31st International Conference
ENGINEERING MECHANICS 2025
Medlov, Czech Republic, May 12 –14, 2025
Paper **#38**, pp. 121–124, doi: 10.21495/em2025-121

DESIGN OF HOLLOW FIBER MEMBRANE MODULE FOR MEMBRANE DISTILLATION

Menshikh M.[1]**, Bartuli E.**[2]**, Kalivoda J.**[3]**, Kučerík J.**[4]

Abstract: *This study presents the design and optimization of a hollow fiber membrane module for membrane distillation (MD) applications. Membrane distillation is a thermally-driven separation process where a hydrophobic membrane facilitates the passage of water vapor while rejecting non-volatile solutes. The hollow fiber configuration offers several advantages, including high surface area-to-volume ratio and compact module design, which are crucial for enhancing the efficiency and scalability of MD systems. The research delves into various design parameters such as fiber material selection, pore size distribution, fiber packing density, and module configuration.*

Keywords: Hollow fiber membranes, Membrane distillation, Polymeric fibers, Mass transfer

1. Introduction

Conventional liquid separation processes such as distillation are usually carried out using distillation columns. The main objective in the design and operation of such systems is to maximize the mass transfer rate by increasing the phase contact area. In the case of distillation columns, this can only be achieved by increasing the area of the parts of the apparatus that are in direct contact with the liquid to be heated and ensuring uniform distribution of liquid and vapor flows. However, classical distillation columns have a number of disadvantages such as feed rate limitation, ebullition effect and foaming, which reduces the efficiency of the process (Lin et al., 2025).

An alternative solution is membrane distillation, a phase separation process based on the use of a microporous hydrophobic membrane. In this method, the more volatile component of the mixture evaporates on one side of the membrane, passing through its pores as vapor, and condenses on the other side, providing selective separation of the solution components (Kebria and Rahimpour, 2020). Membrane distillation combines the advantages of compact equipment, modular design, operation at lower temperatures than traditional distillation and the absence of the need for significant pressure differences between phases (Criscuoli, 2025).

This method has been actively researched since the 1980s and has been used for water purification, concentrating solutions in the food industry, wastewater treatment, seawater desalination and extracting valuable compounds from process streams (Guo et al., 2025; Zare and Kargari, 2024). Depending on the configuration of the membrane module, fluids can move in opposite directions through different sides of the membrane, and the evaporation and condensation process is controlled by the temperature and hydrodynamic parameters of the system. Unlike conventional columns, membrane distillation modules are not prone to flooding at high flow rates, do not require maintaining density differences between phases, and provide a stable contact area regardless of operating conditions.

[1] Ing. Maksim Menshikh.: Heat Transfer and Fluid Flow Laboratory, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, Maksim.Menshikh@vut.cz

[2] Ing. Erik Bartuli, PhD.: Heat Transfer and Fluid Flow Laboratory, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, Erik.Bartuli1@vut.cz

[3] Ing. Josef Kalivoda, PhD.: Department of Chemistry and Technology of Environmental Protection, Brno University of Technology; Purkyňova 464; 612 00 Brno; CZ, Josef.Kalivoda@vut.cz

[4] prof. Ing. Jiří Kučerík, PhD.: Department of Agrochemistry, Soil Science, Microbiology and Plant Nutrition, Mendel University in Brno; Zemědělská 1665/1; 61 300 Brno; CZ, jiri.kucerik@mendelu.cz

In addition, scaling up membrane distillation is a simpler and more predictable process. Membrane technology typically scales linearly, allowing the system capacity to be increased by adding new membrane modules. The modular design allows the plant to operate over a wide range of production capacities. The interfacial contact area is known and remains constant, which makes it easier to predict the efficiency of the process compared to conventional distillation, where the contact area can be calculated but the actual utilization of this area is more difficult to determine. Also, the efficiency of using membrane distillation instead of traditional distillation depends largely on the composition of the separated solution, the type of membranes used and the process conditions (Alkhudhiri et al., 2012).

2. Equipment description

The module for membrane distillation (see Fig. 1) of aqueous solutions and suspensions that distills from the shell space into the fibers. Polypropylene membrane fibres from ZENA Ltd. are used as the active surface. The module is 28.9 cm long with a central diameter of 8.5 cm, tapering at the ends to 5 cm GL45 threads. A key feature is the separation of PP membrane fibers to maximize the distillation area (Fig. 2), achieved using glass flanges for easy bundle replacement, separator installation, and quick commissioning. To prevent clogging by fine particles, an outside-in membrane distillation system is used, ensuring only the easily cleanable outer membrane surface is exposed to fouling (Program TREND, 2024).

Fig. 1: Assembled module

Fig. 2: Separator for fibers

For the outside-in approach a tap water at the temperature of 50 °C as a feed solution was used. The results were obtained during the practical phase of the research and include measurements at different vacuum pressures (0.68-0.80 bar) resulting the maximum yield 0.120 L/h. The measurement results at different pressures are shown in Tab. 1 (Kalnicka, 2023).

Tab. 1: Distillation rates of outside-in approach using hollow fibre polypropylene membranes; the operational temperature of 50 °C, tapwater as a feed solution

Pressure [bar]	0.68	0.72	0.77	0.8
Distillation rate [L/h]	0.099	0.097	0.095	0.097

3. Equipment upscaling

The equipment can be scaled up to increase the distillate yield. For the upscaled version of the equipment, a new membrane bundle insertion base was developed (see Fig. 3 and Fig. 4) to accommodate up to five 700 mm long bundles.

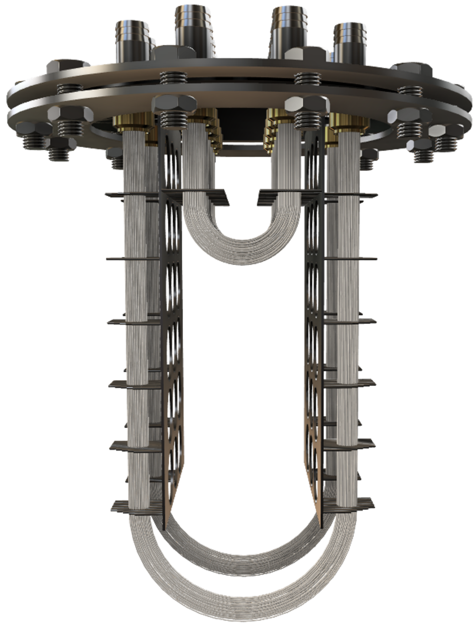

Fig. 3: 3D render of semi-industrial version

Fig. 4: Photo of semi-industrial version

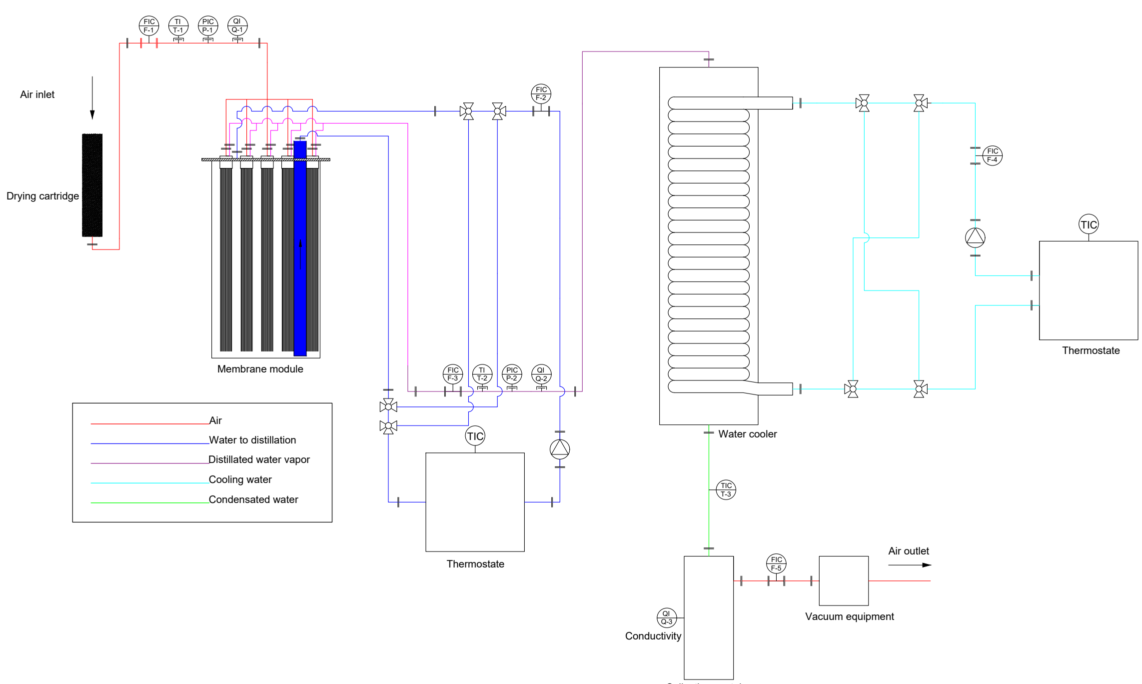

Fig. 5: Technological scheme

This modification allows for a significant increase in processing capacity while maintaining efficiency and ensuring uniform phase contact. Additionally, the redesigned structure improves operational stability and simplifies maintenance, making the system more adaptable for industrial-scale applications. At the expected linear character of distillate yield growth, the capacity of the equipment will be 1.68 L/h. In addition, a complete process flow diagram (Fig. 5) was developed, incorporating measurements of all key process parameters. This detailed mapping provides a foundation for further optimization of the system. Moreover, the collected data and analytical framework open up the possibility of creating a digital twin of the equipment. Such a model would allow for in-depth analysis of fine process parameters, enabling predictive maintenance, performance improvements, and enhanced operational control.

4. Conclusions

This study presents the design, optimization, and scaling of a hollow fiber membrane module for membrane distillation applications. The developed module leverages the advantages of membrane technology, such as a high surface area-to-volume ratio, modularity, and operational efficiency. The integration of glass flanges and an outside-in filtration approach enhances ease of maintenance and minimizes membrane fouling. The development of a complete process flow diagram enables precise monitoring and future optimization. The potential implementation of a digital twin further expands the capabilities of the system by allowing predictive maintenance and deeper analysis of process dynamics.

These advancements contribute to the broader adoption of membrane distillation in industrial applications, offering a scalable, efficient, and reliable alternative to conventional separation processes. Future work will focus on refining the digital model and exploring additional enhancements to improve long-term performance and sustainability.

Acknowledgments

The authors would like to express their sincere gratitude to all organizations and grant agencies who have sponsored the successful completion of this work. The research has been supported by the programme TREND project No. FW06010715, Elimination of volatile substances from wastewater with simultaneous conversion to secondary raw material using microporous hollow fibres, granted by the Technology Agency of the Czech Republic and by the internal grant of the Brno University of Technology Focused on Specific Research and Development no. FSI-S-23-8254.

References

Alkhudhiri, A., Darwish, N., and Hilal, N. (2012) Membrane distillation: A comprehensive review. *Desalination*, 287, pp. 2–18. Special Issue in honour of Professor Takeshi Matsuura on his 75th Birthday.

Criscuoli, A. (2025) Boosting the membrane distillation performance by exploiting its configurations. *Separation and Purification Technology*, 361, pp. 131510.

Guo, X., Qin, B., Guo, Z., Yan, S., Guo, J., Li, J., Li, X., Tian, R., Kang, J., and Zhang, W. (2025) Research on desalination performance of novel free-interface evaporation synergism membrane distillation module: Suitable for solar drive scenarios. *Separation and Purification Technology*, 361, pp. 131350.

Kalnicka, B. (2023) Membrane distillation based on thin polypropylene membranes: development and testing of a laboratory unit. Master thesis, Brno University of Technology, Faculty of Chemistry, Department of Chemistry and Environmental Technology. Thesis supervisor: Jiri Kucerik.

Kebria, M. R. S. and Rahimpour, A. (2020) Membrane distillation: Basics, advances, and applications. In Abdelrasoul, A., edt., *Advances in Membrane Technologies*, IntechOpen, Rijeka, chapter 4.

Lin, Y., Huang, Z., Jiang, P., Wang, Q., Yin, W., Yang, C., and Qiu, T. (2025) Separation process intensification for zero-gravity distillation through sandwich internal structure with ordered hierarchical metal foam. *Separation and Purification Technology*, 360, pp. 131060.

Program TREND (2024) Third generation membrane distillation: Functional Sample No. FW03010181-V3. Technical report, PID: FW03010181.

Zare, S. and Kargari, A. (2024) Process intensification in the direct contact membrane distillation (dcmd) desalination by patterning membrane surface: A cfd study. *Chemical Engineering and Processing - Process Intensification*, 205, pp. 110027.