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Studies in vacuum membrane distillation with flat membranes

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ABSTRACT

How microporous membrane characteristics affect membrane desalination performance in vacuum membrane distillation (VMD) is of significant interest. Different microporous hydrophobic flat membranes of polyvinylidene fluoride (PVDF) and expanded polytetrafluoroethylene (ePTFE) were investigated to that end. The ranges of variation of the membrane thickness and the nominal pore size were respectively 23–125 μm and 0.05–0.45 μm. The porosity of all membranes was high around 0.7–0.8. Experiments were performed with hot brine temperature varying between 65 °C and 85 °C for different vacuum levels and various brine feed flow rates in a rectangular chlorinated polyvinyl chloride (CPVC) cell. The liquid entry pressure (LEP) of each membrane was experimentally determined. Water vapor fluxes predicted as a function of brine flow rate and the vacuum level were compared using two models: the Knudsen diffusion and the dusty-gas model (DGM). Knudsen diffusion is the dominant transport regime in VMD since Knudsen number, K_n, for all membranes was larger than 1 at all temperatures. The brine-side boundary layer heat transfer resistance in the membrane cell and the brine-side membrane surface temperature were determined from experimental data via Wilson plot. The predicted values of the membrane mass transfer coefficient and water vapor fluxes were found to be close to those obtained experimentally.

1. Introduction

Membrane distillation (MD) is an evaporation process for a volatile solvent or solute species from a solution. Membrane distillation was first proposed by Bodell [1,2]. Findley [3] concluded that MD will be a "low cost, high temperature and long-life membranes with desirable characteristics" if this technology is fully developed. However, this was not achieved until the 1980s when membrane manufacturing techniques were advanced and the industry began to show interest in MD. In 1982, Gore [4] published details of Gore-Tex MD systems based on expanded PTFE (ePTFE) membranes. More and more studies have focused on MD wetting, fouling and flux performance after 1985 in various applications: desalination; concentration of dissolved ions, macromolecules, colloids and low concentration of organics; concentration of fruit juices, milk, and industrial waste water.

A major application of MD is desalination, because volatile solutes are minimal in saline water, and the permeate purity will be high. Compared to conventional desalination technologies such as reverse osmosis (RO) and multi-stage flash distillation (MSF), MD has a number of potential advantages such as low operating temperature and hydraulic pressure, very high rejection of non-volatile solutes, smaller footprint, and potentially high permeate flux. Therefore MD has been considered as an emerging technology for producing fresh water from brines.

In desalination based MD processes, hot brine is passed on one side of a porous hydrophobic membrane. Liquid penetration into membrane pores is prevented since surface tension of the liquid is higher than the critical surface tension of membrane polymer. Evaporation occurs when the thermal motion of water molecules overcome the liquid surface tension. Vapor-liquid equilibrium occurs at every pore entrance at the membrane surface. The vapor pressure of water at hot brine–membrane pore interface is much higher than that at the condenser surface; it results in pure water vapor diffusion from one side of the membrane to the other. The partial pressure difference of water vapor between the two sides of the membrane is the driving force for mass transfer. Higher brine temperature and/or brine side flow rates, results in higher evaporation rate, therefore, a higher driving force.

There are four types of condenser surfaces to recover pure water vapor, which defines four type of MD technologies: (a) In direct contact MD (DCMD), water vapor is in direct contact with a colder water; (b) in vacuum MD (VMD), water vapor is withdrawn by vacuum and condensed elsewhere; (c) in sweep gas MD (SGMD), water vapor is swept by inert gas; (d) in air gap MD (AGMD), water vapor is condensed on a cold surface separated by a thin air gap [5,6].

Extensive studies have been conducted in the past for various VMD

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Nomenclature

A_m	membrane area (m^2)
B_0	function of membrane properties
C_{pb}	heat capacity of brine (J/K g)
C_v	heat capacity of water vapor (J/K g)
d_M	membrane pore diameter (μm)
d_{max}	maximum membrane pore size (μm)
d_p	nominal membrane pore diameter (μm)
F	volumetric liquid flow rate (mL/min)
$H_v(T)$	enthalpy of water vapor (kJ/kg)
h	heat transfer coefficient (W/m^2 K)
h_m	membrane heat transfer coefficient (W/m^2 K)
h_0	overall heat transfer coefficient (W/m^2 K)
J	water vapor flux (kg/m^2 h)
K_n	Knudsen number
K_0	function of membrane properties
k_B	Boltzmann constant (J/K), 1.381×10^{-23} J/K
k_m	membrane mass transfer coefficient (kg/m^2 h Pa)
k_{mt}	thermal conductivity (W/m K)
M	molecular weight (kg/mol)
P_{BP}	bubble point pressure (Pa)
$P_{w,1}$	water vapor partial pressure on the feed side of the membrane surface (Pa)
P_v	vacuum pressure (Pa)
P_T	total pressure in the membrane pore (Pa)
P_m	mean partial pressure of water vapor on two sides of membrane
P_l^0	actual water vapor pressure
Q	rate of heat transfer (J/min)
q	heat flux (W/m^2)
q_m	heat flux through membrane (W/m^2)
q^t	total heat flux (W/m^2)
R	gas constant (J/mol K)
T	temperature (K)
T_{bi}	brine inlet temperature (K)
T_0	reference temperature (273.15 K, 0 °C)
T_1	membrane surface temperature on the feed side (K)
T_m	membrane mean surface temperature (K)
v	flow velocity (m/s)
x	length along membrane thickness
x_w	mole fraction of water on the membrane surface

Greek letters

γ	surface tension of liquid (N/m)
γ_w	activity coefficient of water on the membrane surface
δ_M	membrane thickness (m)
ε_M	membrane porosity
η	thermal efficiency
θ	contact angle between IPA and the membrane surface
μ	water vapor viscosity
λ_w	mean free path of water vapor (m)
λ_H	latent heat of water vapor (2260 kJ/kg)
ρ	liquid density (kg/m^3)
χ_M	membrane tortuosity

Subscripts

b	brine
f	feed
i	inlet
m	mean, membrane
o	outlet
s	polymer
t	total
v	water vapor

Superscripts

n	constant in Eq. (27)

applications: ethanol/water separation, removal of trace gases and VOCs from water, and often desalination. Compared to the three other types of MD technologies, heat loss due to conduction across the membrane is minimal in VMD; higher water vapor flux can be achieved if a sufficiently high vacuum level is supplied on the permeate side [7–12]. A major deficiency of current VMD literature is lack of guidance on the membrane properties and operating conditions for optimum performance of water vapor flux and energy consumption.

A variety of studies have investigated water vapor transport mechanism in MD using Knudsen flow model, viscous flow model, ordinary molecular diffusion model, and combinations thereof as well as the dusty-gas model (DGM) [13–15] and those by Schofield et al. [16,17]. The dusty-gas model is the most general model of gas transport in a porous medium. Although it is formulated based on kinetic theory of gases for isothermal conditions, the small temperature differences in VMD are not expected to pose a problem. Other models listed above describe gas/vapor transport under specific conditions. It will be useful to compare their predictions in VMD with those from DGM. However, major obstacles in modeling are encountered due to the complexity of the fluid mechanics of the boundary layers and unknown convective heat transfer coefficient. In a recently concluded DCMD study [18], we have successfully determined membrane surface temperatures using Wilson plot and predicted membranes mass transfer coefficient for a variety of membranes using existing models for membranes having a wide range of membrane properties (pore size, porosity, thickness and tortuosity). It would be useful to conduct a study of VMD using a variety of membranes having considerable variation in membrane properties such as, membrane pore size, membrane thickness, membrane material, etc.

In this study, eight different flat membranes of two different materials, PVDF and ePTFE, have been investigated. The membrane thickness range was: 23–125 μm; the pore size variation was from 0.05 μm to 0.45 μm. The range of porosity was: 0.7–0.8. Hot brine temperature was varied between 65 °C and 85 °C for different hot brine feed flow rates and vacuum levels in a rectangular chlorinated polyvinyl chloride (CPVC) cell. The boundary layer heat transfer coefficient of the hot brine was characterized via the Wilson plot method. Knudsen diffusion and DGM were employed to predict the membrane mass transfer coefficient and water vapor flux. The behavior of the observed water vapor flux was simulated as a function of the brine flow rate, brine temperature, vacuum level and membrane properties.

2. Modeling considerations

In VMD-based desalination (Fig. 1), a porous hydrophobic membrane serves as the barrier between hot brine and vacuum. Water vapor diffuses through the membrane pores when the partial pressure of water vapor over the brine is higher than the vacuum side pressure. Membrane porosity is generally high to provide enhanced membrane permeability of water vapor. Membrane pore size especially membrane maximum pore size, is a critical factor; it should be large enough to deliver high membrane permeability, but relatively small to prevent pore wetting by the brine. Liquid entry pressure (LEP) and bubble point experiments are two common methods to determine the relation

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