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Review

Two-phase flow in membrane processes: A technology with a future

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ABSTRACT

Worldwide, the application of a (gas/liquid) two-phase flow in membrane processes has received ample scientific deliberation because of its potential to reduce concentration polarization and membrane fouling, and therefore enhance membrane flux. Gas/liquid flows are now used to promote turbulence and instabilities inside membrane modules in various membrane processes such as microfiltration, ultrafiltration, nanofiltration, reverse osmosis, membrane distillation, electrodialysis, and membrane bioreactors. This paper provides a comprehensive and critical literature review of the state of the art in this research area. A total of 205 scientific papers published in peer-reviewed journals from 1989 to 2013 were collected. The data in 195 of these papers (published up to 2011) were compiled and analyzed. These data were analyzed and normalized based on gas and liquid superficial velocities, gas/liquid ratio and feed types, trans-membrane pressure and membrane module type in order to make a fair comparison and identify general characteristics. The objective was to identify key factors in the application of two-phase flows in aqueous separation and purification processes, deliver new insights in how to optimize operations for implementation of this technology in the industry, discuss the importance of energy saving, provide a brief overview of current commercial applications and suggest future directions for research.

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1. Introduction

Demands for sufficient clean water are foreseen to increase rapidly in the coming decades. Membrane technology provides robust solutions in the purification and treatment of groundwater, wastewater and saline water, such as required for environmental reasons and in agriculture [1]. Overarching impacts for maintaining clean water are securing drinking water, food, energy and industrial productions [2].

Membrane processes in aqueous applications can be grouped according to the applied driving forces: (1) pressure-driven processes, namely micro-, ultra-, and nanofiltration as well as reverse osmosis, (2) concentration-driven processes, namely dialysis and forward osmosis, (3) processes driven by an electrical potential, *i.e.* electrodialysis, (4) processes driven by partial pressure and vapor pressure, namely pervaporation and membrane distillation, and finally (5) processes driven by differences in chemical potential, *e.g.* supported liquid membranes, membrane contactors, and membrane reactors. The mechanism of transport through a membrane can also be very different. For example for porous membranes, solvent transport through the membrane pores occurs under a hydrostatic pressure difference between two phases; the solutes that are larger than the pores are rejected (sieving mechanism). Typical solute sizes in the feed mixtures handled by pressure-driven membrane processes are $0.01-0.001\ \mu m$ for nanofiltration, $0.2-0.005\ \mu m$ for ultrafiltration and $10-0.1\ \mu m$ for microfiltration. In dense membranes, separation of various components in a mixture is determined by their diffusivity and solubility in the membrane matrix as caused by pressure, concentration or chemical potential gradients. If the membrane has electrical charges, separation is achieved mainly by exclusion of ions of the same charge as the fixed ions of the membrane structure [3]. Table 1 summarizes common membrane processes in aqueous applications with regard to membrane type, driving force, transport mechanism and areas of application.

Membrane processes in aqueous applications, especially those in pressure-driven processes, suffer from solute buildup on the membrane wall (*i.e.* concentration polarization) and membrane fouling [5]. Concentration polarization is the development of a concentration gradient across the boundary layer near the membrane surface [6]. The concentration gradient occurs due to a difference in mass transport between bulk solution and membrane. In pressure-driven membrane processes, a concentration profile develops because of the accumulation of mass at the membrane wall, as the mass transport through the membrane is slower than in the bulk. In other membrane processes in which transport across the membrane occurs by diffusion rather than by convection, *e.g.* pervaporation or dialysis, a concentration profile develops because of a decrease of mass at the membrane wall because transport through the membrane is faster than in the bulk [7]. Another critical issue of membrane processes in aqueous applications is membrane fouling, which can be distinguished into inorganic, particulate, microbial and organic fouling [8–10]. Fouling causes deposits on the membrane surface or blocks the pores, thereby limiting permeation. Fouling results in an increasing pressure drop over the membrane and an uneven flow distribution over the total membrane surface; this leads to increased energy consumption, lower production and therefore higher operating costs. Fouling also requires the use of chemicals to clean the membrane, which in turn deteriorates the membrane and lowers its lifetime. To overcome this problem, a great deal of research in membrane process technology took place, next to progress in developments in membrane material and membrane surface modifications, *e.g.* tangential-flow instead of dead-end filtration [11,12], operation below critical flux [13], promotion of instabilities in the flow by using a secondary flow or turbulence promoters [14–16], dynamic filtration by moving parts or by vibrations [17] and inducing multiphase flow inside membrane elements. The term multiphase is used to refer to any fluid consisting of two or more phases, *i.e.* solid, liquid, and gas, moving together in a conduit [18]. In membrane processes, gas–liquid two-phase flow [19] and gas–liquid–solid three-phase flow are used to enhance flux and rejection. However, the use of solid (ion-exchange resin) particles in three-phase flow is likely to encourage clogging of