Synthetic Membranes: Basic Principles and Challenges of Large-Scale Production

Chinedum Osuji
Department of Chemical and Environmental Engineering, Yale University

The development of membrane science as a well-recognized and industrially relevant field is relatively recent, having largely occurred over the past 50-60 years. This development was significantly enabled by the seminal discovery by Loeb and Sourirajan in the early 1960s of a method for producing high flux, defect-free membranes that set reverse osmosis (RO) on the path to becoming an industrially viable process. The Loeb-Sourirajan method provided the means to generate anisotropic membranes which featured a very thin but dense skin layer on one side, and a microporous open structure on the other. The dense skin layer was permselective and provided the ability to separate salt from water, while the porous structure allowed high flux. RO was significantly advanced by the later contribution of John Cadotte who developed thin film composite membranes based on interfacial polymerization of a permselective polyamide layer. This technology is in wide use today and represents the state of the art of RO desalination, with an estimated 15,000-20,000 desalination plants worldwide producing 20,000 m^3 per day of treated water from various sources. The non-solvent induced phase inversion process that Loeb and Sourirajan used to develop their RO membranes is still used, in various forms, for the fabrication of the vast majority of commercial microfiltration and ultrafiltration membranes.

The persistence of early forms of membrane technology in many industrial sectors today highlights the difficulties associated with successfully navigating the path from promising lab findings to large scale deployment of new technologies. There have certainly been advancements in polymer chemistry that have provided new materials for membrane science, and an opening up of applications in the medical field. Nevertheless the principal drawbacks associated with permselective desalination in thin-film composite membranes, and with size-selective sieving in membranes produced by phase inversion remain with us, and these must be overcome to advance the field. In the first case, the permeability and selectivity of the membrane are intrinsically linked such that increasing the water permeability of the membrane results in a degradation of the water quality due to a decrease in selectivity and therefore increased permeation of salt. In the second case, the non-equilibrium or kinetic nature of the phase inversion process results in a distribution of pore sizes that is inherently broad. Such broad pore size distributions yield selectivities that vary only slowly as a function of molecular-weight or size, whereas one would rather have highly selective membranes, i.e. those which exhibit a very sharp transition from retention to permeation as a function of molecular weight or size.

At the same time as we are faced with bottlenecks in traditional membrane technology, there are clear and present needs for new approaches to address a number of critical areas. These include (1) energy generation and storage, where membranes for fuel cells and batteries are critical components in the performance of the devices and where the realization of energy generation by pressure retarded osmosis specifically requires the development of new membranes; (2) water purification which represents a grand engineering challenge for today's scientists, particularly the remediation of produced waters in the oil and gas industry; (3) drug delivery where the need to provide controlled linear release of actives rather than burst release depends on development of new membrane technology. In this talk I will review traditional approaches for membrane fabrication and briefly highlight canonical examples of successful large scale deployments of membrane technology. I will survey emerging membrane technologies which hold promise for successfully addressing the critical areas outlined above and discuss the challenges associated with large scale production of such membranes.