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Fouling and its control in membrane distillation—A review

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ABSTRACT

Membrane distillation (MD) is an emerging thermally-driven technology that poses a lot of promise in desalination, and water and wastewater treatment. Developments in membrane design and the use of alternative energy sources have provided much improvement in the viability of MD for different applications. However, fouling of membranes is still one of the major issues that hounds the long-term stability performance of MD. Membrane fouling is the accumulation of unwanted materials on the surface or inside the pores of a membrane that results to a detrimental effect on the overall performance of MD. If not addressed appropriately, it could lead to membrane damage, early membrane replacement or even shutdown of operation. Similar with other membrane separation processes, fouling of MD is still an unresolved problem. Due to differences in membrane structure and design, and operational conditions, the fouling formation mechanism in MD may be different from those of pressure-driven membrane processes. In order to properly address the problem of fouling, there is a need to understand the fouling formation and mechanism happening specifically for MD. This review details the different foulants and fouling mechanisms in the MD process, their possible mitigation and control techniques, and characterization strategies that can be of help in understanding and minimizing the fouling problem.

Contents

Abbreviations: AFM, atomic force microscopy; APS, Accelerated precipitation softening; AGMD, air gap membrane distillation; BSA, bovine serum albumin; CA, contact angle; $CaCl_2$, calcium chloride; $CaCO_3$, calcium carbonate; $CaSO_4$, calcium sulfate; CFU, colony forming unit; CLSM, confocal laser scanning microscopy; COD, chemical oxygen demand; DCMD, direct contact membrane distillation; DLVO, Derjaguin–Landau–Verwey–Overbeek; EDS, energy dispersive X-ray spectroscopy; EPS, extracellular polymeric substances; $FeCl_3$, ferric chloride; FIFFF, flow field-flow fractionation; FTIR, Fourier-transform infrared spectroscopy; HA, humic acid; HCl, hydrochloric acid; HPSEC, high pressure size exclusion chromatography; LC-OCD, liquid chromatography-organic carbon detection; LEP, liquid entry pressure; LGMD, liquid gap membrane distillation; LSI, Langelier saturation index; MB, methylene blue; MD, membrane distillation; MDBR, membrane distillation bioreactor; MEF, multi-effect distillation; MEMD, multi-effect membrane distillation; MF, microfiltration; MGMD, material gap membrane distillation; MMBF, macromolecular or biofouling; MSF, multistage flash; MWT, magnetic water treatment; NaCl, sodium chloride; NaOH, sodium hydroxide; Na_2SO_4, sodium sulfate; NF, nanofiltration; NOM, natural organic matters; OMW, olive mill wastewater; PACl, poly-aluminum chloride; PAM, polypropylene acid ammonium; PP, polypropylene; PSD, pore size distribution; PTFE, polytetrafluoroethylene; PVDF, polyvinylidene fluoride; RCW, recirculating cooling water; RO, reverse osmosis; SEM, scanning electron microscopy; SGMD, sweeping gas membrane distillation; SI, saturation index; TCM, traditional Chinese medicine; TDS, total dissolved solids; TEM, transmission electron microscopy; TOC, total organic carbon; TPC, temperature polarization coefficient; UF, ultrafiltration; UTDR, ultrasonic time-domain reflectometry; VMD, vacuum membrane distillation; V-MEMD, vacuum multi-effect membrane distillation; XRD, X-ray diffraction

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1. Introduction

The shortage of fresh water is one of the biggest challenges in the modern era [1,2]. As water is a major need for survival, there is a necessity for new technologies to help provide fresh water supply [3]. Desalination is considered as one of the major key solutions that is sustainable and effective technology to the problem of fresh water scarcity [4,5]. As the population balloons to more than 7 billion people, demand for fresh water has been increasing steadily. In the Arabian Peninsula, the demand for fresh water is reported to increase at a rate of at least 3% annually [6]. Thus, environmental and safety regulations are becoming more stringent to ensure sustainable solutions, and more efforts have been focused on improving the current membrane-based desalination technologies such as RO. Among the promising techniques is by MD.

MD is one of the emerging desalination technologies for the production of fresh water. MD is a thermally-driven transport of water molecules (in vapor phase) through porous and hydrophobic membranes. One side of the porous membrane is a hot feed with high salinity and the other side is a cold permeate. The temperature gradient between the two sides creates a vapor pressure difference that drives the vapor to pass through the membrane and collected or condensed to pure water in the other side. MD has reduced sensitivity to concentration polarization, allowing it to operate even at high NaCl concentrations at the feed side [7]. MD has several advantages such as: (a) theoretically 100% salt rejection, (b) lower operating temperature than conventional distillation processes, (c) low energy consumption when waste heat or alternative energy source is used, (d) less requirements of membrane mechanical properties, and (e) lower operating pressure compared to conventional pressure-driven membrane processes such as RO [8–12]. MD can be employed for water desalination, removal of organic matters in drinking water production, treatment of water and wastewater, recovery of valuable components, and treatment of radioactive wastes [13–18]. However to date, MD has not found large-scale industrial application yet although a number of pilot systems have been carried out in recent years [19–28].

Like all other membrane processes, a major inefficiency of MD is fouling, which causes a decline in the membrane permeability due to the accumulation of deposits on the membrane surface and inside the membrane pores. Theoretically, MD has 100% salt rejection and only water vapor is allowed to pass through the pores of the membranes; however, several factors such as poor long term hydrophobicity of the material, membrane damage and degradation, very thin thickness of the membrane, and the presence of inorganic, colloidal and particulate matters, organic macromolecules and microorganisms in the feed water could lead to fouling deposition and pore wetting, which can lower the salt rejection and deter the MD performance [29]. For MD, the issue on fouling is still not well understood, but is believed to have lesser degree of propensity compared to those in pressure-driven membrane processes such as RO and NF. However, the fouling phenomenon is a time-dependent process, wherein its long-term effect cannot be easily predicted [30]. Several studies have indicated the negative effect of membrane fouling on the MD process.

A number of studies have investigated the effect of fouling on the overall MD process utilizing different types of membranes such as flat-sheet and hollow fibers, as well as using different modules [30]. However, from our review of the literature, we have not found any review paper dedicated mainly to fouling and scaling in MD. Though, a number of review articles have been published detailing the occurrences and control of fouling in RO, NF, and UF [31–34], the fouling mechanism and propensity are expected to be different in MD due to differences in membrane structure and operational conditions. As fouling is an important issue that should be addressed to enhance the efficiency of MD process, there is a need to understand its formation mechanism, and the different parameters that affect its propensity and possible mitigation or cleaning strategies. Thus, it is deemed necessary to provide an up-to-date review of the fouling propensity of MD membranes during the MD operation. This review includes a brief overview of MD and its fundamentals, a literature review of the different kinds of fouling mechanisms that can be found in MD processes, the possible fouling mitigation and cleaning methods to enhance the MD efficiency, and the use of advanced membrane fouling characterization methods.