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Performance assessment of membrane distillation for skim milk and whey processing

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ABSTRACT

Membrane distillation is an emerging membrane process based on evaporation of a volatile solvent. One of its often stated advantages is the low flux sensitivity toward concentration of the processed fluid, in contrast to reverse osmosis. In the present paper, we looked at 2 high-solids applications of the dairy industry: skim milk and whey. Performance was assessed under various hydrodynamic conditions to investigate the feasibility of fouling mitigation by changing the operating parameters and to compare performance to widespread membrane filtration processes. Whereas filtration processes are hydraulic pressure driven, membrane distillation uses vapor pressure from heat to drive separation and, therefore, operating parameters have a different bearing on the process. Experimental and calculated results identified factors influencing heat and mass transfer under various operating conditions using polytetrafluoroethylene flat-sheet membranes. Linear velocity was found to influence performance during skim milk processing but not during whey processing. Lower feed and higher permeate temperature was found to reduce fouling in the processing of both dairy solutions. Concentration of skim milk and whey by membrane distillation has potential, as it showed high rejection (>99%) of all dairy components and can operate using low electrical energy and pressures (<10 kPa). At higher cross-flow velocities (around 0.141 m/s), fluxes were comparable to those found with reverse osmosis, achieving a sustainable flux of approximately 12 kg/h·m^2 for skim milk of 20% dry matter concentration and approximately 20 kg/h·m^2 after 18 h of operation with whey at 20% dry matter concentration.

Key words: membrane distillation, milk concentration, whey concentration, membrane performance

INTRODUCTION

Membrane distillation (**MD**) is a new membrane process that is thermally driven and can use low-grade waste or solar heat and can be integrated into industry heat paths (Hausmann et al., 2012). A hydrophobic membrane ensures that only water in the vapor state can pass through the membrane driven by the vapor pressure gradient between feed and permeate side. Its ability to use waste heat is advantageous for concentration applications, especially considering that concentration and drying are the most energy-intensive operations in the dairy industry (Ramírez et al., 2006).

Preconcentration before powder production via spray drying is currently performed using reverse osmosis (**RO**) and evaporation. The use of MD is proposed to potentially improve the cost and primary energy efficiency of the process. Reverse osmosis has low specific energy requirements but the separation function requires electrical energy, whereas MD can use low-grade thermal energy (Hanemaaijer et al., 2006). Compared with evaporation, the ability of MD to operate at low temperatures can also be advantageous for heat-sensitive dairy components. Because only vapor crosses the membrane, MD is capable of producing high-purity water without being influenced by feed stream concentration. Reverse osmosis performance, on the other hand, is directly influenced by concentration in terms of flux as well as retention, whereas evaporation enthalpy is hardly influenced by concentration. However, the water produced by normal evaporation operations is often contaminated, as the vapor may carry small droplets of liquid that contain contaminants (Sääsk, 2009). Advantages of MD over evaporation include the ability to avoid this due to the membrane barrier, leading to high-quality product water. Also, the smaller vapor space indicates that MD can offer a much larger area for evaporation with a given footprint and the contained feed channel results in liquid velocities that can be sustained without surface instabilities (Nii et al., 2002).

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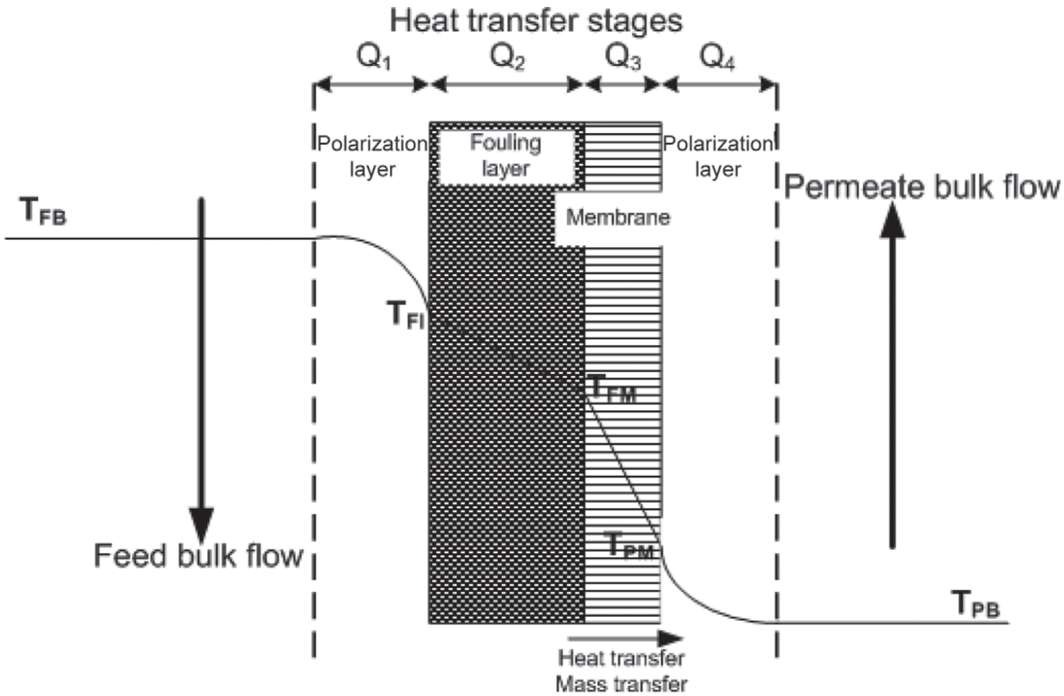

Figure 1. Temperature profile across the membrane in a typical direct-contact membrane distillation (DMCD) process. Q = heat transfer; T_{FB} = temperature of feed bulk; T_{Fl} = temperature of fouling layer; T_{FM} = temperature of feed membrane; T_{PM} = temperature of permeate membrane; T_{PB} = temperature of permeate bulk.

In MD, high flow velocities (shear) are used to improve the temperature profile along the membrane, and also to minimize temperature polarization (Zhang et al., 2010) and cake formation to achieve the best fluxes. However, the increased pressure associated with increased shear can exceed the liquid entry pressure, causing untreated liquid feed to pass through the membrane. This is more likely to occur at the module inlet as the pressure gradually decreases toward the outlet (Piry et al., 2008). Also, flow-induced wall shear stress can preferentially remove larger particles rather than small ones (Gryta, 2008; Ding et al., 2010), resulting in a denser filter cake. Whereas fouling adds an additional thermal resistance to the direct-contact membrane distillation (**DCMD**) process, the morphology of the fouling layer can also affect the mass transfer from the bulk to the membrane surface (e.g., in a dense gel layer, water needs to diffuse through the layer to reach the membrane surface), whereas a porous layer may not affect mass transfer.

Fouling models proposed in MD literature are used to calculate temperatures at the membrane surface (Gryta and Tomaszewska, 1998; Srisurichan et al., 2006; Martínez and Rodríguez-Maroto, 2008). Figure 1 shows a schematic of the DCMD separation function, including the temperature distribution across the membrane. This model allows calculation of membrane and fouling resistances and changes to these during MD processing at constant operating parameters over time. Also, heat transfer efficiency can be quantitatively estimated and analyzed.

At steady state, the heat energy difference from inlet to outlet of the module equals the heat energy transferred across the boundary layers, fouling layer, and membrane:

$$\Delta Q = \dot{m}C_f\left(T_{FB,in} - T_{FB,out}\right) = h_{FP}\left(T_{FB} - T_{Fl}\right) = h_{Fl}\left(T_{Fl} - T_{FM}\right)$$
$$= JH_{latent} + h_M\left(T_{FM} - T_{PM}\right) = h_{PP}(T_{PM} - T_{PB}), \quad [1]$$

where ΔQ = heat transfer, $\dot{m}$ = mass flow, C_f = specific heat of water on the feed side of the membrane, T_{FB} = temperature of feed bulk, T_{Fl} = temperature of fouling layer, T_{FM} = temperature of feed membrane, T_{PM} = temperature of permeate membrane, T_{PB} = temperature of permeate bulk, h_{FP} = heat transfer coefficient of the feed side polarization layer, h_{Fl} = heat transfer coefficient of the fouling layer, h_M = heat transfer coefficient of the membrane, h_{PP} = heat transfer coefficient of the temperature polarization layer on the permeate side, J = flux through the membrane, and H_{latent} = latent heat of evaporation. From the heat balance in Equation 1, T_{Fl}, T_{FM}, T_{PM} can be estimated.