Advancing Membrane Distillation: Multi-Channel Designs for Enhanced Energy Efficiency and Performance

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Abstract: Membrane Distillation (MD) is a thermally driven desalination process with high rejection rates for non-volatile contaminants. However, traditional single-channel (SC) modules are limited by severe temperature polarization, reducing energy efficiency and overall productivity. This study explores two novel MD module configurations—Multiple Feed Channels (MFC) and Multiple Permeate Channels (MPC)—designed to improve mass and heat transfer, ultimately enhancing system performance and reducing energy consumption. Experiments were conducted using PTFE and PVDF membranes with and without spacers across a feed temperature range of 30°C to 70°C. The MFC and MPC modules demonstrated significant improvements over SC modules, achieving flux enhancements of up to 86% and reducing specific energy consumption (SEC) by up to 63%. Computational fluid dynamics (CFD) simulations validated these findings, revealing improved temperature distribution, reduced polarization effects, and optimized hydrodynamics. These findings highlight the potential of multi-channel MD designs for scalable and energy-efficient desalination and wastewater treatment applications, particularly when coupled with low-grade heat sources.

Keywords: Membrane Distillation, Multi-Channel Module Design, Energy Efficiency, Computational Fluid Dynamics, Thermal Management

1. Introduction

The increasing global demand for freshwater has intensified interest in energy-efficient desalination technologies (Elimelech & Phillip, 2011). Membrane Distillation (MD) is a promising thermal-driven process, particularly suited for treating high-salinity waters and brine management. Unlike pressure-driven membrane processes such as reverse osmosis, MD leverages a hydrophobic membrane to facilitate water vapor transport across a temperature gradient, ensuring near-complete rejection of non-volatile solutes (El-Bourawi et al., 2006). However, the widespread adoption of MD has been hindered by high energy consumption, mass transfer inefficiencies, and significant temperature polarization effects (Kharraz et al., 2022).

Conventional single-channel (SC) MD modules exhibit severe temperature and concentration polarization, leading to decreased driving force for vapor transport and reduced flux. To address these limitations, novel module configurations that optimize fluid flow and thermal gradients are needed. This study introduces two innovative multi-channel MD designs—Multiple Feed Channels (MFC) and Multiple Permeate Channels (MPC)—engineered to improve mass transfer, minimize temperature polarization, and enhance overall energy efficiency. Experimental evaluations and CFD modeling were employed to compare the performance of these novel designs against traditional SC configurations.

2. Materials and Methods

The study investigated the performance of SC, MFC, and MPC modules under controlled conditions. Experiments were conducted using PTFE and PVDF membranes with and without spacers to assess their impact on flux and SEC. Feed temperatures ranged from 30°C to 70°C, with a fixed permeate temperature of 15°C. The permeate flux was continuously monitored using a precision balance, while SEC was calculated based on the measured thermal energy input. Additionally, CFD simulations provided insights into flow dynamics and temperature distributions within the modules (Kharraz et al., 2025). Performance was assessed using permeate flux (J, L/m²·h) and SEC (kWh/m³). Flux was determined using Equation 1:

$$J = \frac{m}{A \times t} \quad (1)$$

where m is the permeate mass (kg), A is the membrane area (m²), and t is the experiment duration (h).

SEC was calculated using Equation 2 as follows:

$$SEC = \frac{Q}{J \times A} \quad (2)$$

where Q represents the total thermal energy input (kWh). Identical operating conditions were maintained across all tests for accurate comparisons.

3. Results and Discussion

The MFC and MPC modules significantly outperformed the SC module across all tested conditions. Flux improvements of up to 86% and SEC reductions of up to 63% were observed, with the greatest enhancements occurring at higher feed temperatures. The improved performance was attributed to more efficient heat and mass transfer, reduced temperature polarization, and optimized flow distribution, as confirmed by CFD simulations.

CFD analysis revealed that the multi-channel configurations minimized boundary layer effects and maintained a uniform temperature gradient across the membrane surface, reducing conductive heat losses. Figure 1 presents schematics and photos of the engineered modules and illustrates the comparative performance of the SC, MFC, and MPC modules, highlighting the enhanced flux and energy efficiency of the multi-channel designs.

The use of spacers further influenced performance by improving flow distribution and reducing channeling effects. However, their impact varied depending on the membrane material. PTFE membranes generally exhibited higher fluxes due to their superior hydrophobicity and thermal conductivity, while PVDF membranes demonstrated lower SEC values, suggesting potential advantages in energy efficiency.

These findings underscore the potential for MFC and MPC modules to be integrated with low-grade heat sources, making them suitable for industrial-scale desalination and wastewater treatment applications. The reduction in temperature polarization and energy consumption presents a compelling case for adopting these novel designs in practical MD systems.

4. Conclusion

This study demonstrates that multi-channel MD configurations, specifically the MFC and MPC modules, significantly enhance performance compared to traditional SC modules. The experimental results confirmed that these novel designs mitigate temperature polarization, enhance mass transfer, and improve thermal efficiency. CFD simulations provided further validation by illustrating the multi-channel configurations' improved hydrodynamic and thermal behavior.

The findings suggest that MFC and MPC modules offer a scalable and energy-efficient solution for water desalination and wastewater treatment, particularly in conjunction with low-grade heat sources. Future research should focus on evaluating long-term operational stability and optimizing these designs for industrial-scale applications.

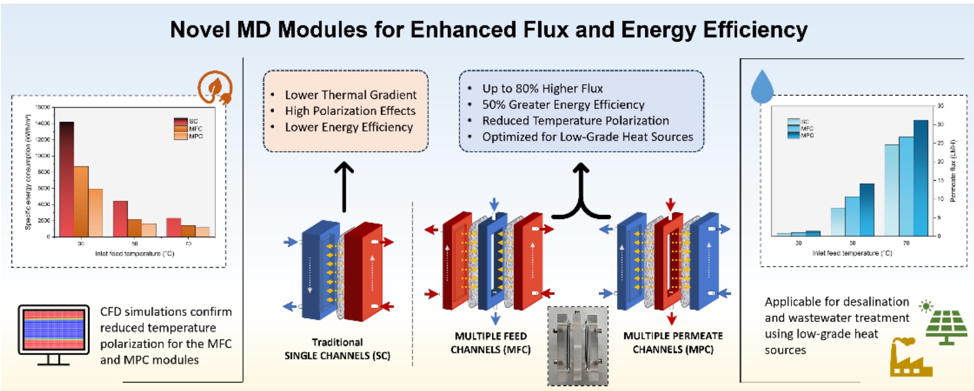

Figure 1. Comparison of the traditional and the fabricated novel multi-channel MD modules. The SC module suffers from lower thermal gradients, higher polarization effects, and reduced energy efficiency. The MFC and MPC modules demonstrate up to 80% higher flux and 50% greater energy efficiency due to improved thermal management and reduced temperature polarization.

References

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