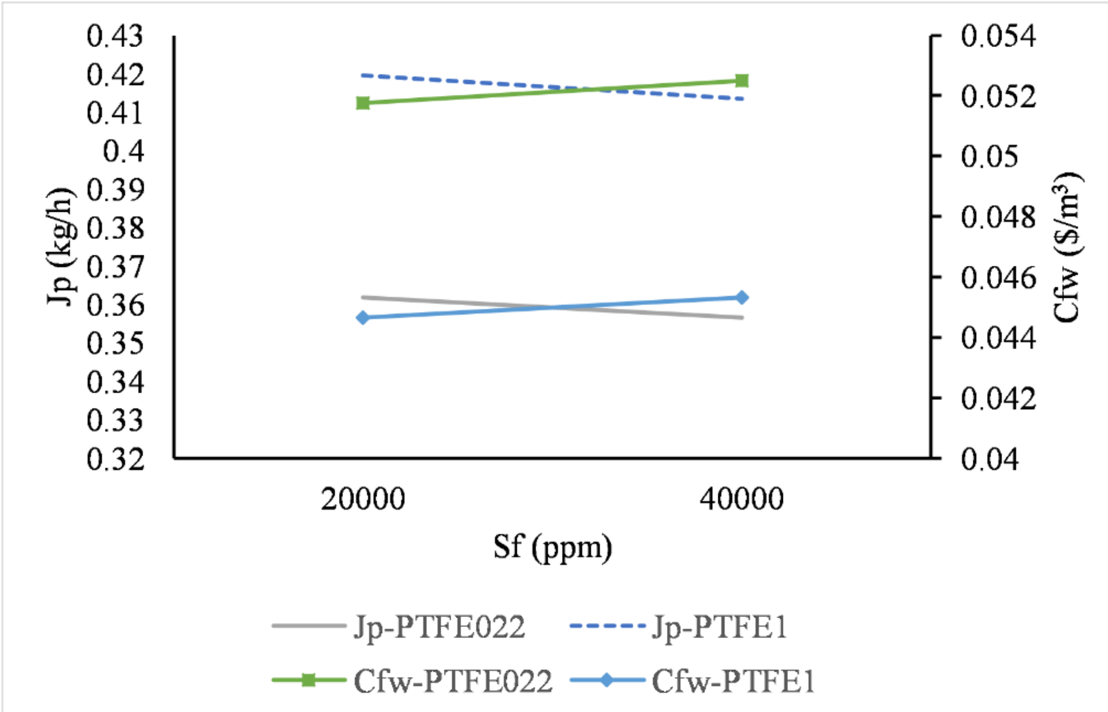


Figure 9 Effect of feed concentration on Jp and Cfw in DCMD configuration

The cost per cubic meter of desalinated water for the DCMD configuration using the PTFE1 membrane was lower than that for the DCMD configuration using the PTFE022 membrane. At the same operating condition (Tfi=500C; Vf=Vp=0,03L.s-1; Sf=20000 ppm), the Cfw for the PTFE1 membrane in the DCMD system was nearly 14% lower than that for PTFE022 membrane, as shown in (Figure 8a).

4. CONCLUSIONS

Energy-related aspects including EE, GOR, SEC, and the cost per cubic meter of freshwater production were experimentally studied under various operating conditions and membrane pore sizes. The feed inlet temperature had the most significant influence on the EE, GOR, SEC, and Cfw, compared the volume flow rate and feed concentration. Although the specific energy consumption of the DCMD system using the PTFE1 membrane was higher than that of the DCMD system using the PTFE022 membrane, the Cfw for the former system was lower than that for the latter system. Therefore, incorporating renewable energy such as solar energy into the DCMD system should be considered to freduce the SEC and the cost per cubic meter of freshwater production.

Acknowledgment

We thank the participants who all contributed to the study. We also thank HUE UNIVERSITY who supported the fund for this research.

Author Contributions

Conceptualization, Linh Ve; Investigation, Cuong Nguyen and Huy Nguyen; Methodology, Linh Ve, Cuong Do and Lich Nguyen; Software, Linh Ve; Supervision, Linh Ve; Validation, Linh Ve, Cuong Do, and Lich Nguyen; Visualization, Cuong Nguyen, and Huy Nguyen; Writing – original draft, Linh Ve; Writing – review & editing, Linh Ve, Cuong Do, and Lich Nguyen. All authors have read and agreed to the published version of the manuscript.

Informed consent

Not applicable.

Ethical issues

Not applicable

Funding

This study was funded by HUE UNIVERSITY, (grant number DHH2022-02-162).

Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

Nomenclature

A	–	Membrane area, m2
CA	–	Annual capital cost, $/Year
Cci	–	Total capital investment cost, $
Cfw	–	Cost of freshwater production ($/m3)
CL	–	Annual labor cost ($/Year)
CM	–	Maintenance cost ($/Year)
Cm	–	Membrane distillation coefficient, kg.m-2.s-1.Pa-1
Cmg	–	Membrane distillation coefficient for Knudsen-molecular diffusion mechanism, kg.m-2.s-1.Pa-1
CP	–	Annual power cost, $/Year
Cp,f	–	Specific heat coefficient of water at the feed side, J.kg-1.K-1
Cp,p	–	Specific heat coefficient of water at the permeate side, J.kg-1.K-1
CRR	–	Capital recovery ratio
CT	–	Total freshwater cost, $/Year
EE	–	Thermal efficiency, %
GOR	–	Gain output ratio
$\Delta H_{v,w}$	–	Vapour enthalpy of water, kJ/kg
Jw	–	Experimental mass flux, kg.m-2.s-1
Jp	–	Permeate flow rate, kg/h
M	–	The molecular weight of water, kg.mol-1
Pa	–	Entrapped air pressure, Pa
$\dot{Q}_F$	–	The heat released by the feed, W
$\dot{Q}_m$	–	Heat transfer rate through the membrane, W
$\dot{Q}_P$	–	Heat gained by the permeate, W
R	–	Gas constant, J.mol-1.K-1
SEC	–	Specific energy consumption, kWh.m-3
Sf	–	Feed concentration, ppm
Tfi	–	Feed inlet temperature, K
Tfo	–	Feed outlet temperature, K

Tm	–	The mean temperature at the membrane surface, K
Tpi	–	Permeate inlet temperature, K
Tpo	–	Permeate outlet temperature, K
UCE	–	Unit cost of electricity, $/kWh
$\dot{V}_f$	–	Feed volume flow rate, L.s-1
$\dot{V}_p$	–	Permeate volume flow rate, L.s-1
e	–	Energy per unit mass of the freshwater, kJ/kg
f	–	Availability of the plant
i	–	Interest rate, %
l	–	Labor cost, $/m3
$\dot{m}_f$	–	Mass flow rate at the feed side, kg.s-1
$\dot{m}_{fw}$	–	Mass flow rate of desalinated water, kg.s-1
$\dot{m}_p$	–	Mass flow rate at permeate side, kg.s-1
pv,swf	–	The partial pressure of water vapour at the feed-membrane surface, Pa
pv,swp	–	The partial pressure of water vapour at the permeate-membrane surface, Pa
r	–	Mean pore size radius, m
y	–	Life expectancy of the plant, year
Greek symbols		
τ	–	Membrane tortuosity
εm	–	Membrane porosity, %
δm	–	Membrane thickness, m
μ	–	Dynamic viscosity, kg.m-1.s-1
ϱ	–	Density of fluid, kg.m-3
Subscripts		
f	–	Feed
p	–	Permeate

REFERENCES

1. Ahmed FE, Hashaikeh R, Hilal N. Solar powered desalination – Technology, energy and future outlook. Desalination 2019; 4 53:54-76. doi: 10.1016/j.desal.2018.12.002
2. Alazab AA, Qasem NAA, Baaqeel H. Performance evaluation of a novel integrated adsorption desalination system with direct contact membrane distillation plant. Desalination 2023; 552:116441. doi: 10.1016/j.desal.2023.116441
3. Al-Hrari M, Ceylan İ, Nakoa K, Ergün A. Concentrated photovoltaic and thermal system application for fresh water production. Appl Therm Eng 2020; 171:115054. doi: 10.1016/j. applthermaleng.2020.115054
4. Ali K, Hassan-Ali MI. Energy and cost analysis of a multiple channel direct contact membrane distillation module: Case study. Case Stud Chem Environ Eng 2023; 8:100449. doi: 10.1 016/j.cscee.2023.100449
5. Al-Karaghouli A, Kazmerski LL. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. Renew Sust Energ Rev 2013; 24:343-356. doi: 10.1016/j.rser.2012.12.064
6. Alkhudhiri A, Darwish N, Hilal N. Membrane distillation: a comprehensive review. Desalination 2012; 287:2-18. doi: 10.10 16/j.desal.2011.08.027

7. Al-Obaidani S, Curcio E, Macedonio F, Di-Profio G, Al-Hinai H, Drioli E. Potential of membrane distillation in seawater desalination: thermal efficiency, sensitivity study and cost estimation. J Membr Sci 2008; 323(1):85-98. doi: 10.1016/j.memsci.2008.06.006
8. Anand B, Shankar R, Murugavelh S, Rivera W, Midhun-Prasad K, Nagarajan R. A review on solar photovoltaic thermal integrated desalination technologies. Renew Sust Energ Rev 2021; 141:110787. doi: 10.1016/j.rser.2021.110787
9. Baghbanzadeh M, Rana D, Lan CQ, Matsuura T. Zero thermal input membrane distillation, a zero-waste and sustainable solution for freshwater shortage. Appl Energy 2017; 187:910-928. doi: 10.1016/j.apenergy.2016.10.142
10. Choi J, Cho J, Shin J, Cha H, Jung J, Song KG. Performance and economic analysis of a solar membrane distillation pilot plant under various operating conditions. Energy Convers Manag 2022; 268:115991. doi: 10.1016/j.enconman.2022.115991
11. Courel M, Dornier M, Rios GM, Reynes M. Modelling of water transport in osmotic distillation using asymmetric membrane. J Membr Sci 2000; 173(1):107-122. doi: 10.1016/S0376-7388(00)00348-3
12. Dahiru UL, Atia EK. Flux prediction in direct contact membrane distillation. Int J Mater Mech Manuf 2014; 2(4):302-308. doi: 10.7763/IJMMM.2014.V2.147
13. Deshmukh A, Elimelech M. Understanding the impact of membrane properties and transport phenomena on the energetic performance of membrane distillation desalination. J Membr Sci 2017; 539:458-474. doi: 10.1016/j.memsci.2017.05.017
14. Ding Z, Ma R, Fane AG. A new model for mass transfer in direct contact membrane distillation. Desalination 2003; 151 (3):217-227. doi: 10.1016/S0011-9164(02)01014-7
15. Durham RJ, Nguyen MH. Hydrophobic membrane evaluation and cleaning for osmotic distillation of tomato puree. J Membr Sci 1994; 87(1-2):181-189. doi: 10.1016/0376-7388(93)E0142-7
16. Elmarghany MR, El-Shazly AH, Salem MS, Sabry MN, Nady N. Thermal analysis evaluation of direct contact membrane distillation system. Case Stud Therm Eng 2019; 13:100377. doi: 10.1016/j.csite.2018.100377
17. Gilron J, Song L, Sirkar KK. Design for Cascade of Crossflow Direct Contact Membrane Distillation. Ind Eng Chem Res 2007; 46(8):2324-2334. doi: 10.1021/ie060999k
18. Gryta M, Tomaszewska M. Heat transport in the membrane distillation process. J Membr Sci 1998; 144(1-2):211-222. doi: 10.1016/S0376-7388(98)00050-7
19. Kabeel AE, Elmaaty TA, El-Said EMS. Economic analysis of a small-scale hybrid air HDH–SSF (humidification and dehumidification–water flashing evaporation) desalination plant. Energy 2013; 53:306-311. doi: 10.1016/j.energy.2013.02.042
20. Khayet M. Solar desalination by membrane distillation: dispersion in energy consumption analysis and water production costs (a review). Desalination 2013; 308:89-101. doi: 10.1016/j.desal.2012.07.010
21. Khayet M, Matsuura T, Souhaimi MK. Membrane distillation: principles and applications. Elsevier 2011. doi: 10.1016/B978-0-444-53126-1.10001-6
22. Kim YD, Thu K, Ghaffour N, Choon-Ng K. Performance investigation of a solar-assisted direct contact membrane distillation system. J Membr Sci 2013; 427:345-364. doi: 10.1016/j.memsci.2012.10.008
23. Kimura S, Nakao SI, Shimatani SI. Transport phenomena in membrane distillation. J Membr Sci 1987; 33(3):285-298. doi: 10.1016/S0376-7388(00)80286-0
24. Laganà F, Barbieri G, Drioli E. Direct contact membrane distillation: modelling and concentration experiments. J Membr Sci 2000; 166(1):1-11. doi: 10.1016/S0376-7388(99)00234-3
25. Lawson KW, Lloyd DR. Membrane distillation. J Membr Sci 1997; 124(1):1-25. doi: 10.1016/S0376-7388(96)00236-0
26. Levy PF, Earle RS. The effect of channel height and channel spacers on flux and energy requirements in crossflow filtration. J Membr Sci 1994; 91(1-2):135-143. doi: 10.1016/0376-7388(94)00034-4
27. Li Z, Peng Y, Dong Y, Fan H, Chen P, Qiu L, Jiang Q. Effects of thermal efficiency in DCMD and the preparation of membranes with low thermal conductivity. Appl Surf Sci 2014; 317:338-349. doi: 10.1016/j.apsusc.2014.07.080
28. Manawi YM, Khraisheh M, Fard AK, Benyahia F, Adham S. Effect of operational parameters on distillate flux in direct contact membrane distillation (DCMD): comparison between experimental and model predicted performance. Desalination 2014; 336:110-120. doi: 10.1016/j.desal.2014.01.003
29. Maqbool F, Soomro MI, Kumar L, Harijan K. Modeling and simulation of direct contact membrane distillation system integrated with a photovoltaic thermal for electricity and freshwater production. Front Energy Res 2024; 12. doi: 10.3389/fenrg.2024.1344214
30. Martínez L, Rodríguez-Maroto JM. On transport resistances in direct contact membrane distillation. J Membr Sci 2007; 295(1-2):28-39. doi: 10.1016/j.memsci.2007.02.029
31. Phattaranawik J, Jiraratananon R. Direct contact membrane distillation: effect of mass transfer on heat transfer. J Membr Sci 2001; 188(1):137-143. doi: 10.1016/S0376-7388(01)00361-1

32. Phattaranawik J, Jiraratananon R, Fane AG. Heat transport and membrane distillation coefficients in direct contact membrane distillation. J Membr Sci 2003; 212(1-2):177-193. doi: 10.1016/S0376-7388(02)00498-2
33. Phattaranawik J, Jiraratananon R, Fane AG, Halim C. Mass flux enhancement using spacer filled channels in direct contact membrane distillation. J Membr Sci 2001; 187(1-2):193-201. doi: 10.1016/S0376-7388(01)00344-1
34. Qasem NAA, Zubair SM. Performance evaluation of a novel hybrid humidification-dehumidification (air-heated) system with an adsorption desalination system. Desalination 2019; 461:37-54. doi: 10.1016/j.desal.2019.03.011
35. Sayed MM, Noby H, Zkria A, Mousa HM, Yoshitake T, ElKady M. Engineered eco-friendly composite membranes with superhydrophobic/hydrophilic dual-layer for DCMD system. Chemosphere 2024; 352:141468. doi: 10.1016/j.chemosphere.2024.141468
36. Schofield RW, Fane AG, Fell CJD, Macoun R. Factors affecting flux in membrane distillation. Desalination 1990; 77:279-294. doi: 10.1016/0011-9164(90)85030-E
37. Singh D, Sirkar KK. Desalination of brine and produced water by direct contact membrane distillation at high temperatures and pressures. J Membr Sci 2012; 389:380-388. doi: 10.1016/j.memsci.2011.11.003
38. Singh D, Sirkar KK. High temperature direct contact membrane distillation based desalination using PTFE hollow fibers. Chem Eng Sci 2014; 116:824-833. doi: 10.1016/j.ces.2014.05.042
39. Taamneh Y, Bataineh K. Improving the performance of direct contact membrane distillation utilizing spacer-filled channel. Desalination 2017; 408:25-35. doi: 10.1016/j.desal.2017.01.004
40. Termpiyakul P, Jiraratananon R, Srisurichan S. Heat and mass transfer characteristics of a direct contact membrane distillation process for desalination. Desalination 2005; 177(1-3):133-141. doi: 10.1016/j.desal.2004.11.019
41. Ullah R, Khraisheh M, Esteves RJ, McLeskey JT, AlGhouti M, Gad-el-Hak M, Vahedi-Tafreshi H. Energy efficiency of direct contact membrane distillation. Desalination 2018; 433:56-67. doi: 10.1016/j.desal.2018.01.025
42. Ve QL, Do MC, Nguyen TC, Nguyen QH, Nguyen QL, Hoang MT, Mahmoudi F. Mass transfer mechanism within commercial PTFE membranes in spacer-filled Direct Contact Membrane Distillation. Int J Membr Sci Technol 2024a; 11(1):281-295. doi: 10.15379/ijmst.v11i1.3623
43. Ve QL, Do MC, Nguyen TC, Nguyen QH, Nguyen QL, Mahmoudi F. Thin Film Theory and Boundary Layer Theory, an Approach for Analysing Heat and Mass Transfer in Spacer-filled Direct Contact Membrane Distillation. Indian J Eng 2024b; 21(55).
44. Ve QL, Koirala R, Bawahab M, Faqeha H, Do MC, Nguyen QL, Date A, Akbarzadeh A. Experimental investigation of the effect of the spacer and operating conditions on mass transfer in direct contact membrane distillation. Desalination 2021a; 500:114839. doi: 10.1016/j.desal.2020.114839
45. Ve QL, Koirala R, Bawahab M, Faqeha H, Do MC, Nguyen QL, Date AS, Akbarzadeh A. Theoretical modelling and experimental study of spacer-filled direct contact membrane distillation: Effect of membrane thermal conductivity model selection. Desalin Water Treat 2021b; 217:63-73. doi: 10.5004/dwt.2021.26921
46. Ve QL, Rahaoui K, Bawahab M, Faqeha H, Date A, Akbarzadeh A, Do MC, Nguyen QL. Experimental investigation of heat transfer correlation for direct contact membrane distillation. J Heat Transfer 2019; 142(1):012001. doi: 10.1115/1.4044707
47. Wang P, Chung TS. Recent advances in membrane distillation processes: Membrane development, configuration design and application exploring. J Membr Sci 2015; 474:39-56. doi: 10.1016/j.memsci.2014.09.016
48. Wang Y, Lior N. Thermoeconomic analysis of a low-temperature multi-effect thermal desalination system coupled with an absorption heat pump. Energy 2011; 36(6):3878-3887. doi: 10.1016/j.energy.2010.09.028
49. Zare J, Abbasi M, Hashemifard SA, Dizge N, Dibaj M, Akrami M. Eco-Friendly Superhydrophobic Modification of Low-Cost Multi-Layer Composite Mullite Base Tubular Ceramic Membrane for Water Desalination. Water 2024; 16(11):1593. doi: 10.3390/w16111593