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Hydrodynamic Enhancement of Direct Contact Membrane Distillation Using a Corrugated Feed Channel: A Numerical Study

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ABSTRACT

A numerical simulation of a direct contact membrane distillation (DCMD) cell with rectangular corrugations placed in the feed channel was conducted to investigate the influence of corrugated feed-channel geometry on hydrodynamic behavior and permeate flux in DCMD systems. The coupling of flow and mass transfer in conventional and modified channel geometries was simulated using a two-dimensional steady-state model. The effects of rib height, width, and pitch on pressure drop and permeate flux were systematically investigated. The findings indicated that rib geometry is a critical factor in determining mass-transfer effectiveness and flow patterns. Specifically, increasing the rib height from 1 to 3 mm resulted in a significant reduction in permeate flux, mainly because of increased flow obstruction and the formation of concentration boundary layers. Similarly, permeate flux gradually decreased with increasing rib width. In contrast, increasing the rib pitch from 5 to 15 mm provided a small improvement in flux by reducing excessive flow blockage while maintaining satisfactory mixing. Pressure-drop analysis showed that smaller rib pitches increased hydraulic resistance, indicating a trade-off between enhanced mass transfer and increased flow losses. In general, the best configuration was achieved with a low rib height, intermediate width, and increased pitch, which balanced flux enhancement and minimum pressure loss. The results provide useful insight into the influence of rib geometry on mass-transfer behavior and hydraulic performance in DCMD modules. The study demonstrates that geometric optimization of corrugated channels is necessary to balance flow disturbance and hydraulic resistance in DCMD systems.

1. INTRODUCTION

Freshwater scarcity has become an increasingly important challenge, especially in the Gulf region, where population growth, industrialization, and climate change combine to intensify the problem (Sherif et al. 2023, Salman et al. 2025). Consequently, desalination technologies have become necessary for securing a sustainable water supply, particularly in arid and semiarid regions (Almasoudi & Jamoussi 2024, Al-Sairfi et al. 2026). Membrane distillation (MD) is an effective thermally driven separation process that operates at relatively low temperatures, can use low-grade and renewable heat, and provides high salt rejection (Soumbati et al. 2025, Drioli et al. 2015).

A microporous hydrophobic membrane separates a hot saline feed from a chilled permeate, allowing only water vapor to pass through the pore network

(Nthunya & Mamba 2025). Vapor transport is driven by the vapor-pressure difference created by the temperature difference across the membrane. Despite its advantages, the commercial application of MD remains limited because of relatively low permeate flux and thermal efficiency compared with conventional desalination methods (Gobran et al. 2025, Zaragoza et al. 2018). These limitations can mainly be attributed to temperature and concentration polarization and heat losses in the membrane module (Suleman et al. 2021).

Among the MD configurations, direct contact membrane distillation (DCMD) has been widely studied because of its simplicity and ease of implementation (Sheikh et al. 2025, Qasim et al. 2021). In DCMD, hot saline feed and cold permeate streams contact opposite membrane surfaces, and the resulting temperature gradient creates a vapor-pressure difference across the membrane. DCMD has lower mass-transfer resistance and greater vapor flux than air-gap, vacuum, and sweeping-gas MD configurations (Francis et al. 2022, Boubakri et al. 2017). However, its thermal performance is limited by substantial conductive heat losses across the membrane and temperature polarization, which reduce the driving force for vapor transport (Jing et al. 2025). Therefore, optimization of DCMD cell design is essential to improve performance and support larger-scale deployment (Cancilla et al. 2026).

Previous membrane distillation research has focused largely on materials and operational optimization to enhance performance (Farid et al. 2024, Xu et al. 2022). The fabrication of hydrophobic polymer membranes, surface functionalization, and pore-structure engineering have produced significant gains in vapor flux and wetting resistance. Numerous experimental and numerical studies have also examined the effects of operating parameters, including feed temperature, salinity, flow velocity, and membrane thickness, on heat and mass transfer in DCMD systems (Hu et al. 2025, Lou et al. 2019). These studies have consistently identified temperature polarization and conductive heat losses across the membrane as major constraints on overall productivity and thermal efficiency. Researchers have used turbulence promoters, spacers, and corrugated flow channels to alleviate these effects and increase convective heat transfer while decreasing boundary-layer thickness (Taamneh & Bataineh 2017, Swaidan et al. 2024).

The current study investigates the influence of corrugated feed-channel geometry on the hydrodynamic and mass-transfer behavior of a DCMD system under different geometric conditions. A numerical model is developed to examine heat and mass transport in the redesigned cell and evaluate the effects on vapor flux, the temperature

polarization coefficient, and overall thermal efficiency. The behavior of the modified design is systematically compared with that of a conventional membrane cell under the same conditions. Parametric simulations assess the effects of feed temperature, salinity, flow velocity, and membrane parameters on system performance.

The remainder of the paper is organized as follows: Section 2 presents the mathematical model; Section 3 describes the mesh dependency test; Section 4 presents and discusses the effects of rib height, rib width, and rib pitch on the hydrodynamic characteristics; and Section 5 summarizes the key findings and conclusions.

2. MATHEMATICAL MODEL

2.1. Physical Description

To investigate mass transfer in conventional and modified membrane cells, a two-dimensional, steady-state model of DCMD was formulated. The computational domain was divided into three regions: the hot saline feed channel, the hydrophobic microporous membrane, and the cold permeate channel. The hydrophobic membrane separates the two fluid streams, allowing vapor to pass while preventing liquid penetration.

The standard flat-plate DCMD cell was modified by adding a corrugated feed channel to increase productivity and reduce salt concentration and temperature polarization. The corrugations were rectangular and positioned at fixed locations on the feed-channel wall near the membrane surface, creating a structured flow channel that promotes flow disturbance and disrupts the boundary layer. Corrugation geometry was characterized by height, width, and pitch, and these parameters were systematically varied to determine their effects on hydrodynamic performance (Sherif et al. 2023). In addition, the overall feed-channel height was used as a design parameter to examine its effects on temperature polarization and vapor flux (Elhenawy et al. 2020, Darman et al. 2023). This parametric design methodology allows a thorough evaluation of how structural changes at the cell level influence membrane distillation performance and provides useful guidance for improving DCMD module design.

The schematic of the proposed DCMD cell shown in Fig. 1 includes the hot feed channel, hydrophobic membrane, and cold permeate channel. The modified design has rectangular corrugations with different widths, heights, and pitches on the feed-channel wall near the membrane. The selected rib dimensions were based on practical manufacturability constraints and previous corrugated-channel studies reported in the literature. Excessively

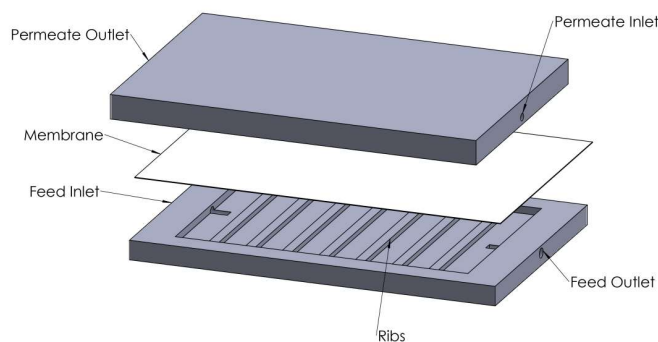


Fig. 1: Schematic diagram of the proposed cell.

large ribs may cause severe channel blockage and unstable flow behavior, whereas very small ribs produce negligible hydrodynamic disturbance.

The computational calculations were conducted at an inlet velocity of 0.01 m s^{-1} , with the feed and permeate inlet temperatures held at 343 K and 293 K, respectively. The geometric characteristics of the ribs were systematically varied to evaluate their influence on thermal and flow behavior, with rib heights ranging from 1–3 mm, rib widths from 2–4 mm, and rib pitches (spacing between successive ribs) from 5–15 mm.

2.2. Governing Equations

The transport phenomena in the feed and permeate channels are described by the steady-state incompressible Navier–Stokes, energy, and species conservation equations (Qtaishat et al. 2008).

Continuity

$$\nabla \cdot \mathbf{u} = 0 \quad \dots(1)$$

Momentum

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} \quad \dots(2)$$

Energy

$$\rho c_p (\mathbf{u} \cdot \nabla)T = k \nabla^2 T \quad \dots(3)$$

2.3. Vapor Transport Through the Membrane

The vapor flux across the membrane is governed by the vapor-pressure difference across the membrane surfaces, which can be represented as follows:

$$J = C_m (P_{v,f} - P_{v,p}) \quad \dots(4)$$

$C_m P_{v,f}, P_{v,p}$ where C_m is the membrane mass-transfer coefficient and $P_{v,f}, P_{v,p}$ are the vapor pressures at the feed and permeate membrane surfaces, which can be calculated using the Antoine equation (Lee 2025).

The membrane mass transfer coefficient is expressed as:

$$C_m = \left(\frac{1}{C_K} + \frac{1}{C_M} \right)^{-1} \quad \dots(5)$$

Where C_K and C_M are the Knudsen and molecular diffusion coefficients.

In this study, the numerical model was established based on several simplifying assumptions. The flow was assumed to be steady-state, two-dimensional, laminar, and incompressible, with constant thermophysical properties throughout the domain. Membrane wetting was neglected, and complete salt rejection was assumed. Moreover, water vapor within the membrane pores was assumed to obey the ideal gas law, and local thermal equilibrium was maintained at the membrane interfaces.

2.4. Boundary Conditions and Numerical Procedure

At the feed-channel inlet, a uniform velocity profile of 0.01 m s^{-1} and a temperature of 343 K were imposed. The permeate inlet temperature was fixed at 293 K. Atmospheric-pressure boundary conditions were applied at both outlet boundaries. No-slip velocity conditions were imposed at all solid walls. The membrane was considered hydrophobic and nonwetted, with complete salt rejection. Heat transfer through the membrane included both conductive and latent heat-transport mechanisms. The membrane surfaces were thermally coupled with the adjacent fluid domains. The governing equations were solved using the finite volume method in ANSYS Fluent. Pressure-velocity coupling was achieved using the SIMPLE algorithm. Second-order upwind discretization schemes were applied to the momentum and energy equations to improve numerical accuracy. The convergence criterion for all governing equations was set to 10^{-6} for the continuity, momentum, and energy residuals. Simulations continued until stable values of permeate flux and temperature distribution were achieved. Table 1 presents the membrane and operating parameters.

Table 1: Membrane and operating parameters.

Parameter	Value
Membrane thickness	0.12 mm
Membrane porosity	0.75
Membrane tortuosity	2.0833
Mean pore size	0.22 μm
Feed inlet temperature	343 K
Permeate inlet temperature	293 K
Feed velocity	0.01 m s^{-1}
Membrane material	PVDF

3. MESH DEPENDENCY TEST

A mesh dependency test was performed in ANSYS by progressively increasing the number of elements until a quantitative convergence criterion was achieved. A finer mesh was used at the corners to improve boundary-layer resolution and accurately capture the steep temperature and velocity gradients. The relative errors of key output parameters, including permeate flux and temperature distribution, were evaluated between successive mesh refinements, and the final mesh was selected when the relative error dropped below 1% at 38,945 elements. Fig. 2(a) shows the computational domain and mesh, and Fig. 2(b) shows the variation in relative error with increasing number of elements.

The final computational mesh was selected after the relative error fell below 1%, thereby minimizing numerical uncertainty in the predicted permeate-flux results.

3.1. Model Validation

To validate the developed numerical model, the predicted permeate flux values were compared with previously published numerical and experimental DCMD studies. The comparison was conducted under similar operating

Table 2: Validation of the present numerical model with published literature.

Study	Method	Permeate Flux ($\text{kg m}^{-2} \text{h}^{-1}$)
Qtaishat et al. (2008)	Numerical	14.9
Lou et al. (2019)	CFD simulation	15.2
Present study	Numerical simulation	15.4

conditions, including feed and permeate temperatures, membrane characteristics, and flow configuration. Table 2 presents a comparison between the present numerical model and the published results reported by Qtaishat et al. (2008) and Lou et al. (2019). The comparison shows good agreement between the current simulation and the literature data, with deviations within an acceptable range for CFD-based DCMD investigations. This supports the capability of the present model to predict the coupled heat- and mass-transfer behavior in direct contact membrane distillation systems.

The maximum deviation between the present model and the literature results was below 4%, indicating satisfactory agreement and supporting the reliability of the numerical methodology used in this study.

4. RESULTS AND DISCUSSION

A parametric study was conducted to determine the effects of rib height, rib width, and rib pitch on the hydrodynamic characteristics and membrane flux of the modified cell. The performance of the corrugated feed-channel configurations was evaluated relative to the conventional flat-channel DCMD configuration under the same operating conditions. All simulations were performed under identical inlet conditions to isolate the influence of geometric parameters on the hydrodynamic and mass-transfer behavior of the DCMD system.

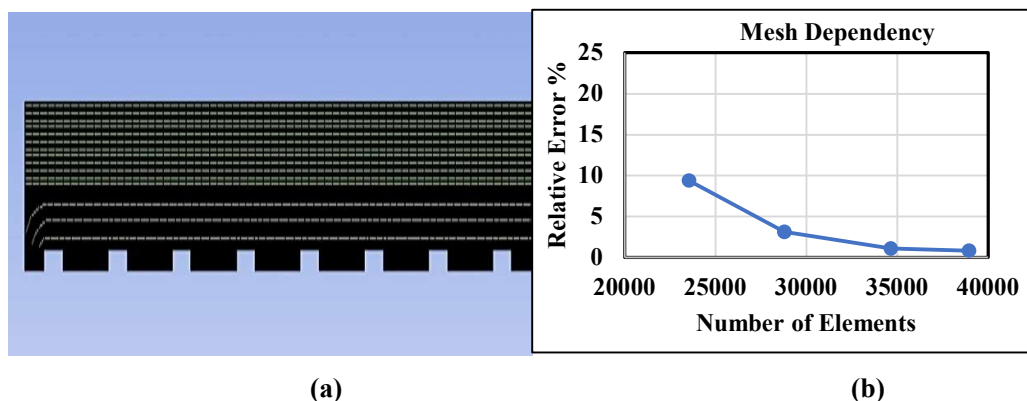


Fig. 2: (a) Computational domain and mesh; (b) variation in relative error with increasing number of elements.

4.1. Effect of Rib Height

The relationship between permeate flux and rib height is shown in Fig. 3, with rib pitch and width kept constant at 15 mm and 4 mm, respectively. The results show a clear pattern: permeate flux decreases as rib height increases. At a rib height of 1 mm, the ribs disturb the flow sufficiently to improve mixing near the membrane surface and mitigate concentration polarization without greatly obstructing the flow. In contrast, increasing rib height increases channel blockage, leading to larger recirculation zones and a smaller effective flow cross-sectional area. This change reduces the overall fluid velocity in regions where convective transport is less efficient and promotes the development of thicker concentration boundary layers near the membrane. This reduces the mass-transfer driving force, resulting in lower permeate flux at greater rib heights. Therefore, the results highlight the importance of using sufficiently small rib heights to facilitate mass transfer while still providing useful flow disturbance. Although corrugated structures may improve local mixing near the membrane surface, excessive

rib height increases channel blockage and weakens overall mass-transfer performance.

4.2. Effect of Rib Width

Fig. 4 shows the variation in permeate flux with rib width, with rib height and pitch remaining constant at 1 mm and 15 mm, respectively. The data indicate a steady reduction in permeate flux as rib width increases from 2 to 4 mm. In particular, the flux is about $15.4 \text{ kg m}^{-2} \text{ h}^{-1}$ at a rib width of 2 mm, $15.1 \text{ kg m}^{-2} \text{ h}^{-1}$ at 3 mm, and $14.8 \text{ kg m}^{-2} \text{ h}^{-1}$ at 4 mm. This trend can be explained by the fact that narrower ribs occupy less space in the channel, allowing higher local fluid velocities and stronger shear near the membrane surface. These conditions increase mixing and reduce concentration polarization. Increasing rib width, on the other hand, increases channel blockage and reduces near-wall convection, promoting the formation of thicker concentration boundary layers. This, in turn, increases mass-transfer resistance and leads to lower permeate flux. In general, these results indicate that ribs can beneficially

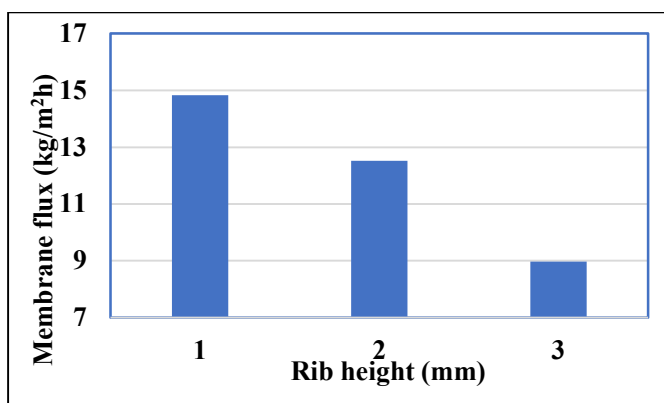


Fig. 3: Effect of rib height on permeate flux at fixed rib width = 4 mm and rib pitch = 15 mm.

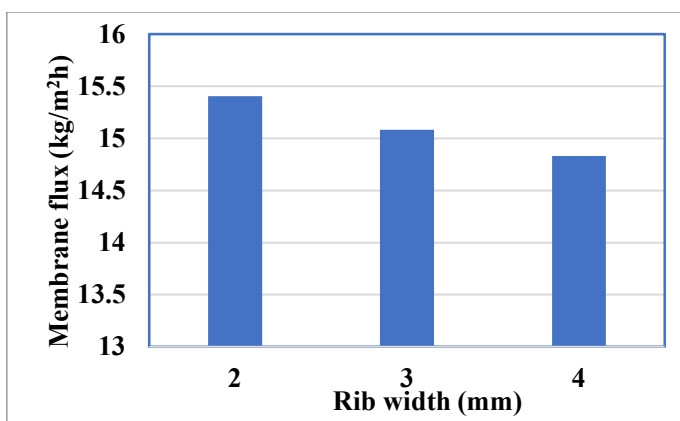


Fig. 4: Effect of rib width on permeate flux at fixed rib height = 1 mm and rib pitch = 15 mm.

disturb the flow, but very wide ribs may hamper mass transfer by restricting effective flow development near the membrane surface. Therefore, rib width should be optimized to maximize permeate flux. These findings indicate that corrugation geometry does not necessarily guarantee flux enhancement, and improper rib dimensions may negatively affect mass-transfer efficiency.

4.3. Effect of Rib Pitch

Fig. 5 shows the effect of rib pitch on permeate flux, with rib width and height maintained at 2 mm and 1 mm, respectively. The results indicate that permeate flux gradually increases as rib pitch increases from 5–15 mm. Specifically, the flux is $15.1 \text{ kg m}^{-2} \text{ h}^{-1}$ at 5 mm, $15.2 \text{ kg m}^{-2} \text{ h}^{-1}$ at 10 mm, and $15.4 \text{ kg m}^{-2} \text{ h}^{-1}$ at 15 mm. At smaller rib pitches, more obstacles are introduced into the flow, resulting in larger recirculation regions between the ribs. Although mixing near the membrane can be enhanced, excessive obstruction reduces flow near the membrane surface and limits mass transport across it. At larger rib pitches, the channel is less restricted, allowing fluid to flow more freely while still creating sufficient disturbance to disrupt concentration boundary layers. This improved balance between mixing and flow resistance increases mass transfer, leading to higher permeate flux at larger rib pitches. Therefore, the results demonstrate the importance of optimizing rib spacing to obtain maximum flux without imposing unnecessary flow resistance and energy loss.

4.4. Effect of Rib Dimensions on Pressure Drop

Table 3 summarizes the effects of rib geometry and arrangement on the pressure drop across the feed channel. The results show that pressure drop decreases steadily with increasing rib pitch, regardless of rib width. Closer ribs increase flow resistance. For instance, with ribs 1 mm high

Table 3: Pressure drop at the feed side of the DCMD cell.

$\Delta P \text{ (Pa)}$				
Height (mm)	Width (mm)	Pitch = 5 mm	Pitch = 10 mm	Pitch = 15 mm
1	2	0.802928	0.7635086	0.6253983
	3	0.822953	0.7731061	0.6513754
	4	0.7866656	0.763927	0.705921

and 2 mm wide, the pressure drop decreases from 0.803 Pa at a 5 mm pitch to 0.625 Pa at a 15 mm pitch. Similar trends are observed for rib widths of 3 and 4 mm, supporting the finding that closer rib spacing increases frictional losses. The effect of rib width, however, is more subtle. At a small pitch of 5 mm, widening the rib from 3 to 4 mm results in a slight decrease in pressure drop. At larger pitches, however, broader ribs generally produce greater pressure drops because they obstruct a larger portion of the flow passage. Overall, these findings suggest that rib pitch is the primary factor affecting pressure loss, whereas rib width has a secondary effect that depends on rib spacing. The results demonstrate that increased permeate flux must be balanced against the additional hydraulic resistance introduced by corrugated structures. Therefore, an optimal rib configuration should simultaneously maximize mass transfer while minimizing pressure losses and pumping-power requirements.

Overall, the results suggest that rib geometry influences not only hydrodynamic behavior and permeate flux but also local thermal-transport characteristics and temperature-polarization phenomena within the DCMD module.

5. CONCLUSIONS

The current study investigated a corrugated feed channel using numerical simulations to identify the effects of its geometric properties on mass transfer and fluid dynamics in

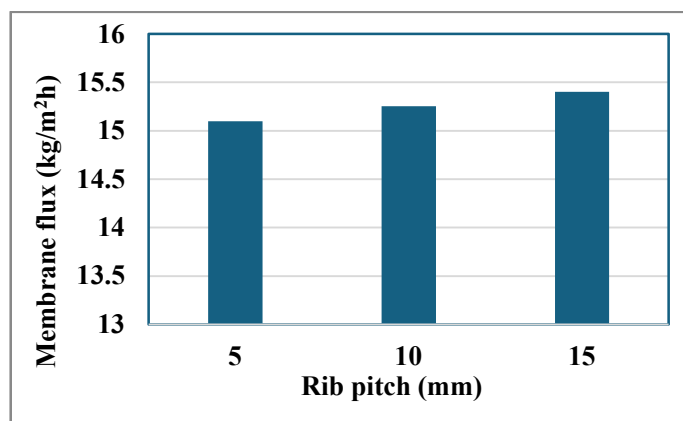


Fig. 5: Effect of rib pitch on permeate flux at fixed rib height = 1 mm and rib width = 2

a direct contact membrane distillation (DCMD) system. The numerical results indicate that the hydrodynamic effects of corrugated channels strongly depend on rib geometry, with both beneficial mixing effects and adverse flow-obstruction mechanisms occurring. The results show that both permeate flux and hydraulic resistance are strongly influenced by rib morphology and dimensions. Rib height was the most significant of the investigated parameters: increasing rib height from 1–3 mm led to a strong reduction in permeate flux, mainly because of increased channel blockage and the formation of thicker concentration boundary layers near the membrane surface. Rib width also had a significant influence, as permeate flux decreased from 15.4 to about 14.8 kg m⁻² h⁻¹ as rib width increased to 4 mm. Conversely, increasing rib pitch to 15 mm led to a small improvement in flux, from 15.1 to about 15.4 kg m⁻² h⁻¹, as the flow encountered less obstruction while still benefiting from adequate mixing.

It was also observed that the pressure drop across the channel decreased from approximately 0.80 Pa to 0.63 Pa as rib spacing increased, supporting the finding that closely spaced ribs increase hydraulic resistance. These observations highlight the importance of balancing the additional energy needed to overcome flow resistance against the gains from improved mass transfer. Among the investigated configurations, a rib height of 1 mm, rib width of 2 mm, and rib pitch of 15 mm provided the most balanced performance in terms of permeate flux and pressure drop under the investigated operating conditions. Therefore, channel corrugation should be carefully optimized to improve performance without introducing excessive hydraulic resistance or flow blockage. Overall, these findings show that even small changes in channel geometry can significantly affect system performance and can inform the design of more efficient DCMD modules without requiring complicated structural changes.

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