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The heat and mass transfer of vacuum membrane distillation: Effect of active layer morphology with and without support material

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ABSTRACT

The aim of this research was the analysis of heat and mass transfer in vacuum membrane distillation (VMD), specifically for a dead-end feed set-up. The influence of support material on the supported membranes VMD performance was identified. A mathematical model was proposed to evaluate the membrane/feed interface temperature, membrane tortuosity, membrane mass transfer coefficient, and temperature polarization coefficient (TPC). The model was solved by an excel solver based on experimental results of feed temperature, system pressure and the evaporative fluxes. The SEM images showed that the thickness of unsupported membrane was reduced by 42% after the VMD test. Pore shrinkage and tortuosity increase were also expected during this pore collapsing process. On the other hand, the cross-sectional views of the supported membranes did not show significant changes. These results show that the support material can help prevent the membrane pore channel structure from collapsing during the VMD experiment. TPC is close to unity at low feed temperatures. However, it decreases with an increase in evaporation flux as the feed temperature increases, or when a high flux supported membrane is applied.

1. Introduction

Vacuum membrane distillation (VMD) is a separation process for various aqueous solution treatments. The downstream of VMD is maintained under vacuum conditions, while vapor is thermally driven through a porous hydrophobic membrane. The applications of VMD can be grouped into three major processes based on the feed types, the single component transport process, the binary component transport process and the multicomponent transport process [1]. Evaporative cooling devices are one of the relatively new applications of VMD membranes [2–6]. It is primarily a single component transport process, in which only the water vapor evaporates and transports through the membrane, while the liquid water as the single component feed, is kept outside of the membrane pore due to its high membrane hydrophobicity. The cooling effect is achieved due to the latent heat of evaporation required for water to evaporate, while the membrane serves as the physical barrier between liquid water and the desiccant pad. The reported evaporative cooling devices mostly have a dead-end design [3,7,8] for the water distribution pads (feed chamber) instead of a continuous feed system for most of the common VMD aqueous solution separation applications [9–11]. Since vacuum membrane cooling has a different configuration from the traditional VMD setup, specific heat and mass transfer modeling needs to be performed on the dead-end setup for further design and optimization.

Practically, a supported membrane has enhanced mechanical strength over an unsupported membrane, which gives the supported membrane a higher durability and preference in the common VMD membrane applications. The desired support material needs to be highly porous, resistant to chemicals and pH variations, and durable. A common choice for membrane support is nonwoven fabrics made of polyester. Even though polyester supports have been widely used, and the effects of the support material on the membrane performance for VMD have been reported by a few researchers [12–18], there are no literature reports performing heat and mass transfer modeling on supported membranes to mathematically reveal the impacts of the support material.

The objective of this study is to investigate heat and mass transfer through a VMD supported membrane in a dead-end feed set-up for a single component (water) transport process in a temperature range of 23–35 °C. This temperature range was chosen based on the temperatures used in evaporative cooing devices. Membrane flux data are analyzed to reveal the effects of support materials on the performance of supported poly(vinylidene fluoride) (PVDF) membranes.

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Nomenclature

C_p	heat capacity of liquid water (J/kg K)
d_p	collision diameter of the transporting molecule (m)
ΔH_{evap}	heat of evaporation (43.99×10^6 J/kmol at 298.2 K) of water
h_f	heat transfer coefficient at the liquid boundary layer (W/m^2 K)
J_m	evaporation flux through the membrane
K	thermal conductivity of the fluid (W/m K)
k_B	Boltzmann constant (J/K)
K_m	membrane mass transfer coefficient (kg/m^2 s Pa)
K_n	Knudsen number
L_c	characteristic length (m)
M	molecular weight of water (18.02 kg/kmol)
P	average pressure within the membrane pore (Pa)
p_m, p_v	the partial water vapor pressure (Pa) at the membrane surface on the feed side and the permeate side
P_r	Prandtl number
Q	the total heat flux (W/m^2)
Q_m	heat flux through the membrane (W/m^2)
Q_f	heat flux through the feed boundary layer (W/m^2)
R	universal gas constant (8.314×10^3 J/kmol K)
r	pore radius (m)
T	absolute temperature (K)
T_f	temperature of the feed bulk (K)
T_m	temperature at membrane/feed boundary layer (K)
TPC	temperature polarization coefficient
N_u	Nusselt number
G_r	Grashof number

Greeks

λ	mean free path of the transported molecule
ε	membrane porosity
τ	pore tortuosity
δ	thickness (m)
μ	viscosity of water vapor (Pa s)
ρ	density of liquid water (kg/m^3)
β	volume thermal expansion of liquid water (1/K)

2. Mass transfer

In a VMD process, a feed solution, usually an aqueous solution, is brought into contact with one side of a micro-porous hydrophobic membrane while the vacuum is applied on the permeate side. The pore is filled with vapor since no liquid enters the pore due to the high hydrophobicity of the membrane material. Thus, the vapor is driven through the membrane pore by the difference in the partial pressure of the water vapor between two sides of the membrane. The transport process in VMD is divided into the following three steps: (1) transport from the feed bulk to the membrane surface (feed side); (2) transport through the membrane pores from the feed to the permeate side; (3) transport from the membrane surface (permeate side) to the condenser surface. Usually, the first and the third steps are ignored in the VMD of pure water [19,20], for the reasons that diffusion inside the pores of the vapor molecules at the feed/membrane interface is favored, and also that the mass transfer resistance is neglected on the permeate side due to vacuuming.

Thus, the VMD flux, J (kg/m^2 s), can be given in analogy to Fick's law [21] as:

$$J = J_m = K_m(p_m - p_v) \tag{1}$$

where J_m is the flux through the membrane, K_m (kg/m^2 s Pa) is the membrane mass transfer coefficient, and p_m and p_v are the partial water vapor pressure (Pa) at the membrane surface on the feed side and the permeate side, respectively. In VMD, p_v is maintained close to vacuum. p_m depends on the temperature, T_m (K), at the membrane surface (feed side) and can be given by the Antoine equation [22] as:

$$p_m(T_m) = exp\left(23.1964 - \frac{3816.44}{T_m - 46.13}\right) \tag{2}$$

Transport mechanisms for mass transfer across the membrane involve molecular diffusion, the Knudsen diffusion, and viscous flow, depending on the Knudsen number, K_n. In VMD, molecular diffusion is considered negligible since only a trace amount of air is present within the pores. Knudsen number (K_n) [23], is defined as the ratio of the mean free path, λ (m) of the transported molecule to the membrane characteristic length, also known as pore diameter, d (m), providing a guideline of which mechanism is active inside the membrane pore. The mean free path can be calculated by Eq. (3) [24].

$$\lambda = \frac{k_B T}{\sqrt{2}\pi p d_p^2} \tag{3}$$

where k_B (J/K), T (K) and p (Pa) are the Boltzmann constant, absolute temperature, and average pressure within the membrane pore, respectively, and d_p (m) is the collision diameter of the transporting molecule. In particular, T_m and $(p_m + p_v)/2$ can be used for T and p in VMD and this rule is maintained throughout this article, unless they are specified otherwise.

When $K_n > 10$ or $d < 0.1\lambda$, the mean free path of water molecules is large compared to the membrane pore size, which means the molecule-pore wall collisions are dominant over molecule–molecule collision [19,25–27]. This flow regime is known as Knudsen diffusion. When $K_n < 0.01$ or $d > 100\lambda$, the mean free path of the molecule is negligible compared to the pore size, the molecule–molecule collisions will dominate and a viscous flow exists in the membrane pores. The intermediate region in between $0.01 < K_n < 10$ is considered as the transition region. In the slip flow region, the no-slip boundary condition is no longer true, as a layer of about one mean free path thickness, known as the Knudsen layer, starts to become dominant between the bulk of the fluid and the wall surface. And within the transition flow region, both the Knudsen diffusion and viscous flow exist [28], as represented by Eq. (4).

$$K_m = K_{knudsen} + K_{viscous} \tag{4}$$

Furthermore, the following equations are known for $K_{Knudsen}$ and $K_{viscous}$ [19]:

$$K_{knudsen} = \frac{2}{3}\frac{r\varepsilon}{\tau\delta}\sqrt{\frac{8M}{\pi RT}} \tag{5}$$

$$K_{viscous} = \frac{r^2\varepsilon M p}{8\tau\delta\mu RT} \tag{6}$$

where ε (–), τ (–), r (m) and δ (m) are membrane porosity, pore tortuosity, pore radius and thickness, respectively. M (18.02 kg/kmol) is the molecular weight of water, μ (Pa s) is viscosity of water vapor, R (8.314×10^3 J/kmol K) is the universal gas constant.