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Review of thermal efficiency and heat recycling in membrane distillation processes

Yonggang Zhang [a], Yuelian Peng [a,*], Shulan Ji [a,*], Zhehao Li [b], Ping Chen [c]

[a] Department of Chemistry and Chemical Engineering, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124 PR China
[b] Changchun Gold Research Institute, 130012 PR China
[c] The Research Institute of Environmental Protection, North China Pharmaceutical Group Corporation, 050015 PR China

HIGHLIGHTS

- Membrane distillation (MD) is a promising desalination technology.
- Enhancing the thermal efficiency of MD is a major research focus.
- Transfer mechanism of the MD process was introduced.
- Various factors affecting the thermal efficiency were analyzed.
- Several heat recovery techniques in the MD field were reviewed.

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ABSTRACT

Membrane distillation (MD) is a promising desalination technology for water recovery from high-salinity solutions such as RO brine. Despite its great potential, MD has not been industrially realized because this technique generates a lower flux than reverse osmosis processes and exhibits a lower thermal efficiency than multi-stage flash. Enhancing the flux and thermal efficiency of MD is a major research focus for membrane researchers. In this study, the principles, transfer mechanism and thermal efficiency characterization of the MD process were introduced. Various factors affecting the thermal efficiency were analyzed. Several heat recovery techniques in the MD field that have been developed and widely employed were reviewed.

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* Corresponding authors.
E-mail addresses: pyl@bjut.edu.cn (Y. Peng), jshl@bjut.edu.cn (S. Ji).

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1. Introduction

Membrane distillation (MD) is a new technology that combines distillation and membrane separation, i.e., the thermally driven transport of vapor through the pores of a hydrophobic microporous membrane using simultaneous mass and heat transfer [1]. A porous hydrophobic membrane, which serves as both a thermal insulator and a physical barrier, permits the free transport of water vapor through the membrane pores but prevents the liquid phase from passing through the membrane. As a result, a 100% rejection of the nonvolatile solute can be theoretically achieved. This technique has been widely studied for many applications, including water desalination and dewatering [2–7], which is the volatilization of water from aqueous solution, and the removal of volatile organic compounds from aqueous solution [8]. Compared with the normal separation process, MD is an efficient separation technology that has few operating limitations and moderate membrane mechanical strength [9]. Generally, MD can be divided into the following configurations based on the different methods of creating a vapor pressure gradient across the membrane: (a) direct contact MD (DCMD); (b) air gap MD (AGMD); (c) sweeping gas MD (SGMD); and (d) vacuum MD (VMD) [10], as shown in Fig. 1.

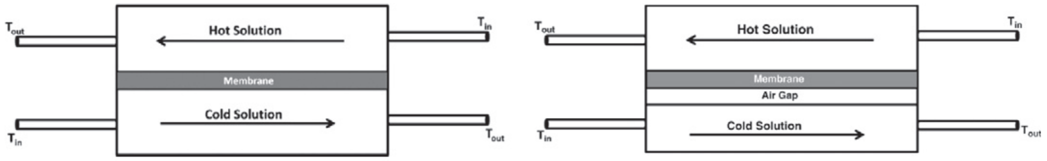
A phase change occurs in MD: water on the hot side vaporizes and crosses the hydrophobic membrane matrix. The heat of vaporization comes from the sensible heat of a hot solution, which results in a temperature decrease on the hot side. When the vapor crosses the membrane matrix, heat (i.e., vaporization heat) is transferred from the hot side to the cold side across the membrane. To obtain a high vapor flux, a high temperature gradient between both sides of the membrane must be maintained; this also generates a conductive heat loss across the membrane. The loss of vaporization heat and conduction heat causes high thermal consumption in MD. The thermal efficiency of MD systems is very low (20%–30%) [11]. Even with large quantities of cooling water available for the condensation of water vapor across the membrane, it is difficult to achieve this abatement. High energy consumption and high cold water consumption in the MD process are the two key factors that limit its use in industry.

Kubota [12] examined the thermal efficiency of seawater desalination via AGMD. The authors showed that it was necessary to use a multi-stage MD process to develop a high efficiency membrane module to increase the thermal efficiency. A heat recycle should be considered to reduce the heat loss as much as possible. Peng [13] simulated the effects of the membrane properties and operating conditions on the thermal efficiency of a DCMD process. The author found that thermal efficiency was increased when the vapor flux increased. A polysulfone (PSF) support and polyvinylidene difluoride (PVDF) membrane were modified using a SiO_2 aerogel coating to reduce the thermal conductivity. The resultant composite membrane had a higher vapor flux and a better thermal efficiency than the support.

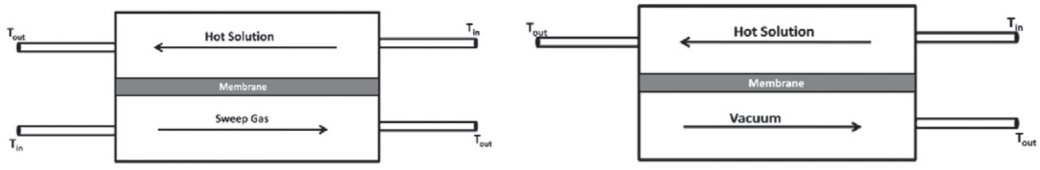
Although only a few of the many studies focused on the thermal efficiency of the MD process, a general review is required to summarize and systematically discuss the effects of thermal efficiency in the MD process. This paper introduced the transfer mechanism, the concept and effects of thermal efficiency and the development of a heat recycle path in the MD process.

2. Transfer mechanism in MD

In the MD process, heat transfer simultaneously occurs with mass transfer. The mass transfer process influences the rate and coefficients of the heat transfer process, which results in a complex heat transfer model. As shown in Fig. 2, the mass transfer process of MD can be divided into three steps: (1) water in the hot feed bulk transfers to the surface of the hydrophobic membrane; (2) water evaporates on the membrane surface into water vapor, which crosses the membrane matrix to the cold side; and finally, depending on the type of MD process, (3) either water vapor mixes with cold water and condenses (DCMD), water vapor crosses an air gap and condenses on a cold plate (AGMD), water vapor is flushed with a purge gas to a condenser (SGMD) or water vapor is pumped to a condenser (VMD) [11]. The heat transfer that occurs in MD can also be divided into three steps [14]: (1) convective heat transfer from the hot feed across the boundary layer to the membrane surface; (2) heat transfer through the



A. Direct Contact Membrane Distillation (DCMD) B. Air Gap Membrane Distillation (AGMD)



C. Sweeping Gas Membrane Distillation (SGMD) D. Vacuum Membrane Distillation (VMD)

Fig. 1. Different types of MD configurations [10].