Bibliography and Major Accomplishments of Prof. (Neal) Tai-Shung Chung

Department of Chemical & Biomolecular Engineering
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websites: 1) http://www.chee.nus.edu.sg/people/faculty_chungneal.html
2) http://www.chbe.nus.edu.sg/membrane/
(March 8 2009)

1. Educational background:

- BEng, Chemical Engineering; 1973; Chung Yuan Christian University, Taiwan
- MEng, Chemical Engineering; 1977; National Taiwan University, Taiwan
- PhD, Chemical Engineering; 1981; State University of New York at Buffalo
- PE (Registered Professional Engineer) 1977; Taiwan

2. Professional Experience:

July 2007 to the present	**Fellow**, Chemical and Pharmaceutical Engineering Program, Singapore-MIT Alliance
July 2001 to the present	**Professor,** Department of Chemical and Biomolecular Engineering (ChBE), National University of Singapore (NUS) *Teach and conduct world-class research on membrane science and engineering, purification and separation technologies for water, energy (gas and bio-fuel), chemicals and pharmaceutics (proteins and chiral drugs).*
Jan 2001 to Aug 2001	**Deputy Director** and **Chemical Cluster Director,** Singapore's National Institute of Materials Research and Engineering (IMRE) *Lead technology development and industry driven research in polymers, membranes, & chemicals for electronic, energy and medical applications.*
Feb 2000 to July 2001	**Professor (Research)**, Department of Chemical and Environmental Engineering, NUS
1998-2000	**Program Director,** Advanced Polymers and Chemicals Program, IMRE
1995-2000	**Associate Professor**, ChBE, NUS
1997-1998	**Program Manager,** Advanced Polymers Program, IMRE
1996-1997	**Program Coordinator**, Advanced Polymers Group, IMRE
1993 to 1995	**Project Manager/Consulting Engineer** Aeroquip Corporate Technology Lab., Ann Arbor, Michigan *Conducted materials research and developed thermoplastic connectors*
1988 to1993	**Research Associate (equivalent to Group Leader)** Hoechst Celanese Research Division, Summit, New Jersey *Conducted materials research on fluoro-polyimides and invented high-flux and high-selectivity hollow fibers for gas separation.*
1986 to 1988	**Staff Engineer (equivalent to Project Leader)** Hoechst Celanese Research Division, New Jersey • *Lead engineer in Vectra™ liquid crystal polymers for electronic and composite applications.* • *Invented novel technologies to make ethylene tetrafluoroethylene (ETFE) membranes for lithium rechargeable batteries*
1983 to 1986	**Senior Research Engineer**, Hoechst Celanese Research Division, New Jersey • *Principal investigator for fabricating extra-thin coatings (50-100 nm) on substrates for optical data storage for military applications.* • *Lead engineer and team member that invented, developed, and commercialized Vectra™ liquid crystal polymers.*
1980-1983	**Research Engineer**, Celanese Engineering Resins Company, New Jersey

3. Honors and Awards:

- Adjunct Chair Professor, Taiwan Chung Yuan Christian University (Aug. 1, 2008-2010)
- Distinguish Alumni Award (Department level), Dept of ChEE, Chung Yuan Christian University (Oct. 18, 2008)
- Distinguish Alumni Award (University level), Chung Yuan Christian University (Oct. 18. 2008)
- Winner of $10-million CPR grant from Singapore National Research Grant in 2007

4. Professional Service

4.1 Editorial board member of the following journals

i) Journal of Membrane Science (Impact Factor = 2.432 in 2007)

ii) Chemical Engineering Journal (Impact Factor = 1.707 in 2007)

iii) Separation and Purification Reviews (Impact Factor = 1.532 in 2007)

iv) Polymer Engineering and Science (Impact Factor = 1.272 in 2007)

v) Chemical Engineering and Technology (Impact Factor = 1.223 in 2007)

vi) Separation Science and Technology (Impact Factor = 1.048 in 2007)

vii) Journal of Applied Polymer Science (Impact Factor = 1.008 in 2007)

viii) Desalination (Impact Factor = 0.875 in 2007)

ix) Chinese Journal of Chemical Engineering (CJChE) (Impact Factor = 0.462 in 2007)

x) Desalination and Water Treatment

xi) Recent Patents on Engineering

xii) Recent Patents on Chemical Engineering

4.2 Recent committee work and session organization activities

i) Session chairs on membrane formation, mixed matrix membranes, and membranes for water treatment, Annual Meeting of the American Institute of Chemical Engineers, USA, 2009.

ii) Program co-chair on membranes, World Congress of Chemical Engineering, August 23rd-27th, Montreal, Canada, Aug 23-27 (2009).

iii) Session chair on membrane research in Asia, Annual Meeting of the North American Membrane Society (NAMS), Charleston, SC, USA, June 20-24, 2009.

iv) International scientific committee member, the 7th Regional Symposium on Membrane Science and Technology, Lumpur, Malaysia, May 19-22 2009.

v) 3 Session chairs for (1) membrane formation, (2) mixed matrix membranes, and (3) membranes for water treatment, Annual Meeting of the American Institute of Chemical Engineers, Philadelphia USA, November 2008.

vi) Session chair for gas separation membranes. International Congress on Membranes and Membrane Processes (ICOM), Hawaii, USA, 2008, July 12-18, 2008.

vii) International advisory board member, the 6th Regional Symposium on Membrane Science and Technology, Phuket, Thailand Aug 13- 15, 2008

viii) International advisory board member, ICOM 2008, International Congress on Membranes and Membrane Processes, Honolulu, Hawaii, USA, July 2008.

ix) Scientific committee member, Macro 2008, Polymer Membranes, Taipei, Taiwan, June 2008

x) Scientific committee member, European Membrane Society (EWM) 2008, Membrane Processes: Development, Monitoring and Monitoring and Modelling Modelling - From the Nano to the Macro Scale to the Macro Scale, Algarve, Portugal, May 2008.

xi) International scientific board member, the 4th Conference of Aseanian Membrane Society, Taipei, Taiwan. August 2007.

xii) Session chair for membrane formation, AIChE annual meeting, Salt Lake City, Utah USA, November 2007.

xiii) Session chair for membranes for water treatment, AIChE annual meeting, Salt Lake City, Utah USA, November 2007.

xiv) Session chair for pervaporation and vapor separation, Annual Meeting of the North American Membrane Society, Orlando, Florida USA, May 2007.

xv) International scientific board member, the 3rd Conference of Aseanian Membrane Society, Beijing, China, August 2006.
xvi) International advisory board member, the International Conference on Environments, Penang, Malaysia, November 2006.

4.3 Recent invited keynotes and plenary lectures

i) T. S. Chung, "the Future of Water Panel Presentations and Discussion", National Conference on the Advancement of Research (NCAR-61): "WATER: Recourse for a Resource", Georgia, USA, to be announced, 2009.
ii) T. S. Chung, Emerging membrane technologies for water, (A keynote lecture), the 5th IWA Membrane Technology Conference, Beijing, China, Sept 1-3, 2009.
iii) T. S. Chung, Emerging membrane technologies for water, (A plenary talk), the 5th Conference of Aseanian Membrane Society, Kobe, Japan, July 12-14, 2009.
iv) T. S. Chung, Forward osmosis membranes for water reuses, (A keynote lecture), Advanced Membranes ECI- Trondheim, Norway, June 7-12, 2009.
v) T. S. Chung, Membranes for Desalination, KAUST Special Academic Partnerships, Jeddah, Saudi Arabia, October 14-15, 2008.
vi) T. S. Chung, "The future and trend of membrane research: using NUS membrane research as an example", The 6th Regional Symposium on Membrane Science and Technology, Phuket, Thailand Aug 13- 15, 2008
vii) T. S. Chung, Molecular engineering of membrane materials and fabrication for new water production and life science, Macro 2008, the 42nd IUPAC World Polymer Congress, Polymer Membranes, Taipei, Taiwan, June 2008.
viii) T. S. Chung and his team, Materials development and module design in membrane distillation process for water production, the 8th International Membrane Conference on Membrane Science and Technology, Taiwan, June 2008.
ix) T. S. Chung, The Evolutional Understanding of Membrane Formation: From the origins of macrovoids and irregular membrane contour to the formation of macrovoid-free membrane, EWM 2008, Membrane Processes: Development, Monitoring and Monitoring and Modelling Modelling, Algarve, Portugal, May 2008.
x) T. S. Chung, NUS Membrane research in Environment, particularly related to water and energy, HKUST Postgraduate student workshop on Energy, Environment and Health on March 12, Hong Kong 2008.
xi) T. S. Chung, X. Y. Qiao, L. Y. Jiang, R. X. Liu, Fabrication and characterization of polyimide membranes for the pervaporation dehydration of isopropanol, 2nd International Conference on Advances in Petrochemicals and Polymers, Bangkok, Thailand, 2007.
xii) T. S. Chung, N. Widjojo, N. Peng, S. Bonyadi, A historical review on membrane formation:from the origins of macrovoids and irregular membrane contour to the formation of macrovoid-free membranes, (A plenary talk), the 4th Conference of Aseanian Membrane Society, Taiwan, 2007.
xiii) T. S. Chung, Membranes for pharmaceutical and biomedical industry, the International E-Symposium on "Pharmaceutical Engineering – An Insight into Latest Developments", Bharathidasan University, India, 2006.
xiv) T. S. Chung, L. Y. Jiang,, Y. Li, P. S. Tin, S. Kulprathinanja. Fabrication of polymer/zeolite and carbon/zeolite mixed matrix membranes for gas separation, North American Membrane Conference, Chicago, United States, 2006.
xv) T. S. Chung, X. Y. Qiao, R. X. Liu, Fabrication and characterization of BTDA-TDI/MDI (P84) co-polyimide membranes for the pervaporation dehydration of isopropanol, the 6th International Membrane Conference on Membrane Science and Technology, Taiwan, 2006.
xvi) T. S. Chung, L. Y. Jiang,, Y. Li, S. Kulprathinanja, Fabrication and characterization of zeolite/polymer mixed matrix nano-composite hollow fiber membranes, (A plenary talk), the 3rd Conference of Aseanian Membrane Society, Beijing, China, 2006.
xvii) T. S. Chung, Fabrication and characterization of zeolite/polymer mixed matrix nano-composite membranes for gas separation, ICMAT, Singapore, 2005.
xviii) T. S. Chung, L. Y. Jiang, L. Y., Li, Y. and Kulprathipanja, S., Fundamental understanding of the science and engineering of the fabrication of zeolite/polymer nano-composite, the 5th International Membrane Conference on Membrane Science and Technology, Taiwan, 2005.

5. Novelty and Key Scientific Contributions

Prof. Chung is the author of 1 book (Thermotropic Liquid Crystalline Polymers, CRC Press (2001), 14 book chapters, 312 Journal papers, more than 70 patents (including 35 US patents) and 200 conference papers. He has given many invited talks and plenary addresses at several international conferences. The following summarizes some of his original work, major contributions and scientific impact in (1) membrane science and engineering, (2) advance polymers, and (3) controlled drug release devices.

(1) Advancements in the Fundamentals of Membrane Science and Engineering

i) Leading membrane scientists had debated the validity of Cheng and Gryte (*Cheng and Gryte, Macromolecules, 25, 3293 (1992)*) mathematical results claiming that all isothermal mass-transfer fluxes are zero at the spinodal. We were the first group to solve this controversial subject using Markoffian and Onsager's thermodynamic approach [1]. Our theoretical development unambiguously demonstrated that isothermal mass-transfer fluxes at the spinodal composition can depart from zero for systems operated in a gravitational field.

ii) The Flory-Huggins theory for polymer solutions derived in 1942 has been used extensively to describe the phase-inversion process during membrane formation. Prof. Chung is the pioneer to point out the limitations of using Flory-Huggins theory to describe the Gibbs free energy for the solution states during hollow-fiber membrane formation [2]. At least two additional terms have to be included if the fiber is spun isothermally; one is the work done by the external stresses on the as-spun nascent fiber, and the other is an extra entropy change induced by these stresses. Experimental results confirmed our analysis.

iii) We were the pioneer in reporting the effects of shear rate within a spinneret during hollow fiber spinning on membrane morphology and separation performance for gas [3] and liquid separations [4]. The evolution of pore size with shear rate has also been elucidated [5]. Before a critical shear rate is reached, the shear-induced orientation may tighten the pore size and enhance selectivity, whereas when the critical shear rate is exceeded, the effect of shear thinning on dope viscosity may induce defects and lower the separation performance. The discovery of this relationship is essential for engineers to produce useful hollow fiber membranes with desired pore sizes and separation performance.

iv) Spinneret design and geometry for hollow fiber membrane spinning have been treated as proprietary know-how in the membrane community. Almost no publications have appeared in the open literature on this subject. For the first time, we have studied the straight and conical spinneret designs [6-7], spinneret dimension [8-9] and compared the effects of elongational and shear flows on molecular orientation and separation performance with the aid of a computational fluid dynamics model. It was found that the elongational rate plays a more important role in influencing the permselectivity than in affecting the permeance, whereas in contrast, the shear rate has a more significant contribution to the permeance relative to the permselectivity. Prof. Chung is ranked first worldwide in the number of publications on the subjects of "hollow fiber membranes" and "hollow fiber spinning" by both Science Citation and Journal of Membrane Science.

v) The supported liquid membrane (SLM) based separation has been studied for three decades, where the transport through the membrane is facilitated by a carrier. Trial and error is the traditional approach used to identify appropriate carriers. For the first time, Prof Chung and his coworkers have advanced the fundamental science of carrier selection by employing the quantum chemical computational method to theoretically predict carrier extraction capabilities. Validation of their theoretical calculations has been confirmed experimentally with copper [10] and cadmium extraction [11] by means of SLM and impedance spectroscopy. Their discovery not only significantly simplifies the carrier selection process, but also provides the scientific foundation.

vi) Prof. Chung's team has revealed, for the first time, the evolution of nano-particle distribution and the mechanisms of nano-particle movement during hollow fiber spinning [12-13]. Three factors; namely, shear flow, die swell and elongational drawing determine the nano-particle distribution. Shear flow induces a parabolic-shaped particle distribution; die swell flattens the distribution, whereas elongation stretch redistributes the particles to the inner or outer surfaces because of negative normal stresses and the solvent outflow. The discovery of the science to manipulate particle distribution provides membrane scientists with a powerful tool to control membrane morphology and maximize performance.

vii) Traditional pervaporation dehydration studies use flux and separation factor to analyze membrane performance. Prof Chung and his coworkers were among the pioneers who compared and discussed the advantages and disadvantages of using flux or permeance, and separation factor or selectivity as analysis parameters [14-15]. Using permeance and selectivity instead of flux and separation can significantly decouple the effect of operating conditions on performance evaluation, while clarifying and quantifying the contribution of the nature of the membrane to separation performance. The traditional flux versus separation factor plot might be misleading in analyzing the performance data. These studies may have a significant impact on future pervaporation studies.

(2) Breakthroughs in Integrally-skinned Asymmetric Hollow Fiber Membranes

i) Before 1997, no one had ever demonstrated that hollow fiber membranes with an ultra-thin selective layer for gas separation can be prepared from a binary system (i.e., one polymer and one solvent system). We have demonstrated, for the first time, that hollow fiber membranes with a dense selective layer of 474 Å can be fabricated using a single-polymer and single-solvent system [16]. This is a technology breakthrough. The key factors in fabricating these types of hollow-fiber membranes are (1) to lower the substructure resistance by controlling the chemistry of the internal coagulant and its flow rate, and (2) to minimize skin defects by employing a critical dope concentration exhibiting significant chain entanglement. Prof. Chung was the pioneer proposing the critical concentration concept for the development of gas separation membranes with selective-skins having minimum defects. This practice has been widely used in the membrane community and has proved to be valid for gas separation and pervaporation membranes.

ii) Due to resource depletion, record high oil prices, and clean water shortage, a hollow fiber membrane consisting of a sponge-like cross-sectional structure has a higher market value because it can withstand higher pressures for energy and water production, and is the preferred and safer structure in biomedical dialysis applications. The origins of macrovoid defects and the ways to eliminate them has been a subject of considerable debate for five decades. We have discovered, for the first time, the effects of spinneret design [6] and elonational draw ratio [17] on macrovoid defect formation. For binary spinning solutions, there should be critical values of the polymer concentration, air gap distance and take-up speed. When all of these are optimized, macrovoid-free hollow fibers can be successfully produced [18]. These observations have tremendous value for industrial hollow fiber production.

iii) Irregular cross-sectional geometry is one of the most controversial issues in the hollow fiber fabrication process. Heretofore, no one could provide a satisfactory mechanism to explain how the cross-sectional geometry can be controlled. Many companies treat this as proprietary know-how and rarely openly discuss it in the literature. We have proposed, for the first time, novel mechanisms to explain hollow fiber geometry. For low-speed spinning, the principal instability occurs in the external coagulation bath where the pressure induced in the nascent fiber outer layer as a result of diffusion/convection, precipitation, densification and shrinkage buckles the rigid precipitated polymer shell in the dope and bore fluid interface [19]. For high speed spinning, the insufficient bore fluid supply may create a vacuum on the lumen side and thus induce buckling [20]. Both findings may have considerable application in industrial hollow fiber production.

(3) Leading Dual-layer Hollow fiber Membrane Development

i) We are the leading research group in the academic community in the study of dual-layer composite hollow fibers. The dual-layer technology is the most advanced membrane configuration because it has the advantages of significantly reducing material costs as well as maximizing performance by using a membrane material having optimal properties as the selective layer. The inner porous substrate and outer selective skin are co-extruded from a dual-layer spinneret simultaneously. An ultra-thin outer layer (<10 μm or less) has been achieved. The basic science and engineering of how to fabricate dual-layer hollow fibers have been well documented by Prof. Chung's group [21-23]. Applications of dual-layer hollow fibers for forward osmosis, gas, biofuel, chemical and protein separations have been demonstrated.

(4) Novel Polyimide Membrane Materials and Chemical Modifications for Natural Gas and Hydrogen Purification Separation

i) The discovery of new membrane materials for natural gas purification and separation has received worldwide attention because of energy depletion. Prof. Chung's group is among the world leaders in the study of novel membrane materials for natural gas applications. Several novel and promising fluorinated polyimides containing (2,2-bis(3,4-dicarboxyphenyl) hexafluoro-propane dianhydride (6FDA) with high gas permeability and selectivity have been synthesized and identified for natural gas applications [24-26], while several innovative chemical cross-linking technologies have also been invented to enhance anti-plasticization properties of the resultant membranes [27-29]. The newly discovered cross-linking technologies have received worldwide attention by other membrane scientists.

ii) Separating H_2 and CO_2 using polymeric membranes is problematic because most polymers show poor H_2/CO_2 selectivity. Even though there is a difference in molecular size (H_2: 2.89 Å vs. CO_2: 3.30 Å), the solubility of CO_2 in polymers is much higher than that of H_2. Consequently, the permselectivity is relatively low owing to these competing effects, Prof. Chung and his coworkers discovered a series of aliphatic diamino-modified polyimides that showed the ideal H_2/CO_2 selectivity up to 101 at 35°C in pure gas tests and up to 42 in mixed gas tests [30-31]. Both results are far superior to other polymeric membranes and are well above the Robeson's upper-bound curve that relates membrane selectivity to permeability. The newly invented membrane technology may provide a promising approach for H_2 separation in the methane steam reforming process.

(5) Mixed Matrix Membranes for Gas Separation and Solvent Recovery

i) Mixed matrix membranes (MMMs) have received significant attention because the resultant materials may have the potential to surpass the upper-bound separation limit of polymeric membranes. MMMs are formed by incorporating an active nano-size material such as silica particles and molecular sieves into a polymer matrix, thus combining and synergizing the properties of the two components for practical applications. However, the major challenge in MMMs is the difficulty of choosing a workable and commercially viable system that can be effectively implemented in a hollow fiber configuration. Prof. Chung's group is the pioneer and is recognized as the foremost expertise on the fabrication of dual-layer hollow fibers consisting of an ultra-thin MMM layer of less than 1.5 μm for gas separation. In-depth science and engineering have been provided in their publications for young membrane scientists [32-35].

ii) Prof. Chung's team is one of the leading groups studying MMMs for the dehydration of ethanol and isopropanol (IPA) by pervaporation. Ethanol and IPA have tremendous market value, thus their recovery and concentration have received worldwide attention. Prof. Chung's group has developed several high-performance MMMs such as Matrimid®/MgO MMMs [36], zeolite/ P84 co-polyimide MMMs [37], and multilayer zeolite/poly(vinyl alcohol) [38] for alcohol separation. In addition to publishing peer-reviewed papers on the science and engineering of MMM membrane formation, sorption characterization, chain rigidification and partial pore blockage, a spin-off company has been formed by his researchers to market their products.

(6) New Desalination Technologies: Membrane Distillation (MD)

i) Given a pressing worldwide water shortage in many regions and high oil prices, an urgent need exists for new desalination technologies to provide inexpensive and reliable sources of water for a growing population and to meet industrial needs. MD has been considered as a promising alternative to potentially replace conventional desalination technologies because multistage-flash vaporization and reverse osmosis (RO) involve high energy and high operating pressures, respectively. However, MD still faces difficulties for commercialization because of the pore wetting and fouling of the hydrophobic microporous membrane. Novel materials and fresh configurations of microporous hollow fiber membranes with desired porosity, hydrophobicity, low thermal conductivity and low fouling are essential to advancing MD to commercialization. Prof, Chung's team has recently made a significant breakthrough in MD by developing dual-layer microporous hollow fibers with a superior hydrophobic PVDF (polyvinylidene difluoride) outer layer and a modified hydrophilic inner layer [39]. The newly developed MD has a superior flux compared to the existing MD technologies and may set a new horizon for future MD development. Other macrovoid-free single-layer PVDF hollow fiber membranes have also been developed with enhanced performance [40-41].

(7) Emerging Water Production Technologies: Forward Osmosis (FO)

i) Forward osmosis (FO) is an emerging new desalination and water production technology. Like RO, FO uses a semi-permeable membrane to separate water from dissolved solutes effectively. Instead of employing mechanical pressure as driving force for the separation in RO, FO uses the osmotic pressure gradient across the membrane to induce a net flow of water through the membrane into the draw solution, thus efficiently separating the fresh water from its solutes without requiring significant energy input. However, the major hurdles to fully explore FO potential as a new desalination and water production technology are the lack of commercially available FO membranes with proper separation performance and unavailability of user friendly and economic draw solutions. NUS is the first to publish a study of forward osmosis by fabricating nanofiltration (NF) hollow fiber membranes for osmotically driven membrane processes [42]. A novel polybenzimidazole (PBI) nanofiltration membrane with a narrow pore size and high flux has been invented for the FO process. The newly developed FO membrane systems may greatly reduce energy costs in desalination, while the NF membranes can be used for the removal of multivalent ions and the recycle of industrial wastewater. 2nd and 3rd generation NF FO hollow fiber membranes with much enhanced fluxes have also been developed [43-44]

(8) Membranes for Life Science Applications

i) The demands of the pharmaceutical and biomedical industries provide the impetus in 2005 for Prof. Chung and his coworkers to start working on bio-functional and bio-selective membranes for isomer, chiral, and protein separations, and kidney dialysis membranes. Even though this field is new to us, we have made several breakthroughs. For the first time a dual-coagulation bath technology was developed for the fabrication of kidney dialysis membranes with tailored morphology and desired molecular weight cut-off [45]. Enhanced enantiomer separation of L, D-lactic acid mixtures was demonstrated in a supported liquid membrane by carrier modification and the addition of β-cyclodextrin into the feed [46]. For the first time a membrane-based separation system was also developed for the separation of racemic tryptophan solutions by covalently binding beta-cyclodextrin onto the surface of commercial cellulose membranes, followed by the acetylation reaction with acetic anhydride to form a chiral-selective acetylated β-cyclodextrin immobilized membrane [47]. We are also the pioneer to employ the dual-layer membrane technology consisting of a highly sulfonated polyethersulfone outer layer for enhanced protein separation [48-49].

(9) Pioneering Research in Liquid Crystalline Polymers (LCPs)

i) Prof. Chung was one of the pioneers conducting significant research on thermotropic liquid crystalline polymers (LCPs) for military, aerospace and electronic applications [50-51]. He was on the team that commercialized Vectra™ LCPs by Hoechst Celanese in 1987-1991. His early LCP work had been cited more than 150 times [52]. For the first time, he developed LCP/carbon fiber prepreg as a new aerospace composite material [53]. He invented novel LCP rods as a strength member used in optical fibers [54]. Since he joined NUS, he and his workers developed a novel thin film polymerization process to study in situ the formation of the LC phase and to analyze the kinetics and growth mechanisms of liquid-crystal phase. By applying this technique and the Lifshitz/van der Waals acid-base theory, his team reported, for the first time, the evolution of surface free energy during the polymerization of LCPs. Prof. Chung's team also developed sophisticated analytical methods to unfold the fundamentals of crystallization, morphology change and thermal degradation for aromatic thermotropic liquid crystalline polyimides and polyesters. Five PhD and three MEng students have been mentored in the areas of LCPs. This research is summarized in Prof. Chung's book on LCPs published in 2001 [55].

(10) Controlled Release Devices for Drug Delivery

i) Prof. Chung initiated and established the first research division for controlled release in drug delivery in Singapore when he was the Program Director of the Chemical Cluster at IMRE. Using his materials strengths and membrane phase inversion technologies, he and his coworkers studied the evolution of microsphere formation and the release mechanisms of various microspheres in vivo and in vitro studies. Several microsphere and transdermal devices for protein and drug release have been developed in 1999-2003. Two PhDs and two MEng students have been mentored in the area of controlled release. Several of Prof. Chung's publications in this research area are highly cited [56-59].

6. Other Accomplishments:

i) Co-inventor of Hyflux Kristal 600™ ultra-filtration membranes for water treatment in 2006/2007.
ii) H-index = 29 for Prof. Chung work.
iii) Science citations more than 200 times each year in the years 2003, 2004, 2005, 2006 and more than 336 times in 2007 and 393 times in 2008.
iv) Senior Consultant and advisor for Hyflux (Singapore), helped design and establish its membrane research laboratories in 2004-2008.
v) Established the NUS Initiative on membrane research for life science in 2007.
vi) International advisor, R&D Center for Membrane Technology, Chung Yuan Christian U, Taiwan in 2003-now.
vii) A part of the team that invented, developed and commercialized Vectra™ liquid crystalline polymers with an annual business size of US$150 million in Hoechst Celanese in 1987-1991.
viii) Set up the chemical, membrane, and polymer laboratories at the Institute of Materials Research and Engineering (IMRE) in 1997-2001.
ix) Consultant for Air Products (USA) in 1998-1999.

7. Grants Received since Joining NUS in 1995

- Total: $27,082,355 ≅ US $18.5677 million
- From Ministry of Education, NUS and A-Star (Agency for Sci. & Tech.) = S$9,200,101
- From NRF (National Research Foundation) = S$9,629,062
- From industries, overseas institutes and Singapore defense industry = S$8,253,192

Company list: *Hitachi DuPont (1998-1999), British Gas (1998-2001), UOP (2003-2006), Merck (2003-2006), Hyflux (2005-2008), BASF (2005-2009), Mitsui (2005-2009), KAUST (Saudi) (2008-2010) and PBI (2009-2012).*

8. Human Resource Development (MS and PhD students)

- 24 PhD and 12 MEng degrees granted under the direct supervision of Prof. Chung
- About 35 post-doctoral fellows have been trained under the direct supervision of Prof. Chung

Appendix

1. T. S. Chung, S. K. Teoh, Breaking the limitation of composition change during isothermal mass-transfer processes at the spinodal, *J. Membrane Science*, 130, 141-147 (1997).
2. T. S. Chung, The limitations of using Flory-Huggins equation for the states of solutions during asymmetric hollow fiber formation, *J. Membrane Science*, 126, 19-34 (1997).
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4. J. J Qin, R. Wang, T. S. Chung, Investigation of shear stress effect within a spinneret on flux, separation and thermomechanical properties of hollow fiber ultrafiltration membranes, *J. Membrane Science*, 175, 197-213 (2000).
5. R. Wang and T. S. Chung, Determination of pore sizes and surface porosity and the effect of shear stress within a spinneret on asymmetric hollow fiber membranes, *J. Membrane Science*, 188, 29-37 (2001).
6. N. Widjojo, T. S. Chung, The thickness and air-gap dependence of macrovoid evolution in phase-inversion asymmetric hollow fiber membranes, *Industry and Engineering Chemistry Research, 45,* 7618-7626 (2006).

7. C. Cao, T. S. Chung, S. B. Chen, Z. J. Dong, The study of elongation and shear rates in spinning process and its effect on gas separation performance of poly(ether sulfone) (PES) hollow fiber membranes, *Chemical Engineering Science*, 59, 1053-1062 (2004).
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9. N. Peng, T.S. Chung, J. Y. Lai, The rheology of Torlon® solutions and its role in the formation of ultra-thin defect-free Torlon® hollow fiber membranes for gas separation, *Journal of Membrane Science,* 326 (2009) 608–617.
10. Q. Yang, J. W. Jiang, T. S. Chung, N. M. Kocherginsky, Experimental and computational studies of membrane extraction of Cu(II) in supported liquid membranes, *AIChE J*. 52, 3266–3277 (2006).
11. J. W. Lv, Q. Yang, J. W. Jiang, T. S. Chung, Exploration of heavy metal ions transmembrane flux enhancement across a supported liquid membrane by appropriate carrier selection, *Chemical Engineering Science*, 62, 6032 – 6039 (2007).
12. L. Y. Jiang, T. S. Chung, C. Cao, Z. Huang, S. Kulprathipanja, Fundamental understanding of nano-sized zeolite distribution in the formation of the mixed matrix single- and dual-layer asymmetric hollow fiber membranes, *J. Membrane Science*, 252, 89-100 (2005).
13. Y. C. Xiao, K. Y. Wang, T. S. Chung, J. N. Tan, Evolution of nano-particle distribution during the fabrication of mixed matrix TiO_2 - polyimide hollow fiber membranes, *Chemical Engineering Science*, 61, 6228– 6233 (2006).
14. W. F. Guo, T. S. Chung, T. Matsuuraa, Pervaporation study on the dehydration of aqueous butanol solutions: a comparison of flux vs. permeance, separation factor vs. selectivity, *J. Membrane Science,* 245, 199–210 (2004).
15. X. Y. Qiao, T. S. Chung, W. F. Guo, T. Matsuura, M. M. Teoh, Dehydration of isopropanol and its comparison with dehydration of butanol isomers from thermodynamic and molecular aspects, *J. Membrane Science*, 252, 37–49 (2005).
16. T. S. Chung, S. K. Teoh, X. Hu, Formation of ultra-thin high-performance polyethersulfone hollow fiber membranes, *J. Membrane Science*, 133, 161-175 (1997).
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