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By

Sergey P. Agashichev

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PREFACE

Membrane processes, being of low energy consumption and environmentally friendly, have become a competitive alternative: for processing aggressive fluids at elevated temperatures; for the recovery and purification of pharmaceuticals; for the separation of metabolites in bioreactor systems; for water treatment and desalination in different hybrid schemes; and for other similar purposes. These examples indicate diversification in the spectrum of membrane-based applications. But such applications are often hampered by the existing level of modeling and analysis. Examination of published data indicates growing interest in the development of new methods of design and analysis. These examples require more comprehensive modeling focused on the development of methods of process analysis. A similar approach was demonstrated in the previous study: *Sergey P. Agashichev, Pressure Driven Membrane Processes (Modeling and Analysis), Nova Science Publishers, Inc., NY, 2012* [1]. Since this topic represents one of the most unresolved and debated themes in membrane technology, this book focuses on the processes associated with phenomena such as shear-dependent diffusivity, gel-enhanced concentration polarization, non-Newtonian behavior, conjugated concentration polarization, and so forth. These phenomena are considered in the current study and they have to be incorporated into the process model. The material submitted in this book is based on the latest publications [2–7]. This study focuses on the models for process calculation but not for membrane materials or membrane elements themselves.

Membrane processes, while being interpreted as a group of unit operations, can, in turn, be represented as a combination of individual transport mechanisms and physical phenomena in phases. Physical behavior and transport phenomena in phases can then also be quantified using individual mathematical sub-models. The sub-model, in turn, represents the groups of mathematical equations describing the physical mechanisms and the transport in phases. Chapter 2 covers physical behavior, simplifying assumptions, transport mechanisms, and individual sub-models for particular cases. The chapter contains a group of models which are characterized by physical behavior and transport mechanisms in phases. They are: [A] the model in which concentration polarization takes place along with the gel accumulation; [B] the model in which concentration polarization occurs without gel accumulation; [C] the model in which gel polarization occurs without back diffusion; [D] the mono-component model with shear-induced concentration polarization; and [E] the mono-component model with enhancement of the concentration polarization due to hindered diffusion within the gel accumulated at the membrane surface. The model in which the conjugated behavior of boric acid, deprotonated borate, and monovalent cations takes place will also be considered in Chapter 2.

Particular attention has been paid to the application of a hierarchical or systemic approach to model development. Assume that an object can be represented as a set of submodels of different hierarchy levels. They can be subdivided into certain groups conditionally corresponding to their hierarchy level. The first group includes input mathematical formulations based on underlying models of physical behavior. The next group covers modeling at arbitrary transverse cross section (models in terms of the transverse Z-variable). The last group covers the longitudinal modeling (models in terms of longitudinal X-variable). Application of this approach allows the synthesis of flexible algorithms according to the physical behavior of the object.

The group of sub-models considered in Chapter 3 includes mathematical formulations for velocity, temperature, shear rate, and so forth. Chapter 4 focuses on the concentration polarization at the transverse section (in terms of the transverse Z-variable) implying different physical behavior and transport mechanisms. Section 4.1 considers a model for the concentration profile based on the mechanism of shear-induced back migration where the concentration polarization depends on the particle size distribution, since any dispersed fraction is characterized by its specific concentration distribution (in terms of transverse Z-variable). The proposed model has the following possible implications: (A) it can be used for quantitative estimation of the probability of fouling caused by different fractions at existing hydrodynamic conditions; (B) it allows analysis of the impact of hydrodynamic conditions (such as shear stress and transverse velocity) on the probability of fouling caused by certain dispersed fractions; (C) it allows estimation of the threshold value of the shear rate being specific for the certain fraction that should be exceeded in order to prevent accumulation of this fraction; (D) it permits analysis of the influence of the shear rate at the surface of the membrane on the transverse concentration distribution; and (E) it can be used for quantitative analysis of the CP distribution of individual fractions while considering poly-disperse systems as soon as any fraction is characterized by its individual migrating behavior.

Section 4.2 encompasses the case in which the conjugated behavior of boric acid, deprotonated borate, and monovalent cations takes place. A model for the analysis of concentration polarization and the degree of rejection of boric acid, borate anions, and monovalent cations is presented in the model. It is based on the physical assumptions implying that boron exists in the form of boric acid and deprotonated borate ions. It is shown that the conjugated behavior of boric acid, deprotonated borate, and monovalent cations takes place. It is demonstrated that the growth of pH is accompanied by the decrease of boric acid along with the increase of borate ions and monovalent cations at the membrane surface and in the permeate. The model was applied for analysis of pilot data on low-pressure RO at the stage of post-treatment, that is, after RO desalination. The calculations based on this model match the experimental data.

One of the central themes the chapter deals with is the modeling and analysis of so-called gel-enhanced concentration polarization, implying the deformation of the concentration profile due to hindered diffusion within the gel or fouling layer. Distribution of chemical potential and concentration polarization enhanced by gel accumulated on the membrane surface is considered in Section 4.3. It provides a distribution of the chemical potential and concentration in the liquid phase and within the gel layer. The model allows the analysis of the influence of the thickness of the fouling gel layer on the CP degree, surface concentration, and chemical potential. The following conclusions have been drawn: (A) diffusion resistance within the gel layer becomes dominant and cannot be ignored; (B) in the presence of a gel layer the concentration of the membrane surface is enhanced due to the hindered back diffusion of salt ions that, in turn, results in the growth of osmotic pressure and chemical potential at the membrane surface. It provides an elevated salt concentration in the permeate and decreases the net driving force; and (C) analysis of the calculated data indicates the high sensitivity of the CP degree to the coefficient of hindered back diffusion within the gel layer.

Section 4.4 presents a model analyzing an impact of temperature and degree of membrane rejection on the degree of concentration polarization. This model can be used for the interpretation of laboratory-scale and pilot data at different observed values of the degree of membrane rejection. The model also allows the analysis of the influence of the temperature on the concentration profile. For membranes with a high degree of rejection one can observe the growth of surface concentration and CP degree with an increase in temperature. This is essential for the analysis of RO at elevated temperatures within the hybrid RO/MSF schemes. The model has no digital integration and can be easily built into optimization procedures. The sub-models proposed in Chapter 4 can be incorporated into an algorithm for the analysis of the membrane process in which all the process variables (such as CP degree, observed degree of rejection, resistance, trans-membrane flux, etc.) are dependent on the longitudinal X-coordinate.

Chapter 5 focuses on the modeling of the process characteristics along the membrane surface (in terms of the longitudinal X-variable). This chapter includes longitudinal sub-models for mass and energy balance. The distribution of concentration- and temperature-polarization, and the structure of the transport integral are considered. The longitudinal sub-models can be recommended for analysis of pressure-driven processes at non-isothermal conditions and thermo-driven processes (such as trans-membrane distillation) where the driving force can be expressed as a temperature difference. These sub-models can be recommended for cases in which conjugated heat and mass transfer across the membrane takes place, and for cases in which the surface values of temperature and concentration are interrelated.

Developed mathematical solutions can be used as the mathematical background of algorithms in different applications. Proposed models and techniques can be used: for the development of the procedure for engineering calculation; for the process alteration and modification; for development of optimal operating regimes; and as a tool for analysis of the data from experimental and pilot systems. In particular these aspects are essential for the design and analysis of hybrid seawater desalination schemes at elevated temperatures. The material in this book represents an updated synthesis of recently published papers and some material from a DSc dissertation submitted by the author at D. Mendeleev University of Chemical Technology in Moscow. This material can be recommended for engineers and experts specializing in the modeling and analysis of pressure-driven membrane processes. The reader is expected to have a basic knowledge of mass transfer and applied hydraulics. The material may be of interest to graduate and undergraduate students and it may also be recommended as a supplement to textbooks.

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CHAPTER 1

MEMBRANE SCIENCE AND TECHNOLOGY: RECENT TRENDS IN ACADEMIC RESEARCH, TECHNOLOGICAL DEVELOPMENT, AND COMMERCIAL APPLICATIONS

Membrane processes driven by a pressure difference are referred to as "pressure-driven membrane processes." This group includes reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) [8]. Due to their low energy consumption and environmental attractiveness these processes have a wide scope of potential applications in biotechnology, medicine, desalination, oil processing, and many others areas. Various aspects of these processes have been studied in detail [9–13]. In addition, it is worth mentioning that integration and the hybridization of membrane processes with conventional processes increases technological flexibility and removes physical limitations inherent in conventional processes [14]. Along with conventional applications for seawater desalination and water reuse, they provide sustainable solutions for the development of cleaner production, the rational use of energy, a decrease in "carbon footprints," and hybridization with conventional processes. In addition, they represent an efficient tool in integrated water resource management.

MEMBRANE TECHNOLOGY IN THE DEVELOPMENT OF CLEANER PRODUCTION

The implementation of the cleaner production concept and a reorientation toward environmentally friendly processes are becoming a new focus of contemporary technological policy. Membrane processes, being low consumers of reagents and environmentally friendly, are an effective tool for the implementation of cleaner production and a strategic reorientation toward less polluting processes [10]. Membrane processes are an indispensable part of disposal and recycling technology. Recent achievements in material sciences, nanotechnology, and process engineering have unlocked a new domain in potential applications of membrane processes.

MEMBRANE TECHNOLOGY AS A RELIABLE TOOL FOR INCREASING ENERGY EFFICIENCY AND DECREASING "CARBON FOOTPRINTS"

Environmental documents and guidelines, namely the Kyoto Protocol, the treaties of Maastricht and Amsterdam, and the Rio and Oslo Accords [15], have laid the foundations of environmentally sound technological policy that, in turn, enhances the commercial potential and the rate of proliferation of environmentally sound processes in the world of technology. In this regard, membrane technologies play an important role in the optimization of processes and the rational use of energy, for example, by substituting less energy consuming membrane alternatives or combining with conventional processes. Hybridization of reverse osmosis with existing thermal desalination will decrease "carbon footprints" in terms of specific CO_2 emissions per cubic meter of desalinated water.

HYBRIDIZATION AND INTEGRATION OF MEMBRANE PROCESSES WITH CONVENTIONAL PROCESSES AND TECHNOLOGIES

The concept of the hybridization of conventional technologies with membrane processes has been studied extensively [16–17]. It has been shown how integrated processes can enhance flexibility and overcome the limitations and disadvantages inherent in conventional processes, such as vulnerability to fouling factors, elevated osmotic pressure, and high energy consumption [18]. We have witnessed an evolution from a pure theoretical concept to a diversified spectrum of different technological combinations with various levels of integration [19–23]. Suk and Matsuura [24] considered different categories of membrane-based hybrid processes for different applications. Analysis of published data indicates a growth of interest in membrane-based hybrids in biotechnology, in waste water treatment and reuse, and in seawater desalination, among others.

There are different configurations of the hybrids such as membrane/conventional hybrids and membrane/membrane hybrids. Particular attention has been given to UF-, MF-, NF-, and MBR-included hybrids. Membrane-based pretreatment before reverse osmosis desalination was considered in [25]. The analysis done in [26] showed that UF-, MF-, and NF-based pretreatment processes are characterized by low energy consumption and, therefore, expand the areas of potential application of membrane desalination. Matsuura [27] highlighted four main critical areas in R&D related to membranes and membrane processes: membrane development; membrane characterization; intensification of the membrane transport; and membrane system design.

Another example is the integrated processes, including the stages of biological treatment and separation within a single unit that represents the membrane bioreactor (MBR). This innovative process is considered in [28–32]. Analysis of the trends and perspectives of the European MBR market reveals that between 10% and 15% of the annual value of the EU MBR market was invested in R&D [31]. Annual market growth is expected to be 10%. Analysis of membrane bioreactor technology in North America was conducted in [32], where the main trends in academic research, technological development, and commercial applications were considered.

Analysis of published data reveals that particular attention has been given to hybridization of thermally and electrically driven desalination [16, 24]. Conventional technologies, referred to as co-generative technologies, are based on integration of the power plant with thermal desalination systems such as multi-stage flush (MSF) or multi-effect distillation (MED). Existing types of co-generative technologies are characterized by inflexible limits of power-to-water production and cannot, therefore, keep up with changes in the patterns of demand for power and water in many regions (e.g., the Middle East). In addition, they are characterized by certain technological and environmental disadvantages such as high energy consumption and elevated greenhouse gas emissions [18]. Implementation of a policy of emissions trading and reconfiguration of the system of eco-taxation has enhanced the shift toward more sustainable technological options. Hybridization of thermally and electrically driven desalination processes is an example of a new generation of co-generative technology. There is now significant development of integrated or hybrid schemes, driven by these factors and using membrane-based operations such as NF, UF, and MF. There are different levels and types of hybridization, for example: (A) incorporation of reverse osmosis (RO) into existing co-generative schemes; (B) application of membrane-based operations such as NF, UF, and MF as a pretreatment before RO; (C) implementation of low-pressure RO as a post-treatment for boron elimination; and (D) NF softening before MSF. There is a wide spectrum of technological combinations from using common intakes for MSF-RO; applying NF pretreatment for MSF; and using membrane-based pretreatment for RO to mutual coordination of technological regimes between power generation and desalination plants. The term “hybrid” used in published literature has rather wide and sometimes contradictory connotations; it covers cases from just using a common intake and blending permeate with distillate all the way to complete integration of existing co-generative plants with RO and ASR. Different aspects of analysis of integrated systems, such as accounting for CO_2 emissions, were considered in [21–23]. Hybridization can provide essential economic, environmental, and operational advantages over conventional dual and mono-purpose stand-alone plants. These advantages are, in particular: (1) increased technological flexibility that is characterized by the ability to diversify the range of the power-to-water ratio; (2) the possibility to use seasonal surpluses of idle power and unused water; (3) the decrease of specific fuel consumption given that RO consumes less energy than thermal desalination; (4) the growth in the use of installed capital and the decreases in capital recovery costs per unit of production; (5) the decrease of “carbon footprints” in terms of specific CO_2 emissions; and finally (6) the decrease in the “levelized” cost of the water produced. In addition, it will decrease the technology’s sensitivity and commercial risk to fluctuations in, for example, nominal interest rates, the cost of primary fuel, and the rate of carbon tax [18]. Special attention has been given in [33–

37] to the applications of membrane-based operations for the development of sustainable desalination.

MEMBRANE PROCESSES IN BIOTECHNOLOGY, IN MEDICINE, AND IN THE PHARMACEUTICAL AND FOOD INDUSTRIES.

Technologies based on bioprocessing are characterized by multicomponent feed streams with different physico-chemical properties and functional behaviors. They contain components in different forms such as dissolved, colloidal, emulsified, and suspended. Bioprocessing streams may include cells, cell fragments, cell debris, viruses, ribonucleic acids, aggregates of colloids, protein aggregates, protein mixtures, and so on. Dairy feeds may contain fat globules, casein micelles, and lactose. Natural waters may contain humic substances, polysaccharides, lignin, inorganic oxides, silicates, and so forth. Membrane processes have been used in biotechnology since a long time before membrane technology itself was established [38]. Nowadays, the shifts from the processes of chemical synthesis to biomanufacturing (biotechnology production) can be seen in the pharmaceutical industry [39]. The role of membrane-based processes (such as UF and MF) in biotechnology for purification, sterile filtration, clarification, virus removal, protein concentration, buffer exchange, and protein purification has been examined in [40]. MF can be used to retain cells and cell debris, while proteins and dissolved solutes pass through membranes. UF processes can be used for protein purification thereafter. Commercial-scale manufacturing of the high-value biological products are used to operate predominantly in batch mode [41–42]. But recent studies have highlighted the shift to continuous regimes in biomanufacturing [42–43]. Some authors draw attention mainly to performance characteristics and parameters of product quality [41–43] but incorporation of membrane-based operations into technological schemes also produced economic benefits; cost reductions can be ~55% [44]. There are major applications of membrane operations in biotechnology: bioprocessing [45] and bioreactors [13]. Typical biotech process include between 10 and 20 membrane-based separation steps, where MF is used predominantly upstream for the retention of cells and cell debris allowing the biopharmaceutical products to get through the membrane, while UF is used for the treatment of bioactive organics. Biotech companies producing monoclonal antibodies (Mab) use a relatively standard platform comprising a suspension bioreactor (steel CSTR Chateau de Grangeneuve Sainte-Foy Bordeaux 2016 or disposable plastic bags for multiple and single uses, respectively), membrane filters, and chromatographic columns including Mab capture by a protein column.

There are some objective reasons that dictate the development of separation techniques for protein-based solutions: (a) the requirement for a high-purity product; (b) concentration enrichment; (c) the removal of specific impurities (e.g., toxins from therapeutic products); (d) the prevention of catalysis other than the type desired (as with enzymes); (e) the prevention of catalysis poisoning (as with enzymes); and (f) the enhancement of protein stability or minimization of protein denaturation [46]. A generalized flow-diagram for monoclonal antibody production was considered in [47] where there are almost 20 small buffer membrane filters and about four large membrane filters for concentration and purification. In addition, there are three large chromatographic columns. Hollow fiber bioreactors were used for the first time to grow hybridoma cells to produce high Mab titers [48]. The application of submerged membrane bioreactors for water treatment, sterilization/clarification and wastewater purification has increased exponentially. Integrated upstream and downstream production along with purification of bacillus lipopeptides has been reported in [49]. Future trends in membrane-based operations in biotechnology are outlined in [39]. Integration of membrane-based operations with conventional processes can remove the technological limitations of stand-alone conventional processes. These are driven by the capability for higher productivity, lower cost, and increased development speeds. These aspects are considered in [13, 39]. Application of membrane-based operations especially in biotechnology has the following potential advantages [50]: (a) a large variety of applications including clarification, concentration, buffer exchange, purification, sterilization, and so forth; (b) versatility, such as depth filtration, ultrafiltration, diafiltration, nanofiltration, reverse osmosis, and microfiltration; (c) ease of operation and general robustness for various feeds and operating conditions; and (d) lower capital costs relative to other options [50]. These advantages make all membrane-based operations absolutely essential in technologies where bioprocessing is widely used.

Membrane-based processes offer plenty of promising applications in medicine as well. The global medical membrane market is projected to reach US$3,306.5 million by 2022 with annual growth of 9.2% between 2017 and 2022. It was noted that within the subcategories, such as membrane material, membrane process, and membrane-based schemes, the following was forecast: (1) nanofiltration is expected to be the fastest growing process since research and development of solvent-stable membranes has allowed the application of nanofiltration membranes for the treatment of pharmaceuticals and fine chemicals; (2) the largest application of medical membranes is expected to be within the subcategory of pharmaceutical filtration; and (3) the dominating materials are expected to be PSU and PESU [51].

The successful application of membrane-based operations in medicine is often hampered by the complex behavior of bioactive liquid phases. Blood consists of 45% blood cells, together called Hemacrit, which, in turn, consist of the following fractions: Granulocytes (Neutrouphils, Eosinophils, Basophils) with an average size of 8 µm; Monocytes with an average size of 20 µm; Lymphocytes with an average size of 5–6 µm; Erythrocytes (donut-shaped with an average diameter of 8 µm and a height of 2 µm) and Platelets with an average size of 2–4 µm. The cells are characterized by different deformability. Erythrocytes are the most flexible and characterized by high deformability; thrombocytes are less deformable (they are pulled toward the wall when blood is moving). The minimum pore diameter an erythrocyte can overcome is just below 1 µm. An erythrocyte will pass through a 3-µm pore with a pressure of only 1cm H_2O. An MF system for the separation of cells (so-called cell-cell separation) was considered in [12]. An MF system consists of a thin perforated plate (microsieve) supported by a grid. It has the advantage that cells will remain only a very short time in the pores leading to a low activation, sticking, or a rupture of cells. An experiment with filtration of white blood cells (leukocytes) from a blood-cell concentrate was presented in [12]. The membrane should meet the criteria of biocompatibility and surface smoothness. The thin films of titanium, titanium oxide, titanium nitride, silicon nitride, and so forth result in a very smooth surface (typical surface roughness < 100 nm) where no adhesion of protein or rupture of cells will take place. Some of these materials are presently used in dental and surgical applications. Membrane-based processes are used successfully for blood purification and for plasma treatment. Some medical applications are outlined in [12]. In those applications non-Newtonian behavior can take place and shear stress must be carefully controlled (since the blood cells' functionality is very shear sensitive as well).

Membrane-based operations also have a wide scope of potential application in the food industry. Commercial implementation of MF in the food industry goes back to the 1980s, when a cross-flow regime was developed. [52]. The early commercial applications (i.e., in the 1990s) were mainly for the treatment of wine, grapes, and vinegar. MF replaced centrifugation and conventional filtration (e.g., diatomaceous earth) for the removal of colloids and high molecular weight metabolic products [52]. In the treatment of wine, MF guarantees microbiological stability without deteriorating the product quality in a single operation. MF-based processes are widely used in the dairy industry as well. These processes are efficient and flexible for improving the hygienic safety of all dairy products with minimal heat treatment, fractionation of valuable components, and the creation of new products [53–55]. Special advantages are found in the food industry where we deal with multicomponent systems characterized by different physical and chemical behaviors. Milk contains micron-sized particles, mainly somatic cells (6–15 μm), fat globules (0.2–15 μm), bacteria (0.2–6 μm), and casein micelles (0.03–0.3 μm). MF can be used for the removal of bacteria, whey defatting, and micellar casein enrichment in cheese-making. Other applications include selective separation of somatic cells from raw whole milk, whey or milk protein fractionation, and milk fat separation. [56–59]. Emerging applications such as on-farm membrane concentration of milk have the following potential advantages: a reduction of transportation costs, a decrease in carbon footprint, and an increase in the sustainability of dairy processing through the treatment of byproduct streams (i.e. whey) and wastewater reuse. MF has been shown to be very effective in the removal of bacteria, spores, and somatic cells from skimmed milk [60–62]. In recent years, MF has gained significant attention as a non-thermal method for removing microorganisms from milk and beverages, which helps ensure their safety and shelf life, while preserving their natural nutritional properties. Membranes in the food industry represent 20% to 30% of the €250 million turnover of membranes worldwide [63].

As for whey, in the past it was primarily considered a waste by-product of cheese-making, and was simply disposed of in rivers, fields, and sewage systems, or sold as animal feed [64]. Recently, federal regulations banned the untreated disposal of whey, due to its serious environmental implications. Currently, the USA, Canada, Australia, New Zealand, the EU, and the UK have strict regulations on the disposal of whey [64]. In recent years, the separation of proteins (α-lactalbumin, β-lactoglobulin), lactose, and salts from whey became feasible due to scientific advances in membrane fractionation, which allowed the transformation and fractionation of the whey by-product into valuable products [65]. In particular, MF, along with UF, was used to produce high-protein, low-fat concentrates (35% to 80% protein) and isolates (85% to 90% protein) [64]. Yet the disposal of whey is still considered a challenge. Worldwide whey wastewater production was estimated recently to be 145 million tons per year, approximately half of which is disposed of into surface waters [66]. Even after membrane filtration, there is still a major by-product produced during this process, specifically, the lactose and mineral rich permeate [64]. A promising tendency for direct use of whey-based lactose is biofuel production [67].

Membrane fouling is an unavoidable phenomenon that hampers the practical implementation of those processes. Due to complex feed streams, including the mixing of potential foulants there are different approaches to the process development and synthesis of the flow-diagram. In some processes, the phenomenon of biofouling can be conjugated with organic, inorganic, and colloidal fouling. Multiple fouling, along with multicomponent diffusion layers consisting of bioactive high molecular organics and fermentation metabolites, further deteriorates the flux decline that in turn represents a challenging task for modeling and analysis of membrane processes. It requires an advanced modeling of the behavior of a diffusive multicomponent boundary layer at different operating conditions. Those models have to account for solute polydispersity, ionic environment, electrostatics, and operating conditions.

High-throughput approaches for process development were considered in [47, 67, 68]. The essential features of any high-throughput approach are: (1) miniaturization of the membrane system; and (2) the ability to conduct operations (e.g., synthesis, modification, filtration) in parallel. Typically, these features go hand in hand. Systems may also vary in their maximum operating pressure specifications, and whether the feed stream can be mixed during filtration (i.e., dead ended or cross-flow). Past studies have proven the efficacy of such high-throughput methods in mimicking the results of the larger-scale systems. Chandler and Zydney [69] demonstrated the potential of using high-throughput methods as a useful tool to screen process variables and optimize microfiltration processes. The effects of cake thickness, solution ionic strength, and poly-cationic flocculant on specific cake resistance observed in 96-well filter plates were consistent with data from larger format filters, including syringe filters, unstirred filtration cells, and small cartridge filters. Jackson et al. [70] described an automated high-throughput system to study the microfiltration of E. coli fermentation broth. Vanysacker et al. [71] described a high-throughput cross-flow system with six parallel flow streams and a direct visual observation system, which could be used with either an optical or a confocal laser scanning microscope. The system accommodates a membrane with an effective area of 26 cm^2. Bacterial fouling using Pseudomonas aeruginosa was evaluated using polyvinylidene fluoride microfiltration membranes under filtering conditions and a polyamide reverse osmosis membrane in a non-permeating mode. An advantage of the cross-flow regime is that it can simulate the dynamics of bacterial attachment more precisely.

THE ROLE OF MEMBRANE TECHNOLOGY IN INTEGRATED WATER RESOURCE MANAGEMENT

Integrated water resource management implies multiple uses of water streams on different levels where the consumers and producers of different water streams will be in same network. This can be done through optimization, integration, and balancing. A set of recent guidelines and documents such as the European Union's Water Framework Directive (WFD), Pollution Prevention Control Directive 96/61/EEC, and the Urban Waste Water Treatment Directive 91/271/EEC represents the legislative framework of this policy. Membrane technology within this context can be characterized as one of the alternative technologies for the development of flexible water resource management strategies. In particular, the combination of conventional co-generative systems with reverse osmosis and ASR technology allows the use of seasonally unused electricity and an excess of desalted water where RO consumes seasonally unused electricity while the ASR accumulates excess of desalted water [23]. The hybrid, including reverse osmosis and ASR technology, is characterized by the following technological, economic, and strategic advantages: (1) an increased range of variation in the power-to-water ratio; (2) the possibility of using any seasonal surplus of unused power for the production of additional quantities of water; (3) decreased specific CO_2 emissions; (4) an improved capital utilization factor and other economic indicators; and (5) the creation of a strategic water reserve for the region.

RO-BASED DESALINATION IN THE DECOUPLING OF POWER AND WATER PRODUCTION

Some experts consider RO desalination to be a promising option in decentralized water and power production. In recent years we have seen the shift away from conventional (co-generative) structures of power and water production to the structure of decoupled power and water projects. This trend can be seen in the technological planning of the power and water sectors in the UAE. Implementation of the nuclear energy program will force the Emirates to move toward independent power and water projects (IWP and IPP) where water and power projects would be represented as independent business streams. In this regard the technological concept of decoupling could be considered an innovative trend in the planning of the technology sector in some countries of the Middle East, and the UAE in particular. It is worth mentioning that some positions of this concept are still the subject of significant dispute and debate as they do not cover the use of low-grade and waste heat. Some indictors of thermodynamics and energy efficiency are outside the scope of this paradigm as well [72].

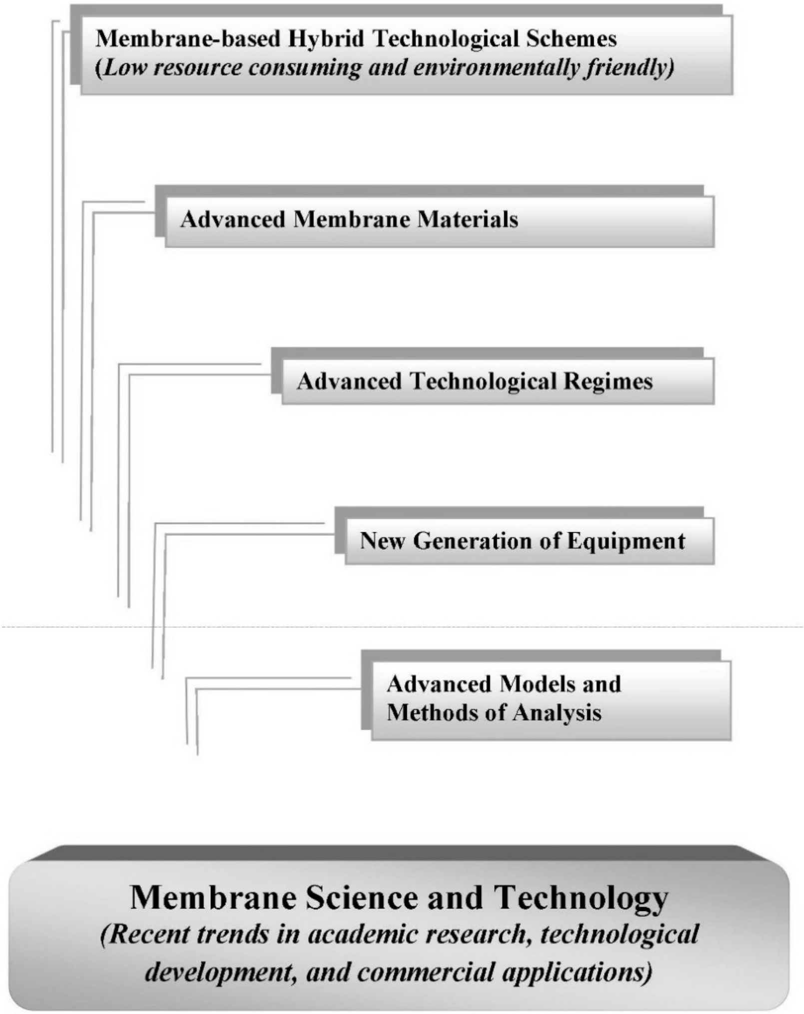

Figure 1 Main trends in the development of membrane science and technology.

THE NEW GENERATION OF MEMBRANE MATERIALS (AQUAPORINS, CARBON NANOTUBE, AND GRAPHENE MATERIALS)

There are two strategies targeting the membrane itself: development of new membrane materials, and a modification strategy. The development of new materials is focused on the synthesis of materials with advanced surface characteristics and behaviors. These include new polymers, new composite materials, inorganic membrane materials, and so forth. The modification implies bulk modification, polymer blending, interfacial polymerization, and graft polymerization. Nowadays membrane science and technology are undergoing a revolution in which a new generation of membrane materials has been developed. They are driven by progress in nanotechnology and the development of biomimetic materials. Manufacturing nanomaterials such as carbon nanotubes (CNT) laid the foundations for technological breakthroughs in membrane materials. Biomimetic membranes incorporate biological elements or borrow concepts or inspiration from biological systems. Such membranes can make use of the advantages of the strategies evolved by nature over billions of years for improving transport efficiency and specificity. The past decade has witnessed many innovations focused on the improvement of water permeability and the development of the group of so-called "ultra-permeable membranes." These groups include aquaporins [73–74], carbon nanotubes (CNT), and graphene materials [75–76]. It was concluded that a threefold increase of water permeability could decrease seawater reverse osmosis (SWRO) energy consumption by ~15% to 20% and brackish water reverse osmosis energy consumption by ~40%.

An aquaporin-based membrane is an example of a biomimetic membrane. The increasing interest in biomimetic membranes across various disciplines has resulted in the publication of several reviews addressing various aspects in the field. The review [77] covers biological paradigms that are relevant to membranes for separation and presents an overview of strategies that are inspired by these paradigms. It also presents both fundamental and practical challenges to the implementation of these strategies. Recent studies have showed the promising future of aquaporin biomimetic membranes in the water purification industry. Laboratory scale experiments demonstrated that aquaporin biomimetic membranes have a high water-purification performance, low fouling tendency, and high flux recovery compared to conventional commercial membranes. Currently these aquaporin biomimetic membranes are being used for processes such as reverse osmosis, forward osmosis, and so on. Continuous research and further study will reveal other types of membranes which can be utilized for different applications ranging from the biomedical to an artificial kidney [78].

Research on novel applications of CNTs in desalination has offered tremendous opportunities and possibilities, holding out much promise for next-generation desalination technologies. The introduction of CNTs marks a potentially significant breakthrough in desalination technology. Previous research studies on the transport properties of CNTs have found that the extremely smooth hollowed structure of the nanotubes could facilitate the rapid transport of liquid and gas molecules in the channels, enabling high flux membrane separation performance. The diameter of the CNTs is the critical dimension to implement physical size exclusion and capillary behavior. The small and precise diameter of CNTs has also been shown to reject most ions due to the energy barrier existing at the channel entries.

Hence only water molecules are able to permeate the nanotube hollows. The findings from some of the simulation studies have shown that water can enter the narrow hydrophobic interior channels of CNTs. This has been confirmed experimentally and opens the door to the incorporation of CNTs into membranes to form smooth pores for desalination applications [79–80].

Published data indicate a growth of scientific, engineering, and commercial interest in pressure-driven membrane processes in particular. Along with the development of membrane materials, improvement in membrane elements, diversification of the technological regimes, and synthesis of advanced membrane-based schemes, the aspects related to modeling and analysis of membrane processes merit particular attention.

It has been shown that the accounting shear rate is essential in the quantitative analysis of the cross-flow microfiltration, accompanied by shear-induced migration. Some published research by Bodekker, Iritani, and others [81–87] has emphasized the importance of the shear-rate accounting in the analysis of concentration polarization. The shear-induced diffusion is important for particles whose diameter is within the intermediate range from 0.5 to 30 μm, although this range can vary with the system parameters [82–87]. It has also been shown that it is the shear rate that is an important factor in the estimation of the rate and morphology of membrane fouling. High sensitivity in the behavior of bio cells to the local value of the shear rate was shown by Böddeker, Fild, Benoit, and others [81–83]. It was emphasized that it is the shear rate that is a more informative variable for design and analysis than the Reynolds number or the longitudinal velocity. (Conventional methods are based on the Reynolds number and longitudinal velocity.)