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Editorial overview: Separation engineering: Recent advances in separation science and technology

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Kang Li is Professor of Chemical Engineering at Imperial College London. His present research interests are in preparation and characterization of polymeric and inorganic hollow fiber membranes, membranes for fluid separation, membrane catalysis, multi-functional membranes and membrane reactors for energy application and CO_2 capture.

Separation processes have been one of the most important unit operations in Chemical Engineering and have played a key role in chemical and energy industries. In spite of the mature separation processes such as distillation, extraction, crystallizations, and absorption, other relatively new and advanced separation processes related to membranes and adsorption have been extensively studied, which is clearly reflected in this issue of Current Opinion in Chemical Engineering where four of the six invited review articles are related to membrane and adsorption separations and characteristics. This themed issue consists of review articles covering topics in recent advances in electrospun nanofiber membranes for microfiltration, ultrafiltration, nanofiltration, reverse osmosis, membrane distillation and adsorption, graphene oxide membranes in fluid separations, adsorption in amine-functionalized sorbents for CO_2 capture, anion-exchange membranes for fuel cells, Bruggeman correlation for analyzing transport phenomena in electrochemical systems, and uphill diffusion in fluid mixtures, electrolytes, alloys, glasses, and porous adsorbents.

Membranes have provided many applications including gas separations, pervaporation, dialysis, electrodialysis, reverse osmosis, ultrafiltration, microfiltration, liquid membrane separations, and membrane contactors [1]. Recently, new membranes such as electrospun nanofiber membranes and graphene oxide membranes have found their applications not only in the above-mentioned areas, but also in membrane adsorption. Adsorption in amine-functionalized sorbents has attracted interest for CO_2 capture from flue gas in coal-fired power plants and from ambient air. Also, new anion-exchange membranes for fuel cell applications have emerged.

Wang and Hsiao have reviewed the recent advances in electrospun nanofiber membranes for microfiltration, ultrafiltration, nanofiltration, reverse osmosis, and membrane distillation and adsorption, especially for water treatment and purification. Their review highlights the fabrication and applications of electrospun nanofiber membranes, recent advances in nanofiber-based membranes for water purification, and recent development of nanofibrous affinity membranes for adsorption. Regarding fabrication, nanoporous electrospun fibers could be obtained when electrospinning was carried out under elevated humidity [2]. The effect of humidity on the fiber structure was strongly coupled to other processing parameters, resulting in different morphology of the nanofibers on their surface and inner structures, including porous, beaded, branched, tubular and zonal structures [3–5]. For fabrication scale-up, one can use an array of syringes as spinnerets or an array of spinnerets connected on a multi-hole distribution plate, and the polymer solution used may be distributed to the multiple spinnerets using a programmable syringe pump to maintain the minimum pressure drop [6–10].

As pointed out by Wang and Hsiao for water purification, electrospun nanofiber membranes can overcome the low flux and high-fouling tendency limitations associated inherently with the conventional porous membranes fabricated through the phase-inversion technique. This is because the nanofiber membranes have relatively high porosity (about 80%), fully interconnected open pore structures and controllable pore sizes from microns to sub-microns, thus providing high permeability for water transport. A nanofiber membrane can show 3–7 times higher pure water flux than a conventional membrane [11]. Nanofiber microfiltration membranes consisting of a combined super-hydrophobic layer and super-hydrophilic electrospun nanofibrous scaffold structure have been designed and demonstrated for oil and water separation [12–14] and for treating and separating water-in-oil [15] and oil-in-water [16,17] micro-emulsions.

Wang and Hsiao have also indicated that several research groups have investigated various PVDF nanofiber membranes for membrane distillation (MD), including systematic studies of the effects of polymer composition, electrospinning parameters, heat-press post-treatment and membrane thickness on direct-contact MD performance [18,19]. Also investigated for MD have been electrospun superhydrophobic nanofiber membranes, such as aromatic fluorinated polyoxadiazoles and polytriazoles, PTFE and dual-biomimetic PS micro/nanofibrous membranes. All of these membranes have shown superior performance in the purification of NaCl feed solutions over conventional MD membranes. Therefore, electrospun nanofiber membranes with super-hydrophobic properties and suitable pore sizes are ideally suited for MD applications.

In this review by Wang and Hsiao, thin-film nanofibrous composite (TFNC) membranes offer unique properties of high porosity and interconnected porous structures. These unique characteristics enable TFNC membranes to have higher permeability (or low energy consumption) than conventional thin-film-composite (TFC) membranes. TFNC membranes have shown great potential for efficient removal of oil emulsions in water from produced water, which has been generated in a very large amount in large-scale oil and gas productions. The TFNC membrane consists of a 'non-porous' hydrophilic top barrier layer (to improve the hydrophobic fouling tendency), a mid-layer electrospun nanofibrous scaffold, and a conventional non-woven micro-fibrous support. For example, the barrier layer may be made of ultra-fine cellulose nanofibers (~5 nm in diameter) or a cross-linked PVA barrier layer derived from a top PVA electrospun layer subsequently swollen or melted using solvent (e.g., water) or solvent vapor to form the barrier layer without the fibrous structure on an electrospun PAN support layer.

Wang and Hsiao have in addition pointed out that TFNC membranes have great potential as well for nanofiltration, reverse osmosis, and pervaporation. In particular, higher flux may result from the replacement of the conventional flux-limited porous substrate with a higher flux electrospun nanofibrous scaffold. For nanofiltration, initial results from the barrier layers of polyamides produced from the interfacial polymerization have shown about two times higher permeation flux than that of the commercial conventional membranes with comparable salt rejections. Initial results for pervaporation using a TFNC membrane system, consisting of a cross-linked PVA hydrophilic barrier layer, a cellulose nanofibrous buffer layer, an electrospinning nanofibrous support layer with high porosity and fully interconnected pore structure, and a PET non-woven substrate, have shown significantly higher fluxes than any commercial pervaporation membranes. Recently, desalination using TFNC membranes by the pervaporation process has also been demonstrated.

On affinity membranes, which require ligand molecules to be introduced into their interior surfaces to capture targeted molecules, the structural characteristics of electrospun nanofiber membranes are ideally suited for this purpose. Wang and Hsiao have reviewed surface functionalized electrospun nanofiber membranes for effective heavy metal adsorption, organic waste adsorption and ion-exchange media. On heavy metal adsorption, the electrospun chitosan (with amino groups) nanofiber membranes have exhibited high equilibrium adsorption capacities for Cu(II), which were about six and 11 times higher than the reported highest values of chitosan microspheres and neat chitosan, respectively, as well as for Pb(II). Chitosan-containing composite nanofiber membranes showed high adsorption capacities for lead, cobalt and nickel ions. Various functional groups, such as carboxylate, sulfonate, amino, thiol, and special ligands, have been immobilized on the nanofiber surface to enable the adsorption capability for different heavy metal ions including Cr(III) and Cu(II).

Wang and Hsiao have also reviewed electrospun nanofiber affinity membranes for organic waste adsorption. Polystyrene is a hydrophobic-oleophilic material and has been widely used in electrospinning of nanofibrous oil absorbent. Its absorption capacities for motor oil and sunflower seed oil were nearly three times larger than those of commercial PP non-woven fabrics. In order to improve the mechanical properties of the membranes, electrospun nanofibers made of polystyrene and polyurethane blends or polystyrene and polyvinyl chloride blends were investigated extensively. All of these membranes showed excellent oil sorption capacities. The nanofiber affinity membranes