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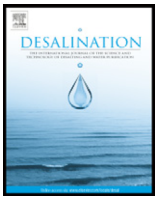

Scaling and fouling in membrane distillation for desalination applications: A review

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HIGHLIGHTS

- Review: temperature, flow rate, SI, feed type, specific salt effects in MD fouling
- Module type, and temperature and concentration polarization greatly affect fouling.
- High temperature prevents MD biofouling.
- Particulate fouling can be easily avoided by microfiltration.
- Reducing feed pH, membrane superhydrophobicity, and antiscalants prevent MD scaling.

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ABSTRACT

Membrane distillation (MD) has become an area of rapidly increasing research and development since the 1990s, providing a potentially cost effective thermally-driven desalination technology when paired with waste heat, solar thermal or geothermal heat sources. One principal challenge for MD is scaling and fouling contamination of the membrane, which has gained growing attention in the literature recently as well. The present paper surveys the published literature on MD membrane fouling. The goal of this work is to synthesize the key fouling conditions, fouling types, harmful effects, and mitigation techniques to provide a basis for future technology development. The investigation includes physical, thermal and flow conditions that affect fouling, types of fouling, mechanisms of fouling, fouling differences by sources of water, system design, effects of operating parameters, prevention, cleaning, membrane damage, and future trends. Finally, numerical modeling of the heat and mass transfer processes has been used to calculate the saturation index at the MD membrane interface and is used to better understand and explain some of trends reported in literature.

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1. Introduction

Membrane distillation (MD) is a promising thermally driven desalination technology still in its infancy in terms of development and commercial deployment [1,2]. The technology purifies water using a hydrophobic membrane, which is permeable to water vapor but which repels liquid water. In seawater desalination applications of MD, as hot saline feed solution flows over the membrane, the increased water vapor pressure from the higher temperature drives vapor through the pores ($d_p \approx 0.2-0.4$ m) of the hydrophobic membrane, where it is collected on the permeate side [3]. MD possesses unique advantages over other desalination technologies, including pressure-driven methods such as reverse osmosis (RO) and thermally-driven methods such flash distillation. MD is free of the specialized requirements of high-pressure RO systems, which includes heavy gauge piping, complex pumps, and maintenance demands [1]. Since MD is not a pressure driven process and only vapor is allowed to cross through the membrane, MD is more fouling resistant than RO [4] and has a potential 100% rejection of ions and macromolecules. MD can be run at lower temperatures than other thermal systems making untapped sources of waste heat usable, it requires significantly fewer parts, and can have a much smaller footprint as result of reduced vapor space [3]. Additionally, recent theoretical and computational work claims potential multistage DCMD configurations with efficiencies greater than that of other thermal technologies [5–7], assuming very large available heat exchanger areas. In practice, GOR values of practical state of the art MD systems with limited exchange areas are more modest [8]. Summers [9] has subsequently shown that multi-stage vacuum MD is thermodynamically identical to MSF, indicating that equivalent energy efficiencies can be achieved. The comparative simplicity makes MD more competitive for small-scale applications such as solar-driven systems for remote areas, especially in the developing world [3, 10–12]. However, significant advancements are needed in membrane technology for MD to reach the theoretical cost competitiveness and develop market share growth [13]. Fouling in MD is of particular importance, as fouling increases costs of energy consumption, downtime, cleaning, required membrane area, required membrane replacement, and creates problems with product water contamination from pore wetting [14,15].

Nomenclature

B	membrane distillation coefficient [kg/m^{2}s Pa]
$f()$	function of
h	heat transfer coefficient [W/m^{2}K]
h_{fg}	enthalpy of vaporization [J/kg]
J	mass flux [kg/m^{2}s]
k	mass transfer coefficient [m/s]
K_{sp}	solubility product constant
P	pressure [Pa]
$\dot{q}$	heat flux [W/m^2]
T	temperature [°C]
x	salinity [g/kg]
ρ	density [kg/m^3]
$(\cdot)_f$	feed
$(\cdot)_b$	bulk/free stream
$(\cdot)_m$	membrane
MED	Multi-Effect Distillation
MD	Membrane Distillation
MSF	Multi-Stage Flash Distillation
RO	Reverse Osmosis
SI	Saturation Index

The first patents on MD were granted in the late 1960s, but it wasn't technologically feasible until ultrafiltration membranes in the 1980s enabled sufficiently high trans-membrane fluxes [3]. Currently, most MD work is done in the laboratory, although a number of test beds across the world for small-scale solar thermal MD have already been deployed, and a few other projects exist [3,11,16].

While increased research interest in MD is relatively recent [17], scaling under high temperature conditions has been a key problem in systems with water heating since the advent of the steam engine. Research in the area, especially for metal heat exchangers, originated well before 1900 [18]. However, with respect to thermal efficiency, these studies mainly focus on conductive resistance due to scale formation, and often do not address the type of transport phenomena that are important in the context of fluid–membrane systems [18]. A somewhat more relevant area of scaling research is that for RO. However, RO membranes are not specifically hydrophobic, are virtually non-porous, are