# MODELING AND OPTIMIZATION OF SPINNING CONDITIONS FOR POLYETHERSULFONE HOLLOW FIBER MEMBRANE FABRICATION USING NON-DOMINATED SORTING GENETIC ALGORITHM-II

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To my beloved mother and father

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# ABSTRACT

Optimization of spinning conditions plays a key role in the development of high performance asymmetric hollow fiber membranes. However, from previous studies, in solving these spinning condition optimization problems, they were handled mostly by using an experimentation that varied one of the independent spinning conditions and fixed the others. The common problem is the preparation of hollow fiber membranes that cannot be performed effectively due to inappropriate settings of the spinning conditions. Moreover, complexities in the spinning process have increased where the interaction effects between the spinning conditions with the presence of multiple objectives also affect the optimal spinning conditions. This is one of the main reasons why very little work has been carried out to vary spinning conditions simultaneously. Hence, in order to address these issues, this study focused on a non-dominated sorting genetic algorithm-II (NSGA-II) methodology to optimize the spinning conditions during the fabrication of polyethersulfone (PES) ultrafiltration hollow fiber membranes for oily wastewater treatment to maximize flux and rejection. Spinning conditions that were investigated were dope extrusion rate (DER), air gap length (AGL), coagulation bath temperature (CBT), bore fluid ratio (BFR), and post-treatment time (PT). First, the work was focused on predicting the performance of hollow fiber membranes by considering the design of experiments (DOE) and statistical regression technique as an important approach for modeling flux and rejection. In terms of experiments, a response surface methodology (RSM) and a central composite design (CCD) were used, whereby the factorial part was a fractional factorial design with resolution V and overall, it consisted of a combination of high levels and low levels, center points, as well as axial points. Furthermore, the regression models were generated by employing the Design Expert 6.0.5 software and they were found to be significant and valid. Then, the regression models obtained were proposed as the objective functions of NSGA-II to determine the optimal spinning conditions. The MATLAB software was used to code and execute the NSGA-II. With that, a non-dominated solution set was obtained and reported. It was discovered that the optimal spinning conditions occurred at a DER of 2.20 $cm^3$/min, AGL of 0 cm, CBT of 30 °C, BFR (NMP/$H_2O$) of 0/100 wt.%, and PT of 6 hour. In addition, the membrane morphology under the influence of different spinning conditions was investigated via a scanning electron microscope (SEM). The proposed optimization method based on NSGA-II offered an effective way to attain simple but robust solutions, thus providing an efficient production of PES ultrafiltration hollow fiber membranes to be used in oily wastewater treatment. Therefore, the optimization results contributed by NSGA-II can assist engineers and researchers to make better spinning optimization decisions for the membrane fabrication process.

# ABSTRAK

Pengoptimuman keadaan pintalan memainkan peranan penting dalam pembangunan membran gentian geronggang asimetrik yang berprestasi tinggi. Walaubagaimanapun, dari kajian lepas, kebanyakan masalah pengoptimuman keadaan pintalan telah diselesaikan menggunakan uji kaji yang hanya mengubah satu keadaan pintalan dan menetapkan keadaan yang lain. Masalah yang kerap berlaku adalah proses pembuatan membran gentian geronggang tidak dapat dijalankan dengan berkesan disebabkan tetapan keadaan pintalan yang kurang sesuai. Tambahan pula, proses pintalan semakin kompleks, di mana interaksi antara keadaan pintalan dengan kehadiran pelbagai objektif juga memberi kesan kepada pengoptimuman keadaan pintalan. Ini merupakan salah satu sebab utama mengapa kurang penyelidikan dilakukan untuk mengkaji keadaan pintalan secara serentak. Untuk menangani isu ini, kajian ini menggunakan metodologi algoritma genetik tidak terdominasi-II (NSGA-II) untuk mengoptimumkan keadaan pintalan dalam pembuatan membran gentian geronggang ultrapenurasan polietersulfon (PES) untuk rawatan air sisa berminyak bagi memaksimumkan fluk dan kadar buangan. Keadaan pintalan yang dikaji adalah kadar penyemperitan dop (DER), ketinggian sela udara (AGL), suhu takungan pengentalan (CBT), nisbah bendalir liang (BFR) dan masa pasca-rawatan (PT). Pertama, kajian ini meramalkan prestasi membran gentian geronggang menggunakan reka bentuk eksperimen (DOE) dan teknik regrasi statistik bagi pemodelan fluk dan kadar buangan. Dari segi eksperimen, kaedah sambutan berpusat (RSM) dan mod reka bentuk komposit pusat (CCD) digunakan, yang mana bahagian faktoran adalah reka bentuk faktoran pecahan dengan resolusi V, dan keseluruhannya, ia terdiri daripada gabungan tahap tinggi dan tahap rendah, titik tengah dan mata paksi. Perisian Design Expert 6.0.5 telah menghasilkan model regrasi dan model didapati penting dan sah. Kemudian, model regrasi yang diperolehi dicadangkan sebagai fungsi objektif NSGA-II untuk menentukan keadaan pintalan optimum. Perisian MATLAB digunakan untuk mengekod dan melaksanakan NSGA-II. Satu set penyelesaian tidak dominasi telah diperoleh dan dilaporkan. Didapati bahawa keadaan pintalan optimum berlaku pada DER 2.20 $cm^3$/min, AGL 0 cm, CBT 30 °C, BFR ($NMP/H_2O$) 0/100 wt.% dan PT 6 jam. Tambahan pula, morfologi membran di bawah pengaruh keadaan berputar berbeza disiasat menggunakan mikroskop elektron pengimbas (SEM). Cadangan kaedah pengoptimuman berdasarkan NSGA-II menawarkan satu cara yang berkesan untuk memperoleh penyelesaian yang mudah tetapi teguh bagi pembuatan membran gentian geronggang ultrapenurasan PES yang digunakan dalam rawatan air sisa berminyak secara cekap. NSGA-II memberi penyelesaian pengoptimuman yang dapat membantu jurutera dan penyelidik membuat keputusan pengoptimuman pintalan secara lebih baik dalam proses pembuatan membran.

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| | | |
|---|---|---|
| ABC | - | Artificial bee colony algorithm |
| ACO | - | Ant colony optimization |
| AGL | - | Air gap length |
| AI | - | Artificial intelligence |
| ANN | - | Artificial neural network |
| ANOVA | - | Analysis of variance |
| BFT | - | Bore fluid temperature |
| BFR | - | Bore fluid ratio |
| BFFR | - | Bore fluid flow rate |
| BSA | - | Bovine serum albumin |
| CA | - | Cellulose acetate |
| CBT | - | Coagulation bath temperature |
| CCD | - | Central composite design |
| DCMD | - | Direct contact membrane distillation |
| DER | - | Dope extrusion rate |
| DOE | - | Design of experiments |
| DP | - | Dynamic programming |
| DT | - | Dope temperature |
| EA | - | Evolutionary algorithm |
| GA | - | Genetic algorithm |
| GFR | - | Gas flushing rate |
| GUI | - | Graphical user interface |
| HMWC | - | High molecular weight component |
| HQ | - | Hydroquinone |
| HT | - | High throughput |

| | | |
|---|---|---|
| ID | - | Inner diameter |
| LMWC | - | Low molecular weight component |
| LP | - | Linear programming |
| MATLAB | - | Matrix laboratory |
| MED | - | Multiple effect distillation |
| MF | - | Microfiltration |
| MINLP | - | Mixed-integer non-linear programming |
| MOEA | - | Multi-objective evolutionary algorithm |
| MOGA | - | Multi-objective genetic algorithm |
| MOP | - | Multi-objective optimization problem |
| MPDA | - | m-Phenylenediamine |
| MWCO | - | Molecular weight cut-off |
| NF | - | Nanofiltration |
| NLP | - | Non-linear programming |
| NMP | - | *N*-methyl-2-pyrrolidone |
| NP | - | Non-deterministic polynomial |
| NPF | - | Number of Pareto front |
| NPGA | - | Niched Pareto genetic algorithm |
| NSGA | - | Non-dominated sorting genetic algorithm |
| NSGA-II | - | Non-dominated sorting genetic algorithm-II |
| OD | - | Outer diameter |
| P | - | Post-treatment |
| PAES | - | Pareto-archieved evolution strategy |
| PAI | - | Polyamide–imide |
| PAN | - | Polyacrylonitrile |
| PBI | - | Polybenzimidazole |
| PDMS | - | Polydimethylsiloxane |
| PE | - | Polyethylene |
| PEEKWC | - | Modified poly(ether ether ketone) |
| PEI | - | Polyetherimide |
| PEG | - | Poly(ethylene) glycol |
| PES | - | Polyethersulfone |
| PI | - | Polyimide |
| PLGA | - | Poly(lactic-co-glycolic acid) |

| | | |
|---|---|---|
| PP | - | Polypropylene |
| PRESS | - | Predicted residual sum of squares |
| PSF | - | Polysulfone |
| PSO | - | Particle swarm optimization |
| PT | - | Post-treatment time |
| PU | - | Polyurethane |
| PVDF | - | Polyvinylidene fluoride |
| PVDF-HFP | - | Poly (vinylidene fluoride-co-hexafluoropropylene) |
| PVP | - | Polyvinylpyrrolidone |
| PWP | - | Pure water permeability |
| RDGA | - | Rank-density based genetic algorithm |
| RH | - | Relative humidity |
| RO | - | Reverse osmosis |
| RSM | - | Response surface methodology |
| RT | - | Residence time |
| RWGA | - | Random weighted genetic algorithm |
| SA | - | Simulated annealing |
| SEM | - | Scanning electron microscope |
| SEPPI | - | Solidification of emulsified polymer solutions via phase inversion |
| SPEA | - | Strength Pareto evolutionary algorithm |
| SS | - | Spinneret size |
| ST | - | Spinneret temperature |
| TBAB | - | Tetrabutylammonium bromide |
| TMP | - | Transmembrane pressure |
| TS | - | Take-up speed |
| UF | - | Ultrafiltration |
| VEGA | - | Vector evaluated genetic algorithm |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $A$ | - | Surface area of hollow fiber membrane |
| $C_f$ | - | Concentration of solute area of feed |
| $C_p$ | - | Concentration of solute area of permeate |
| $D$ | - | Outer diameter of hollow fiber membrane |
| $F_j(x)$ | - | Function of flux |
| $F_r(x)$ | - | Function of rejection |
| $i_{distance}$ | - | Crowding distance |
| $i_{rank}$ | - | Non-domination rank |
| $J$ | - | Flux |
| L | - | Liter |
| $l$ | - | Effective length of hollow fiber membrane |
| $n$ | - | Number of hollow fiber membrane in module |
| $N_p$ | - | Population size |
| $P_c$ | - | Probability of crossover |
| $P_m$ | - | Probability of mutation |
| $P_t$ | - | Population |
| $P^*$ | - | Pareto optimal set |
| $PF^*$ | - | Pareto front |
| $Q$ | - | Water flux reading |
| $Q_t$ | - | Population after selection, crossover and mutation |
| $R$ | - | Rejection |
| $R_t$ | - | Combined population |
| $t$ | - | Time |
| $T_s$ | - | Tournament size |

| | | |
|---|---|---|
| $V$ | - | Permeate volume |
| $w$ | - | Pseudo-weight |
| $\Delta P$ | - | Difference of pressure between feed area and permeation area |
| $\sigma$ | - | Standard deviation |
| $\Omega$ | - | Decision space |
| $\infty$ | - | Infinity |
| $\prec_n$ | - | Crowded comparison operator |
| $\mathbb{R}^n$ | - | Decision variable space |
| $\mathbb{R}^k$ | - | Objective function space |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Research

At present, the global oil demand is rising due to the rapid development of many industries, such as automobile and high fuel consumption for manufacturing industries. As a consequence, massive volumes of oily wastewater have been produced from the oil purifier industry (Agustin *et al*., 2008; Ong *et al*., 2015). Since oily wastewater consists of various hazardous hydrocarbon compositions, chemical elements and heavy metals prior to discharging them to receiving water body, it needs to be treated. However, biological, chemical, and physical treatments are incapable of completely separating the oil molecules from water and the process necessitates a huge area for operation (El-Naas *et al*., 2009).

Therefore, in order to overcome this issue, membrane separation has become one of the most effective and demanding techniques used to fulfill demands in numerous industrial processes based on separation (Gryta *et al*., 2001). The ability of this membrane technology in separating multi-component compositions into two or more preferred outputs has allowed it to become a more popular choice, considering its potentials and benefits. The advances made by Loeb and Sourirajan in 1960s in high-flux asymmetric membranes have led to further development of membrane separation techniques. Since then, this technology has attracted much attention and support for research. In the last thirty years, membrane filtration was not economically realistic, however, with the advanced technological revolutions of new substances, procedures, and targets, membrane technology has been recognized as a very successful and commercially attractive choice for separation and purification system (Wiesner and Chellam, 1999). Thus, the membrane filtration technology offers a promising avenue of study and innovation to provide better solutions for sufficient supply of clear water in fulfilling human, environmental, and industrial demands. Nevertheless, in the development of high performance membranes, several aspects need to be considered, such as membrane process, membrane module, and membrane material, in order to provide some basic understanding of the membrane formation mechanism.

There are numerous membrane separation processes are available. One of the membrane processes that have experienced rapid growth during the past few years is ultrafiltration. Typically, ultrafiltration membranes are used for the separation of very tiny suspended molecules and dissolved macromolecules from mixtures by utilizing asymmetric membranes, which possess the size of pores ranging from 0.01 to 0.1 μm. These membranes are normally conducted in a tangential stream mode where the flow of feed solution that sweeps tangentially passes through an upstream surface of membranes (Chaturvedi *et al.*, 2001). Besides, ultrafiltration has the widest diversity of application in numerous industries compared to other membranes processes since it is a separation technology that possesses high efficiency and low energy consumption (Nunes and Peinemann, 2006).

In addition, materials used for the membranes cover a broad range, from organic polymeric to inorganic substances. In fact, many studies have been carried out in the last few years to enhance membranes performance, as well as to search for new membrane materials and techniques to fabricate high performance membranes. Polymeric membranes have been well-established in most areas of industrial applications due to the significant development by Loeb and Sourirajan in 1960s for their finding to fabricate asymmetric membrane structures. In addition, membrane separation processes using polymeric membranes have been quite marketable. In this study, polyethersulfone (PES) had been chosen as the prime material (polymer) because of its easier accessibility and processing, good characteristics of selectivity, as well as permeability and strong mechanical properties (Li *et al*., 2004). Beside, PES is classified as an amorphous glassy and hydrophilic polymer in the sulfone group and it is appropriate to be utilized in ultrafiltration separation process through dry-wet inversion process. Also, the ultrafiltration membranes fabricated from PES polymer displayed a broad range of pH and temperature resistance (Wang *et al.*, 2010).

The membrane module is another critical aspect to contemplate as the process productivity and performance depend on it. Among membrane modules, hollow fiber configuration is more favorable for industrial applications mainly due to its huge membrane packing density, which permits it to have a high membrane area in a little tool (Darvishmanesh *et al.*, 2011). In addition, in comparison to flat sheet and spiral wound modules, the hollow fiber module is the preferred option for modules in filtration process as it possesses several good benefits, which are greater productivity due to strong mechanical properties, a very flexible module, and easy handling (Khayet *et al*., 2012; Qin and Chung, 1999). These excellent features cause hollow fiber membranes irresistible from the industrial viewpoint. Moreover, at present, hollow fiber membranes are extensively applied in many areas especially in membrane separation areas, such as distillation, nanofiltration, reverse osmosis, and many more.

On the other hand, phase inversion spinning technique has been universally accepted as a standard technique for fabricating commercial membranes. It is also referred to as a process where spinning solution is transfigured from liquid to solid state. It is widely used and has become a favored technique to fabricate asymmetric hollow fiber membranes. In short, an operation of phase inversion spinning technique starts when a spinning solution is submerged and solidified in the coagulation bath. Throughout the process, the solvent and non-solvent in the spinning solution are exchanged. As a result, it produces a property structure of the asymmetric membrane, which comprises of a dense top layer and porous sublayer (Jung *et al.*, 2004). In this research, asymmetric PES ultrafiltration hollow fiber membranes would be fabricated according to the dry-wet phase inversion spinning technique.

In the current state-of-the-art, many researchers are involved in developing, exploring, and expanding high performance membranes. Generally, membrane performance can be classified in terms of two basic attributes, which are membrane productivity (flux) and extent of separation (rejection of various feed components). Flux and rejection are closely related to both the inner and outer skin layers. When inner and outer surfaces possess an open structure, the pure water permeation flux increases, whereas rejection decreases accordingly (Aminudin *et al.*, 2013). In common, membranes with the highest flux and rejection are necessary and can be classified as a high performance membrane, where normally, efforts to maximize one attribute will decrease the other (Qin *et al.*, 2000; Sourirajan and Matsuura, 1985). Hence, the challenge of this research is to maximize membrane performance by enhancing the separation productivity through improving both flux and rejection.

## 1.2 Problem Statement

In the fabrication of hollow fiber membranes via dry-wet spinning technique, spinning conditions will dominate the properties of hollow fiber membranes in terms of morphology and separation performances. Besides, a lot of efforts have been made to study the relationship between membrane characteristics and spinning parameters. So far, numerous studies have reported varied effects of the spinning conditions like composition of dope solution, concentration of dope solution, air gap length and many more concerning the hollow fiber membranes performances. Nevertheless, not much has been said regarding the simultaneous effect of the parameters (i.e. dope extrusion rate, air gap length, coagulation bath temperature, bore fluid ratio and post-treatment time), which are yet to be investigated on the performance of hollow fiber membranes.

On top of that, the optimization of preparation settings of membranes fabrication plays a key role in membranes performance (Yi *et al.*, 2010). Determining an optimal solution by using an appropriate optimization method is quite challenging for researchers. Moreover, the complexities in the spinning process have increased where the interaction effects between the spinning conditions also contribute to finding the optimal spinning conditions. It must be pointed out that from previous studies in solving these spinning condition optimization problems, they were handled mostly by using an experimentation that involved changing one of the spinning conditions while maintaining the others at fixed levels. Moreover, from previous studies, there were many researchers who used the parameter-by-parameter optimization method to optimize the spinning conditions in fabricating hollow fiber membranes and it was based on trial and error investigations. Furthermore, the complexity of membrane preparation problems, as numerous parameters are involved, is one of the main reasons why very little work has been done to vary all these spinning parameters simultaneously (Chung *et al.*, 2002; Xu and Qusay, 2004). For instance, Chung *et al.* (2002), Chung *et al.* (1998), Ismail *et al.* (2006), and Qin *et al.* (2000) varied the dope extrusion rate factor only and fixed other factors in fabricating PES ultrafiltration hollow fiber membranes. Meanwhile, Chung and Hu (1997), Kapantaidakis *et al.* (2002), Khayet (2003), and Qin *et al.* (2001) varied the air gap length only and fixed other factors during membrane fabrication. In addition, there were several researchers who varied two and more factors of these spinning conditions by using the parameter-by-parameter optimization technique. Apparently, the drawbacks of this classical approach are that it needs a lot of experimental work and time, does not consider any interaction between the spinning conditions during the spinning process, and displays lower capability in optimization. Thus, it takes tremendous effort to obtain the best optimal spinning conditions. Even though traditional optimization techniques have the ability of considering several parameters at the same time, they still fail to acquire the relationship equation that links the varied parameters and the outcomes, and besides, it is not easy to discover the optimal parameters combination and optimal response value in the entire area. Furthermore, one of the common problems is that the hollow fiber membrane spinning process cannot be performed effectively due to the inappropriate settings of the spinning conditions (Khayet *et al.*, 2012). In general, most researchers have sought for the most appropriate settings of spinning process using a small number of experiments by keeping all conditions fixed and only varying one condition in a small range as it is more practical to be performed (Chung *et al.*, 2000).

These shortcomings of the classical method can be solved by using the response surface methodology (RSM), in which all parameters are varied simultaneously by using a set of experimental trials. By applying RSM, many spinning condition parameters can be investigated at the same time and the number of experimental trials can be minimized in comparison to the optimization technique based on trial and error attempts (Khayet *et al.*, 2012). In other words, RSM offers more benefits than the familiar conventional optimization method. RSM is faster and reliable, more informative, as well as involves a small number of experiments that save time and operation costs. Nevertheless, the spinning condition optimization problems are indeed challenging and the complexity further increases with the presence of multiple objectives.

From the above discussion, these problems are inherently multi-faceted and involve spinning conditions at various levels, which necessitate multiple objectives to be satisfied. The membranes that possess the highest flux and rejection are classified as high performances membranes (Aminudin *et al.*, 2013; Sourirajan and Matsuura, 1985). Normally, efforts to maximize the flux will have to decrease the rejection. Also, this problem could be categorized as a non-deterministic polynomial (NP)-hard problem. Therefore, multi-objective optimization is one such tool that can come in handy to solve these spinning optimization problems. Hence, a non-dominated sorting genetic algorithm-II (NSGA-II) approach is proposed for solving the spinning problem. NSGA-II is a commonly used global search algorithm due to its outstanding global search ability (Li *et al.*, 2015). Fundamental understanding in optimizing spinning conditions in membrane fabrication is still in its early stage and not many researchers have reported the application of NSGA-II in optimizing spinning conditions in the PES ultrafiltration hollow fiber membrane fabrication. Thus, a crucial task in exploiting and optimizing novel, robust, and high performance membranes is thus to carry out further dynamic search approaches that quickly focus on the most potential optimal spots within the parameter space. As a result, it increases the possibility of discovering the membrane, which possesses the best separation performance (Vandezande *et al.*, 2009).

Thus, the present study in spinning conditions optimization is required to be undertaken in two stages: (i) modeling of input-output and in-process spinning parameter relationship, and (ii) determination of optimal spinning conditions. The spinning conditions considered dominantly affecting the preparation of PES ultrafiltration hollow fiber membranes are the dope extrusion rate (DER), air gap length (AGL), coagulation bath temperature (CBT), bore fluid ratio (BFR) and post-treatment time (PT). Particularly, design of experiments (DOE) (including central composite design (CCD) and response surface methodology (RSM)) integrated with the NSGA-II methodology are used for these purposes in the development of PES ultrafiltration hollow fiber membranes. Regression models are constructed based on DOE to model the spinning conditions during the fabrication of these membranes via phase inversion spinning technique. Then, these models are expressed as a fitness function of NSGA-II with the objective of maximizing the membrane performance in terms of flux and rejection. The optimization of spinning condition parameters that affect the membrane performance will be explored by using NSGA-II.

## 1.3 Research Questions

This research is primary to seek answers for these two major questions.

(i) Which parameters or factors affect membrane performance in terms of flux and rejection?

(ii) What are the optimal spinning conditions for PES ultrafiltration hollow fiber membranes fabrication?

## 1.4 Objective of the Research

The objectives of this research are to produce both high flux and rejection of PES ultrafiltration hollow fiber membranes by optimizing the spinning conditions in membrane fabrication. Based on the problems and research questions discussed in the previous sections, the objectives of this study are given as follows:

(i) To determine the significant spinning parameters and their relationship using DOE. Additionally, the microstructures of PES ultrafiltration hollow fiber membranes are also investigated by using a scanning electron microscope (SEM).

(ii) To optimize the spinning conditions used in the fabrication of PES ultrafiltration hollow fiber membranes by using the NSGA-II method.

## 1.5 Scope of the Research

To achieve the objectives of this research, some guidelines should be followed. Several main scopes for this study have been recognized as guidelines in order to optimize the spinning conditions in membrane fabrication as well as to produce high performance PES ultrafiltration hollow fiber membranes.

(i) The spinning process conditions investigated cover those from the dope formulation stage until the post-treatment process.
(ii) PES as a polymeric material is used in the dope formulation.
(iii) Flux and rejection rate are used to characterize the membrane performance.
(iv) Synthesized oily wastewater is used to characterize the separation performance.
(v) DOE is used to develop the predicted regression models to show the relationships between the spinning conditions and membrane performance.
(vi) NSGA-II is used to find the optimal spinning conditions.
(vii) The MATLAB version 7.9.0529 (R2009b) is used to implement the NSGA-II optimization process.

## 1.6 Significance of the Research

The recent development of PES ultrafiltration hollow fiber membranes via NSGA-II has highlighted several advantages from this study. Most notably, it helps to provide an efficient spinning process, which makes the fabrication of membranes to become more effective and productive, as well as requiring small investment, energy consumption, and operating cost. The process also becomes an economical approach and yields a good quality product, while relatively the PES ultrafiltration hollow fiber membranes with desired properties can be obtained. Thus, the knowledge acquired from this study will boost the future researches on membranes development, especially in the spinning process, to further provide better understanding in treating oily wastewater with a combination of various spinning conditions.

Removal of oily wastewater using the ultrafiltration process is very much crucial to contribute towards the availability of sustainable water supply system. The membrane separation is a good performance separation where the separation is based on a size of molecular, with low energy consumption, thus requiring small operating cost compared to the traditional techniques. Since PES is the most promising membrane to treat oily wastewater, this study developed the PES ultrafiltration hollow fiber membranes, while the membrane performances were evaluated in terms of flux and rejection. The impact of this study is important since the PES ultrafiltration hollow fiber membranes fabricated offers prospect of higher productivity and selectivity, as well as prominent boost in membrane performance. Indirectly, this research can help manufacturers to produce high performance membranes, which can contribute to provide fresh water resources and good quality treated water in regions around the world.

Lastly, the findings obtained from this research had been used to determine the optimal setting of the spinning process during membrane fabrication by presenting a new practical NSGA-II methodology for optimization of the spinning process. The emphasis of this study is to offer engineers or decision makers a preferred solution within a short period of time. Requirements and specifications from them can help and lead to choose the best solution. If they desire higher flux or any specific rejections, the appropriate combinations of spinning conditions can be selected accordingly. Thus, NSGA-II stimulates to enhance the production rate of membranes, besides, reducing spinning operation time that saves a lot of costs.

## 1.7 Structure of the Thesis

This thesis consists of seven chapters. The first chapter introduces the technology of membranes especially in membrane fabrication and its importance in separation and purification systems. It also includes the problem statement, research questions, objectives, scope and significance of the study. Chapter 2 gives a comprehensive overview of the studies conducted on membranes in many aspects especially in membrane manufacturing systems. It reviews the various issues of the usage of NSGA-II for optimizing the spinning conditions in membranes fabrication and its applications. Additionally, the notion and procedures of NSGA-II for solving problems are discussed. Chapter 3 presents the materials and methods as well as detailed procedures of each experiment conducted. Chapter 4 explains the development of the spinning regression models based on the DOE and statistical regression technique. Chapter 5 discusses the optimization process in solving the models using NSGA-II. Chapter 6 analyzes the results of the experimental studies. The last chapter gathers the conclusions of this study and the recommendations for future work.

(ACO), simulated annealing (SA), etc.

# REFERENCES


Abou EL Ela, A. A. & Spea, S. R. (2009). Optimal Corrective Actions for Power Systems using Multi-Objective Genetic Algorithms. *Electric Power Systems Research*, 79(5), 722–733.

Agustin, M. B., Sengpracha, W. P. & Weerachai, P. (2008). Electrocoagulation of Palm Oil Mill Effluent. *International Journal of Environmental Research and Public Health*, 5(3), 177–180.

Ahmadi, M., Vahabzadeh, F., Bonakdarpour, B., Mofarrah, E. & Mehranian, M. (2005). Application of the Central Composite Design and Response Surface Methodology to the Advanced Treatment of Olive Oil Processing Wastewater Using Fenton's Peroxidation. *Journal of Hazardous Materials*, B123, 187–195.

Akdemir, E. O. & Ozer, A. (2009). Investigation of Two Ultrafiltration Membranes for Treatment of Olive Oil Mill Wastewater. *Desalination*, 249(2), 660–666.

Al-Alawy, A. F. & Al-Musawi, S. M. (2013). Microfiltration Membranes for Separating Oil / Water Emulsion. *Iraqi Journal of Chemical and Petroleum Engineering*, 14(4), 53–70.

Alaei Shahmirzadi, M. A., Hosseini, S. S., Ruan, G. & Tan, N. R. (2015). Tailoring PES Nanofiltration Membranes through Systematic Investigations of Prominent Design, Fabrication and Operational Parameters. *RSC Advances*, 5(61), 49080–49097.

Albrecht, W., Weigel, T., Schossig-Tiedemann, M., Kneifel, K., Peinemann, K. V. & Paul, D. (2001). Formation of Hollow Fiber Membranes from Poly(ether imide) at Wet Phase Inversion Using Binary Mixtures of Solvents for the Preparation of the Dope. *Journal of Membrane Science*, 192(1), 217–230.

Ali, N., Halim, N. S. A., Jusoh, A. & Endut, A. (2010). The Formation and Characterisation of an Asymmetric Nanofiltration Membrane for Ammonia-

Nitrogen Removal: Effect of Shear Rate. *Bioresource Technology*, 101(5), 1459–1465.

Aminudin, N. N., Basri, H., Harun, Z., Zaini, M. & Sean, G. P. (2013). Comparative Study on Effect of PEG and PVP as Additives on Polysulfone (PSF) Membrane Structure and Performance. *Jurnal Teknologi*, 4(LiCl), 47–51.

Amirilargani, M., Saljoughi, E., Mohammadi, T. & Moghbeli, M. R. (2010). Effects of Coagulation Bath Temperature and Polyvinylpyrrolidone Content on Flat Sheet Asymmetric Polyethersulfone Membranes. *Polymer Engineering and Science*, 50(5), 885–893.

Antony, J. (2001). Improving the Manufacturing Process Quality Using Design of Experiments: A Case Study. *International Journal of Operations & Production Management*, 21(5/6), 812–822.

Aptel, P., Abidine, N., Ivaldi, F. & Lafaille, J. P. (1985). Polysulfone Hollow Fibers — Effect of Spinning Conditions on Ultrafiltration Properties*. *Journal of Membrane Science*, 22(2), 199–215.

Aroon, M. A., Ismail, A. F., Montazer-Rahmati, M. M. & Matsuura, T. (2010). A Mathematical Analysis of Hollow Fiber Spinning: Bore and Dope Velocity Profiles in the Air Gap. *Journal of Membrane Science*, 348(1), 13–20.

Ayala, H. V. H. & Coelho, L. D. S. (2012). Tuning of PID Controller Based on a Multiobjective Genetic Algorithm Applied to a Robotic Manipulator. *Expert Systems with Applications*, 39(10), 8968–8974.

Ayala, H. V. H. & Coelho, L. dos S. (2008). A Multiobjective Genetic Algorithm Applied to Multivariable Control Optimization. *ABCM Symposium Series in Mechatronics*, 3, 736–745.

Baker, R. W. (2002). *Membrane Technology. Encyclopedia of Polymer Science and Technology*. John Wiley & Sons, Inc.

Bakeri, G., Rana, D., Ismail, A. F., Matsuura, T. & Ghaee, A. (2013). Performance of Surface-Modified Poly(ether imide) Hollow-Fiber Membranes in a Membrane Gas-Liquid Contacting Process with Response Surface Methodology. *Journal of Applied Polymer Science*, 128(2), 1313–1325.

Basu, M. (2008). Dynamic Economic Emission Dispatch Using Nondominated Sorting Genetic Algorithm-II. *Electrical Power and Energy Systems*, 30(2), 140–149.

Basu, M. (2011). Economic Environmental Dispatch of Fixed Head Hydrothermal Power Systems Using Nondominated Sorting Genetic Algorithm-II. *Applied Soft Computing*, 11(3), 3046–3055.

Belfort, G., Weigand, R. J. & Mahar, J. T. (1985). Particulate Membrane Fouling and Recent Developments in Fluid-Mechanics of Dilute Suspensions. In *Reverse Osmosis and Ultrafiltration* (pp. 28–383). American Chemical Society.

Bhajantri, L. B. & Nalini, N. (2013). Optimization of Routing in Distributed Sensor Networks Using Heuristic Technique Approach. *International Journal of Computer Network and Information Security*, 11, 42–50.

Blickle, T. (1996). Evolving Compact Solutions in Genetic Programming: A Case Study. *Proceedings of the International Conference on Evolutionary Computation*. 22–26 September. Berlin, Germany: Springer-Verlag, 564–573.

Blickle, T. & Thiele, L. (1995). A Comparison of Selection Schemes used in Genetic Algorithms. *Evolutionary Computation*, 2(11), 311–347.

Blum, A. (1992). *Neural Networks in C++: An Object-Oriented Framework for Building Connectionist Systems. Professional Computing*. New York, USA: John Wiley & Sons, Inc.

Bonyadi, S. & Chung, T. S. (2007). Flux Enhancement in Membrane Distillation by Fabrication of Dual Layer Hydrophilic-Hydrophobic Hollow Fiber Membranes. *Journal of Membrane Science*, 306(1), 134–146.

Box, G. E. P. & Draper, N. R. (1986). *Empirical Model-Building and Response Surface*. New York, USA: John Wiley & Sons, Inc.

Bulut, M., Gevers, L. E. M., Paul, J. S., Vankelecom, I. F. J. & Jacobs, P. A. (2006). Directed Development of High-Performance Membranes via High-Throughput and Combinatorial Strategies. *Journal of Combinatorial Chemistry*, 8(2), 168–173.

Cano-Odena, A., Spilliers, M., Dedroog, T., De Grave, K., Ramon, J. & Vankelecom, I. F. J. (2011). Optimization of Cellulose Acetate Nanofiltration Membranes for Micropollutant Removal via Genetic Algorithms and High Throughput Experimentation. *Journal of Membrane Science*, 366(1), 25–32.

Cao, C., Chung, T. S., Chen, S. B. & Dong, Z. (2004). 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(5), 1053–1062.

Caro, S., Chablat, D., Ur-Rehman, R. & Wenger, P. (2011). Multiobjective Design Optimization of 3–PRR Planar Parallel Manipulators. In *Global Product Development* (pp. 373–383). Springer-Verlag Berlin.

Chang, H. & Hou, W. C. (2006). Optimization of Membrane Gas Separation Systems Using Genetic Algorithm. *Chemical Engineering Science*, 61(16), 5355–5368.

Chaturvedi, B. K., Ghosh, A. K., Ramachandhran, V., Trivedi, M. K., Hanra, M. S. & Misra, B. M. (2001). Preparation, Characterization and Performance of Polyethersulfone Ultrafiltration Membranes. *Desalination*, 133(1), 31–40.

Chen, Y., Zou, X. & Xie, W. (2011). Convergence of Multi-Objective Evolutionary Algorithms to a Uniformly Distributed Representation of the Pareto Front. *Information Sciences*, 181(16), 3336–3355.

Chou, W. L. & Yang, M. C. (2005). Effect of Take-Up Speed on Physical Properties and Permeation Performance of Cellulose Acetate Hollow Fibers. *Journal of Membrane Science*, 250(1), 259–267.

Chung, T. S. & Hu, X. (1997). Effect of Air-Gap Distance on the Morphology and Thermal Properties of Polyethersulfone Hollow Fibers. *Journal of Applied Polymer Science*, 66(6), 1067–1077.

Chung, T. S. & Kafchinski, E. R. (1997). The Effects of Spinning Conditions on Asymmetric 6FDA/6FDAM Polyimide Hollow Fibers for Air Separation. *Journal of Applied Polymer Science*, 65, 1555–1569.

Chung, T. S., Qin, J. J. & Gu, J. (2000). Effect of Shear Rate within the Spinneret on Morphology, Separation Performance and Mechanical Properties of Ultrafiltration Polyethersulfone Hollow Fiber Membranes. *Chemical Engineering Science*, 55(6), 1077–1091.

Chung, T. S., Qin, J. J., Huan, A. & Toh, K. C. (2002). Visualization of the Effect of Die Shear Rate on the Outer Surface Morphology of Ultrafiltration Membranes by AFM. *Journal of Membrane Science*, 196(2), 251–266.

Chung, T. S., Ren, J., Wang, R., Li, D., Liu, Y., Pramoda, K. P., Chun, C. & Loh, W. W. (2003). Development of Asymmetric 6FDA-2,6DAT Hollow Fiber Membranes for $CO_2/CH_4$ Separation Part 2. Suppression of Plasticization. *Journal of Membrane Science*, 214, 57–69.

Chung, T. S., Shieh, J. J., Lau, W. W. Y., Srinivasan, M. P. & Paul, D. R. (1999). Fabrication of Multi-Layer Composite Hollow Fiber Membranes for Gas Separation. *Journal of Membrane Science*, 152(2), 211–225.

Chung, T. S., Teoh, S. K. & Hu, X. (1997). Formation of Ultrathin High-Performance Polyethersulfone Hollow-Fiber Membranes. *Journal of Membrane Science*, 133(2), 161–175.

Chung, T. S., Teoh, S. K., Lau, W. W. Y. & Srinivasan, M. P. (1998). Effect of Shear Stress within the Spinneret on Hollow Fiber Membrane Morphology and Separation Performance. *Industrial & Engineering Chemistry Research*, 37(10), 3930–3938.

Chung, T. S., Xu, Z. L. & Lin, W. (1999). Fundamental Understanding of the Effect of Air-Gap Distance on the Fabrication of Hollow Fiber Membranes. *Journal of Applied Polymer Science*, 72(3), 379–395.

Chwojnowski, A., Wojciechowski, C., Dudzinski, K. & Lukowska, E. (2009). Polysulphone and Polyethersulphone Hollow Fiber Membranes with Developed Inner Surface as Material for Bio-Medical Applications. *Biocybernetics and Biomedical Engineering*, 29(3), 47–59.

Clausi, D. T. & Koros, W. J. (2000). Formation of Defect-Free Polyimide Hollow Fiber Membranes for Gas Separations. *Journal of Membrane Science*, 167(1), 79–89.

Coelho, L. dos S. & Alotto, P. (2008). Multiobjective Electromagnetic Optimization Based on a Nondominated Sorting Genetic Approach With a Chaotic Crossover Operator. *IEEE Transactions on Magnetics*, 44(6), 1078–1081.

Coello Coello, C. A. (1999). A Comprehensive Survey of Evolutionary-Based Multiobjective Optimization Techniques. *Knowledge and Information Systems*, 1(3), 269–308.

Coello Coello, C. A. (2006). Evolutionary Multi-Objective Optimization: A Historical View of the Field. *IEEE Computational Intelligence Magazine*, 1(1), 28–36.

Coello Coello, C. A., Lamont, G. B. & Van Veldhuizen, D. A. (2007). *Evolutionary Algorithms for Solving Multi-Objective Problems* (2nd ed.). Springer.

Coello Coello, C. A., Van Veldhuizen, D. A. & Lamont, G. B. (2002). *Evolutionary Algorithms for Solving Multiobjective Problems. Genetic and Evolutionary Computation Series* (1st ed.). Springer.

Coit, D. W., Jackson, B. T. & Smith, A. E. (1998). Static Neural Network Process Models: Considerations and Case Studies. *International Journal of Production Research*, 36(11), 2953–2967.

Cojocaru, C. & Zakrzewska-Trznadel, G. (2007). Response Surface Modeling and Optimization of Copper Removal from Aqua Solutions Using Polymer Assisted Ultrafiltration. *Journal of Membrane Science*, 298, 56–70.

Cui, Z. F. & Muralidhara, H. S. (2010). *Membrane Technology: A Practical Guide to Membrane Technology and Applications in Food and Bioprocessing* ($1^{st}$ ed.). Butterworth-Heinemann.

Dahe, G. J., Teotia, R. S. & Bellare, J. R. (2012). Correlation Between Spinning Temperature, Membrane Morphology, and Performance of Psf/PVP/NMP/Water Hollow Fiber Membrane Forming System. *Journal of Applied Polymer Science*, 124, E134–E146.

Darvishmanesh, S., Tasselli, F., Jansen, J. C., Tocci, E., Bazzarelli, F., Bernardo, P., Luis, P., Degreve, J., Drioli, E. & Van der Bruggen, B. (2011). Preparation of Solvent Stable Polyphenylsulfone Hollow Fiber Nanofiltration Membranes. *Journal of Membrane Science*, 384(1), 89–96.

De Rovere, A., Grady, B. P. & Shambaugh, R. L. (2002). The Influence of Processing Parameters on the Properties of Melt-Spun Polypropylene Hollow Fibers. *Journal of Applied Polymer Science*, 83(8), 1759–1772.

Deb, K. (2001). *Multi-Objective Optimization Using Evolutionary Algorithms* ($1^{st}$ ed.). New York, NY, USA: John Wiley & Sons, Inc.

Deb, K. (2005). Multi-Objective Optimization. In *Search Methodologies* (pp. 273–316). US: Springer.

Deb, K., Pratap, A., Agarwal, S. & Meyarivan, T. (2002). A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2), 182–197.

Deb, K., Rao N., U. B. & Karthik, S. (2007). Dynamic Multi-Objective Optimization and Decision-Making Using Modified NSGA-II: A Case Study on Hydro-Thermal Power Scheduling. In *Evolutionary Multi-Criterion Optimization* (pp. 803–817). Springer Berlin Heidelberg.

Digalakis, J. G. & Margaritis, K. G. (2001). On Benchmarking Functions for Genetic Algorithms. *International Journal of Computer Mathematics*, 77, 481–506.

Djebedjian, B., Gad, H., Khaled, I., Rayan, M. A. & Authority, S. D. (2008). Optimization of Reverse Osmosis Desalination System Using Genetic Algorithms Technique. In *Twelfth International Water Technology Conference, IWTC12*. 27–30 March. Alexandria, Egypt: 1047–1067.

Durillo, J. J., Zhang, Y., Alba, E., Harman, M. & Nebro, A. J. (2011). A Study of the Bi-Objective Next Release Problem. *Empirical Software Engineering*, 16(1), 29–60.

Dutczak, S. M., Luiten-Olieman, M. W. J., Zwijnenberg, H. J., Bolhuis-Versteeg, L. A. M., Winnubst, L., Hempenius, M. A., Benes, N. E., Wessling, M. & Stamatialis, D. (2011). Composite Capillary Membrane for Solvent Resistant Nanofiltration. *Journal of Membrane Science*, 372(1), 182–190.

Ekiner, O. M. & Vassilatos, G. (2001). Polyaramide Hollow Fibers for $H_2/CH_4$ Separation. II. Spinning and Properties. *Journal of Membrane Science*, 186(1), 71–84.

El-Naas, M. H., Al-Zuhair, S., Al-Lobaney, A. & Makhlouf, S. (2009). Assessment of Electrocoagulation for the Treatment of Petroleum Refinery Wastewater. *Journal of Environmental Management*, 91(1), 180–185.

Fei, N. C., Mehat, N. M. & Kamaruddin, S. (2013). Practical Applications of Taguchi Method for Optimization of Processing Parameters for Plastic Injection Moulding: A Retrospective Review. *ISRN Industrial Engineering*, 2013, 1–11.

Feng, C. Y., Khulbe, K. C., Chowdhury, G., Matsuura, T. & Sapkal, V. C. (2001). Structural and Performance Study of Microporous Polyetherimide Hollow Fiber Membranes Made by Solvent-Spinning Method. *Journal of Membrane Science*, 189(2), 193–203.

Fernandez, E., Lopez, E., Lopez, F. & Coello Coello, C. A. (2011). Increasing Selective Pressure Towards the Best Compromise in Evolutionary Multiobjective Optimization: The Extended NOSGA Method. *Information Sciences*, 181(1), 44–56.

Fortin, F. A. & Parizeau, M. (2013). Revisiting the NSGA-II Crowding-Distance Computation. *Proceeding of the 15th Annual Conference on Genetic and Evolutionary Computation*. 6–10 July. Amsterdam, Netherlands: 623–630.

Furtuna, R., Curteanu, S. & Leon, F. (2011). An Elitist Non-Dominated Sorting Genetic Algorithm Enhanced with a Neural Network Applied to the Multi-Objective Optimization of a Polysiloxane Synthesis Process. *Engineering Applications of Artificial Intelligence*, 24(5), 772–785.

Gabelman, A. & Hwang, S. T. (1999). Hollow Fiber Membrane Contactors. *Journal of Membrane Science*, 159(1), 61–106.

Gabriel, K. J., Linke, P. & El-Halwagi, M. M. (2015). Optimization of Multi-Effect Distillation Process Using a Linear Enthalpy Model. *Desalination*, 365, 261–276.

Gen, M. & Cheng, R. (1996). *Genetic Algorithms and Engineering Design* ($1^{st}$ ed.). Hoboken, NJ, USA: John Wiley & Sons, Inc.

Ghadimi, A., Sadrzadeh, M. & Mohammadi, T. (2010). Prediction of Ternary Gas Permeation Through Synthesized PDMS Membranes by Using Principal Component Analysis (PCA) and Fuzzy Logic (FL). *Journal of Membrane Science*, 360(1), 509–521.

Ghasem, N., Al-Marzouqi, M. & Zhu, L. (2012). Preparation and Properties of Polyethersulfone Hollow Fiber Membranes with O-Xylene as an Additive Used in Membrane Contactors for $CO_2$ Absorption. *Separation and Purification Technology*, 92, 1–10.

Ghomsheh, V. S., Khanehsar, M. A. & Teshnehlab, M. (2007). Improving the Non-Dominate Sorting Genetic Algorithm for Multi-objective Optimization. *2007 International Conference on Computational Intelligence and Security Workshops CISW 2007*. 15–19 December. Harbin: IEEE, 89-92.

Goel, T., Vaidyanathan, R., Haftka, R. T., Shyy, W., Queipo, N. V. & Tucker, K. (2007). Response Surface Approximation of Pareto Optimal Front in Multi-Objective Optimization. *Computer Methods in Applied Mechanics and Engineering*, 196(4-6), 879–893.

Goldberg, D. E. & Deb, K. (1991). A Comparative Analysis of Selection Schemes Used in Genetic Algorithms. *Foundations of Genetic Algorithms*, 1, 69–93.

Gordeyev, S. A., Lees, G. B., Dunkin, I. R. & Shilton, S. J. (2001). Super-Selective Polysulfone Hollow Fiber Membranes for Gas Separation: Rheological Assessment of the Spinning Solution. *Polymer*, 42(9), 4347–4352.

Gorji, M., Jeddi, A. A. A. & Gharehaghaji, A. A. (2012). Fabrication and Characterization of Polyurethane Electrospune Nanofiber Membranes for Protective Clothing Application. *Journal of Applied Polymer Science*, 125, 4135–4141.

Gryta, M., Karakulski, K. & Morawski, A. W. (2001). Purification of Oily Wastewater by Hybrid UF/MD. *Water Research*, 35(15), 3665–3669.

Gurugubelli, S. & Kallepalli, D. (2014). Weight and Deflection Optimization of Cantilever Beam Using a Modified Non-Dominated Sorting Genetic Algorithm. *IOSR Journal of Engineering*, 4(3), 19–23.

Hillier, F. S. & Liebermann, G. J. (2001). *Introduction to Operations Research* (7$^{th}$ ed.). Boston, MA: McGraw Hill.

Ho, W. S. W. & Sirkar, K. K. (1992). *Membrane Handbook* (1$^{st}$ ed.). Springer Sciences & Business Media.

Horn, J. (1997). *The Nature of Niching: Genetic Algorithms and the Evolution of Optimal, Cooperative Populations*. Doctor of Philosophy, University of Illinois at Urbana Champaign.

Hou, D., Wang, J., Qu, D., Luan, Z. & Ren, X. (2009). Fabrication and Characterization of Hydrophobic PVDF Hollow Fiber Membranes for Desalination Through Direct Contact Membrane Distillation. *Separation and Purification Technology*, 69(1), 78–86.

Hu, X. B., Di Paolo, E. & Wu, S. F. (2008). A Comprehensive Fuzz-Rule-Based Self-Adaptive Genetic Algorithm. *International Journal of Intelligent Computing and Cybernetics*, 1(1), 94–109.

Hu, X.-B., Leeson, M. & Hines, E. (2009). Dynamic Network Coding Problem: An Evolutionary Approach. In *Wireless Communications, Networking and Mobile Computing, 2009. 5th International Conference*. 24–26 September. Beijing, China: IEEE, 1–8.

Hunger, K., Schmeling, N., Jeazet, H. B. T., Janiak, C., Staudt, C. & Kleinermanns, K. (2012). Investigation of Cross-Linked and Additive Containing Polymer Materials for Membranes with Improved Performance in Pervaporation and Gas Separation. *Membranes*, 2(4), 727–763.

Idris, A., Ismail, A. F., Iswandi, S. & Shilton, S. J. (2001). Effect of Methanol Concentration on the Performance of Asymmetric Cellulose Acetate Reverse Osmosis Membranes Using Dry/Wet Phase Inversion Technique. *Jurnal Teknologi*, 34(F), 39–50.

Idris, A., Ismail, A. F., Noordin, M. Y. & Shilton, S. J. (2002). Optimization of Cellulose Acetate Hollow Fiber Reverse Osmosis Membrane Production Using Taguchi Method. *Journal of Membrane Science*, 205(1), 223–237.

Idris, A., Kormin, F. & Noordin, M. Y. (2006). Application of Response Surface Methodology in Describing the Performance of Thin Film Composite Membrane. *Separation and Purification Technology*, 49(3), 271–280.

Idris, A., Noordin, M. Y., Ismail, A. F. & Shilton, S. J. (2002). Study of Shear Rate Influence on the Performance of Cellulose Acetate Reverse Osmosis Hollow Fiber Membranes. *Journal of Membrane Science*, 202(1), 205–215.

Ishibuchi, H., Sakane, Y., Tsukamoto, N. & Nojima, Y. (2009). Evolutionary Many-Objective Optimization by NSGA-II and MOEA/D with Large Populations. *Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics*. 11–14 October. San Antonio, TX: IEEE, 1758–1763.

Ismail, A. F. (1997). *Novel Studies of Molecular Orientation in Synthetic Polymeric Membranes for Gas Separation*. Doctor of Philosophy, University of Strathclyde, Glasgow.

Ismail, A. F., Dunkin, I. R., Gallivan, S. L. & Shilton, S. J. (1999). Production of Super Selective Polysulfone Hollow Fiber Membranes for Gas Separation. *Polymer*, 40(23), 6499–6506.

Ismail, A. F. & Hassan, A. R. (2007). Effect of Additive Contents on the Performances and Structural Properties of Asymmetric Polyethersulfone (PES) Nanofiltration Membranes. *Separation and Purification Technology*, 55(1), 98–109.

Ismail, A. F. & Lai, P. Y. (2004). Development of Defect-Free Asymmetric Polysulfone Membranes for Gas Separation Using Response Surface Methodology. *Separation and Purification Technology*, 40(2), 191–207.

Ismail, A. F., Mustaffar, M. I., Illias, R. M. & Abdullah, M. S. (2006). Effect of Dope Extrusion Rate on Morphology and Performance of Hollow Fibers Membrane for Ultrafiltration. *Separation and Purification Technology*, 49(1), 10–19.

Ismail, A. F., Ng, B. C. & Abdul Rahman, W. A. W. (2003). Effects of Shear Rate and Forced Convection Residence Time on Asymmetric Polysulfone Membranes Structure and Gas Separation Performance. *Separation and Purification Technology*, 33(3), 255–272.

Ismail, A. F., Shilton, S. J., Dunkin, I. R. & Gallivan, S. L. (1997). Direct Measurement of Rheologically Induced Molecular Orientation in Gas

Separation Hollow Fiber Membranes and Effects on Selectivity. *Journal of Membrane Science*, 126(1), 133–137.

Jeyadevi, S., Baskar, S., Babulal, C. K. & Willjuice Iruthayarajan, M. (2011). Solving Multiobjective Optimal Reactive Power Dispatch Using Modified NSGA-II. *Electrical Power and Energy Systems*, 33(2), 219–228.

Jiang, L., Chung, T. S., Li, D. F., Cao, C. & Kulprathipanja, S. (2004). Fabrication of Matrimid/Polyethersulfone Dual-Layer Hollow Fiber Membranes for Gas Separation. *Journal of Membrane Science*, 240(1), 91–103.

Jones, D. F., Mirrazavi, S. K. & Tamiz, M. (2002). Multi-Objective Meta-Heuristics: An Overview of the Current State-of-the-Art. *European Journal of Operational Research*, 137, 1–9.

Julian, H. & Wenten, I. G. (2012). Polysulfone Membranes for $CO_2$/$CH_4$ Separation: State of the Art. *IOSR Journal of Engineering*, 2(3), 484–495.

Jung, B., Yoon, J. K., Kim, B. & Rhee, H. W. (2004). Effect of Molecular Weight of Polymeric Additives on Formation, Permeation Properties and Hypochlorite Treatment of Asymmetric Polyacrylonitrile Membranes. *Journal of Membrane Science*, 243(1), 45–57.

Kapantaidakis, G. C. & Koops, G. H. (2002). High Flux Polyethersulfone–Polyimide Blend Hollow Fiber Membranes for Gas Separation. *Journal of Membrane Science*, 204(1), 153–171.

Kapantaidakis, G. C., Koops, G. H. & Wessling, M. (2002). Effect of Spinning Conditions on the Structure and the Gas Permeation Properties of High Flux Polyethersulfone-Polyimide Blend Hollow Fibers. *Desalination*, 144(1), 121–125.

Kesting, R. E. (1971). *Synthetic Polymeric Membranes* ($1^{st}$ ed.). New York: Mc Graw-Hill Inc.

Kesting, R. E. & Fritzsche, A. K. (1993). *Polymeric Gas Separation Membranes*. New York, USA: Wiley Interscience.

Khalafallah, A. M. (2014). Assessing the Performance of the Non-Dominated Sorting Genetic Algorithm in Optimizing Construction Site Planning. *Computing in Civil and Building Engineering*, 1254–1261.

Khayet, M. (2003). The Effects of Air Gap Length on the Internal and External Morphology of Hollow Fiber Membranes. *Chemical Engineering Science*, 58(14), 3091–3104.

Khayet, M., Cojocaru, C., Essalhi, M., García-Payo, M. C., Arribas, P. & García-Fernández, L. (2012). Hollow Fiber Spinning Experimental Design and Analysis of Defects for Fabrication of Optimized Membranes for Membrane Distillation. *Desalination*, 287, 146–158.

Khayet, M., Cojocaru, C. & Garcia-Payo, C. (2007). Application of Response Surface Methodology and Experimental Design in Direct Contact Membrane Distillation. *Industrial & Engineering Chemistry Research*, 46(17), 5673–5685.

Khayet, M., Cojocaru, C. & Zakrzewska-Trznadel, G. (2008). Response Surface Modelling and Optimization in Pervaporation. *Journal of Membrane Science*, 321(2), 272–283.

Khayet, M., Feng, C. Y., Khulbe, K. C. & Matsuura, T. (2002). Preparation and Characterization of Polyvinylidene Fluoride Hollow Fiber Membranes for Ultrafiltration. *Polymer*, 43(14), 3879–3890.

Khayet, M. & Matsuura, T. (2003). Determination of Surface and Bulk Pore Sizes of Flat-Sheet and Hollow-Fiber Membranes by Atomic Force Microscopy, Gas Permeation and Solute Transport Methods. *Desalination*, 158(1), 57–64.

Khayet, M. & Matsuura, T. (2011). Formation of Hollow Fibre MD Membranes. In *Membrane Distillation: Principles and Applications* (pp. 59–87). Elsevier Science.

Kim, I. C., Yun, H. G. & Lee, K. H. (2002). Preparation of Asymmetric Polyacrylonitrile Membrane with Small Pore Size by Phase Inversion and Post-Treatment Process. *Journal of Membrane Science*, 199(1), 75–84.

Kim, J. H. & Lee, K. H. (1998). Effect of PEG Additive on Membrane Formation by Phase Inversion. *Journal of Membrane Science*, 138(2), 153–163.

Kim, J. H., Park, Y. I., Jegal, J. & Lee, K. H. (1995). The Effects of Spinning Conditions on the Structure Formation and the Dimension of the Hollow-Fiber Membranes and Their Relationship with the Permeability in Dry-Wet Spinning Technology. *Journal of Applied Polymer Science*, 57, 1637–1644.

Kim, K. J., Moskowitz, H. & Koksalan, M. (1996). Fuzzy Versus Statistical Linear Regression. *European Journal of Operational Research*, 92(2), 417–434.

Kim, S., Jang, J. & Kim, O. (1998). The Rheological Properties Optimization of Fumed Silica Dispersions Using Statistical Experimental Design and Taguchi Method. *Polymer Testing*, 17(4), 225–235.

Konak, A., Coit, D. W. & Smith, A. E. (2006). Multi-Objective Optimization Using Genetic Algorithms: A Tutorial. *Reliability Engineering and System Safety*, 91, 992–1007.

Kong, J. & Li, K. (2001). Preparation of PVDF Hollow-Fiber Membranes via Immersion Precipitation. *Journal of Applied Polymer Science*, 81(7), 1643–1653.

Koops, G. H., Nolten, J. A. M., Mulder, M. H. V. & Smolders, C. A. (1994). Integrally Skinned Polysulfone Hollow Fiber Membranes for Pervaporation. *Journal of Applied Polymer Science*, 54(3), 385–404.

Kosuri, M. R. & Koros, W. J. (2008). Defect-Free Asymmetric Hollow Fiber Membranes From Torlon®, a Polyamide-Imide Polymer, for High-Pressure $CO_2$ Separations. *Journal of Membrane Science*, 320(1), 65–72.

Kovasin, K. K., Hughes, R. R. & Hill Jr, C. G. (1986). Optimization of an Ultrafiltration-Diafiltration Process Using Dynamic Programming. *Computers and Chemical Engineering*, 10(2), 107–114.

Kühn, M., Severin, T. & Salzwedel, H. (2013). Variable Mutation Rate at Genetic Algorithms: Introduction of Chromosome Fitness in Connection with Multi-Chromosome Representation. *International Journal of Computer Applications*, 72(17), 31–38.

Kumar, E. R. (2010). A Comparative of Genetic Algorithm with Variable Crossover and Inversion Probability for Operating System Process Scheduling Problem. *Journal of Global Research in Computer Science*, 1(5), 40–44.

Kurada, R. R., Pavan, D. K. K. & Rao, D. A. D. (2013). A Preliminary Survey on Optimized Multiobjective Metaheuristic Methods for Data Clustering Using Evolutionary Approaches. *International Journal of Computer Science & Technology*, 5(5), 57–77.

Kusworo, T. D., Ismail, A. F., Mustafa, A. & Matsuura, T. (2008). Dependence of Membrane Morphology and Performance on Preparation Conditions: The Shear Rate Effect in Membrane Casting. *Separation and Purification Technology*, 61(3), 249–257.

Lau, W. W. Y., Guiver, M. D. & Matsuura, T. (1991). Phase Separation in Carboxylated Polysulfone/Solvent/Water Systems. *Journal of Applied Polymer Science*, 42, 3215–3221.

Lee, C. J., Wang, S. S., Lin, G. C., Hu, W. & Chen, L. T. (1995). Pilot Production of Polysulfone Hollow Fiber for Ultrafiltration Using Orthogonal Array Experimentation. *Industrial & Engineering Chemistry Research*, 34(3), 813–819.

Li, D., Chung, T. S. & Wang, R. (2004). Morphological Aspects and Structure Control of Dual-Layer Asymmetric Hollow Fiber Membranes Formed By a Simultaneous Co-Extrusion Approach. *Journal of Membrane Science*, 243(1), 155–175.

Li, D. F., Chung, T. S., Wang, R. & Liu, Y. (2002). Fabrication of Fluoropolyimide/Polyethersulfone (PES) Dual-Layer Asymmetric Hollow Fiber Membranes for Gas Separation. *Journal of Membrane Science*, 198(2), 211–223.

Li, J., Yang, B., Zhang, D., Zhou, Q. & Li, L. (2015). Development of a Multi-Objective Scheduling System for Offshore Projects Based on Hybrid Non-Dominated Sorting Genetic Algorithm. *Advances in Mechanical Engineering*, 7(3), 1–17.

Li, Y., Cao, C., Chung, T. S. & Pramoda, K. P. (2004). Fabrication of Dual-Layer Polyethersulfone (PES) Hollow Fiber Membranes with an Ultrathin Dense-Selective Layer for Gas Separation. *Journal of Membrane Science*, 245(1), 53–60.

Li, Y. L., Shao, W., Wang, J. T. & Chen, H. (2014). An Improved NSGA-II and its Application for Reconfigurable Pixel Antenna Design. *Radioengineering*, 23(2), 733–738.

Lin, W. Y., Lee, W. Y. & Hong, T. P. (2003). Adapting Crossover and Mutation Rates in Genetic Algorithms. *Journal of Information Science and Engineering*, 19(5), 889–903.

Liu, F., Hashim, N. A., Liu, Y., Abed, M. R. M. & Li, K. (2011). Progress in the Production and Modification of PVDF Membranes. *Journal of Membrane Science*, 375(1), 1–27.

Liu, T., Zhang, D., Xu, S. & Sourirajan, S. (1992). Solution-Spun Hollow Fiber Polysulfone and Polyethersulfone Ultrafiltration Membranes. *Separation Science and Technology*, 27(2), 161–172.

Liu, Y., Koops, G. H. & Strathmann, H. (2003). Characterization of Morphology Controlled Polyethersulfone Hollow Fiber Membranes by the Addition of

Polyethylene Glycol to the Dope and Bore Liquid Solution. *Journal of Membrane Science*, 223(1), 187–199.

Loh, C. H. & Wang, R. (2012). Effects of Additives and Coagulant Temperature on Fabrication of High Performance PVDF/Pluronic F127 Blend Hollow Fiber Membranes via Nonsolvent Induced Phase Separation. *Chinese Journal of Chemical Engineering*, 20(1), 71–79.

Loh, C. H., Wang, R., Shi, L. & Fane, A. G. (2011). Fabrication of High Performance Polyethersulfone UF Hollow Fiber Membranes Using Amphiphilic Pluronic Block Copolymers as Pore-Forming Additives. *Journal of Membrane Science*, 380(1), 114–123.

Lu, X., Bian, X. & Shi, L. (2002). Preparation and Characterization of NF Composite Membrane. *Journal of Membrane Science*, 210(1), 3–11.

Lu, Y. Y., Hu, Y. D., Xu, D. M. & Wu, L. Y. (2006). Optimum Design of Reverse Osmosis Seawater Desalination System Considering Membrane Cleaning and Replacing. *Journal of Membrane Science*, 282, 7–13.

Madaeni, S. S., Hasankiadeh, N. T., Kurdian, A. R. & Rahimpour, A. (2010). Modeling and Optimization of Membrane Fabrication Using Artificial Neural Network and Genetic Algorithm. *Separation and Purification Technology*, 76(1), 33–43.

Makki, H. F., Al-Alawy, A. F., Al-Hassani, M. H. & Rashad, Z. W. (2011). Membranes Separation Process for Oily Wastewater Treatment. *Journal of Engineering*, 17(2), 235–252.

Malaisamy, R., Annadurai, G. & Mohan, D. (2000). Performance Optimization of Polysulfone Ultrafiltration Membranes for Riboflavin Separation using Design Experiments. *Bioprocess Engineering*, 22(3), 227–232.

Mansourizadeh, A. & Ismail, A. F. (2010). Effect of Additives on the Structure and Performance of Polysulfone Hollow Fiber Membranes for $CO_2$ Absorption. *Journal of Membrane Science*, 348(1), 260–267.

Marriott, J. & Sorensen, E. (2003). The Optimal Design of Membrane Systems. *Chemical Engineering Science*, 58, 4991–5004.

Miao, X., Sourirajan, S. & Lau, W. W. Y. (1996). Production of Polyethersulfone Hollow Fiber Ultrafiltration Membranes. II. Effects of Fiber Extrusion Pressure (EP) and PVP Concentration in the Spinning Solution. *Separation Science and Technology*, 31(3), 327–348.

Michalewicz, Z. (1996). *Genetic Algorithms + Data Structures = Evolution Programs* ($3^{rd}$ ed.). London, UK: Springer-Verlag.

Miller, B. L. & Goldberg, D. E. (1995). Genetic Algorithms, Tournament Selection, and the Effects of Noise. *Complex Systems*, 9(3), 193–212.

Mitchell, M. (1998). *An Introduction to Genetic Algorithm*. MIT Press.

Montgomery, D. C. (2005). *Design and Analysis of Experiments* ($6^{th}$ ed.). New York, USA: John Wiley & Sons.

Mulder, M. (1996). *Basic Principles of Membrane Technology* ($2^{nd}$ ed.). Netherlands: Springer Sciences & Business Media.

Munteanu, C. & Rosa, A. (2004). Gray-Scale Image Enhancement as an Automatic Process Driven by Evolution. *IEEE Transactions on Systems, Man and Cybernetics, Part B (Cybernetics)*, 34(2), 1292–1298.

Mustaffar, M. I. (2004). *Development of Asymmetric Polyethersulfone Hollow Fiber Ultrafiltration Membrane for Cyclodextrin Separation*. Master, Universiti Teknologi Malaysia, Skudai.

Nagasawa, K., Irohara, T., Matoba, Y. & Liu, S. (2013). Genetic Algorithm-Based Coordinated Replenishment in Multi-Item Inventory Control. *Industrial Engineering & Management Systems*, 12(3), 172–180.

Nijdam, W., De Jong, J., Van Rijn, C. J. M., Visser, T., Versteeg, L., Kapantaidakis, G., Koops, G. H. & Wessling, M. (2005). High Performance Micro-Engineered Hollow Fiber Membranes by Smart Spinneret Design. *Journal of Membrane Science*, 256, 209–215.

Niwa, M., Kawakami, H., Nagaoka, S., Kanamori, T. & Shinbo, T. (2000). Fabrication of an Asymmetric Polyimide Hollow Fiber with a Defect-Free Surface Skin Layer. *Journal of Membrane Science*, 171(2), 253–261.

Nunes, S. P. & Peinemann, K. V. (2006). *Membrane Technology: in the Chemical Industry* ($2^{nd}$ rev.). Weinheim, Germany: Wiley-VCH Verlag.

Olden, J. D. & Jackson, D. A. (2002). Illuminating the "Black Box": A Randomization Approach for Understanding Variable Contributions in Artificial Neural Networks. *Ecological Modelling*, 154(1), 135–150.

Ong, C. S., Lau, W. J., Goh, P. S., NG, B. C. & Ismail, A. F. (2015). Preparation and Characterization of PVDF–PVP–$TiO_2$ Composite Hollow Fiber Membranes for Oily Wastewater Treatment Using Submerged Membrane System. *Desalination and Water Treatment*, 53(5), 1213–1223.

Peinemann, K. V. & Nunes, S. P. (2008). *Membrane Technology, Volume 1: Membranes for Life Sciences*. John Wiley & Sons.

Peng, N., Chung, T. S. & Wang, K. Y. (2008). Macrovoid Evolution and Critical Factors to Form Macrovoid-Free Hollow Fiber Membranes. *Journal of Membrane Science*, 318(1), 363–372.

Peng, N., Widjojo, N., Sukitpaneenit, P., Teoh, M. M., Lipscomb, G. G., Chung, T. S. & Lai, J. Y. (2012). Evolution of Polymeric Hollow Fibers as Sustainable Technologies: Past, Present, and Future. *Progress in Polymer Science*, 37(10), 1401–1424.

Pereira, C. C., Nobrega, R., Peinemann, K. V. & Borges, C. P. (2003). Hollow Fiber Membranes Obtained by Simultaneous Spinning of Two Polymer Solutions: A Morphological Study. *Journal of Membrane Science*, 226(1), 35–50.

Perera, R., Ruiz, A. & Manzano, C. (2009). Performance Assessment of Multicriteria Damage Identification Genetic Algorithms. *Computers and Structures*, 87(1), 120–127.

Pesek, S. C. & Koros, W. J. (1994). Aqueous Quenched Asymmetric Polysulfone Hollow Fibers Prepared by Dry/Wet Phase Separation. *Journal of Membrane Science*, 88(1), 1–19.

Posada, D. & Buckley, T. R. (2004). Model Selection and Model Averaging in Phylogenetics: Advantages of Akaike Information Criterion and Bayesian Approaches Over Likelihood Ratio Tests. *Systematic Biology*, 53(5), 793–808.

Powell, C. E. & Qiao, G. G. (2006). Polymeric $CO_2/N_2$ Gas Separation Membranes for the Capture of Carbon Dioxide from Power Plant Flue Gases. *Journal of Membrane Science*, 279(1), 1–49.

Qi, R. & Henson, M. A. (1998). Optimal Design of Spiral-Wound Membrane Networks for Gas Separations. *Journal of Membrane Science*, 148, 71–89.

Qin, J. & Chung, T. S. (1999). Effect of Dope Flow Rate on the Morphology, Separation Performance, Thermal and Mechanical Properties of Ultrafiltration Hollow Fibre Membranes. *Journal of Membrane Science*, 157(1), 35–51.

Qin, J. J., Chung, T. S., Cao, C. & Vora, R. H. (2005). Effect of Temperature on Intrinsic Permeation Properties of 6FDA-Durene/1,3-Phenylenediamine (mPDA) Copolyimide and Fabrication of Its Hollow Fiber Membranes for $CO_2/CH_4$ Separation. *Journal of Membrane Science*, *250*(1), 95–103.

Qin, J. J., Gu, J. & Chung, T. S. (2001). Effect of Wet and Dry-Jet Wet Spinning on the Shear-Induced Orientation During the Formation of Ultrafiltration Hollow Fiber Membranes. *Journal of Membrane Science*, 182(1), 57–75.

Qin, J. J., Wang, R. & Chung, T. S. (2000). Investigation of Shear Stress Effect within a Spinneret on Flux, Separation and Thermomechanical Properties of Hollow Fiber Ultrafiltration Membranes. *Journal of Membrane Science*, 175(2), 197–213.

Rahimpour, A., Madaeni, S. S. & Mansourpanah, Y. (2007). The Effect of Anionic, Non-Ionic and Cationic Surfactants on Morphology and Performance of Polyethersulfone Ultrafiltration Membranes for Milk Concentration. *Journal of Membrane Science*, 296(1), 110–121.

Rahimpour, A., Madaeni, S. S. & Mehdipour-Ataei, S. (2008). Synthesis of a Novel Poly(amide-imide) (PAI) and Preparation and Characterization of PAI Blended Polyethersulfone (PES) Membranes. *Journal of Membrane Science*, 311(1), 349–359.

Raja, P. V. & Bhaskaran, V. M. (2013). Improving the Performance of Genetic Algorithm by Reducing the Population Size. *International Journal of Emerging Technology and Advanced Engineering*, 3(8), 86–91.

Ramirez, J. H., Costa, C. A. & Madeira, L. M. (2005). Experimental Design to Optimize the Degradation of the Synthetic Dye Orange II Using Fenton's Reagent. *Catalysis Today*, 107-108, 68–76.

Rana-Madaria, P., Nagarajan, M., Rajagopal, C. & Garg, B. S. (2005). Removal of Chromium from Aqueous Solutions by Treatment with Carbon Aerogel Electrodes Using Response Surface Methodology. *Industrial & Engineering Chemistry Research*, 44(17), 6549–6559.

Ravikumar, K., Pakshirajan, K., Swaminathan, T. & Balu, K. (2005). Optimization of Batch Process Parameters Using Response Surface Methodology for Dye Removal by a Novel Adsorbent. *Chemical Engineering Journal*, 105(3), 131–138.

Razali, N. M. & Geraghty, J. (2011). Genetic Algorithm Performance with Different Selection Strategies in Solving TSP. *Proceedings of the World Congress on Engineering 2011 Vol II WCE 2011*. 6–8 July. London, UK.

Ren, J., Chung, T. S., Li, D., Wang, R. & Liu, Y. (2002). Development of Asymmetric 6FDA-2,6 DAT Hollow Fiber Membranes for $CO_2/CH_4$ Separation

1. The Influence of Dope Composition and Rheology on Membrane Morphology and Separation Performance. *Journal of Membrane Science*, 207(2), 227–240.

Ren, J., Wang, R., Zhang, H. Y., Li, Z., Liang, D. T. & Tay, J. H. (2006). Effect of PVDF Dope Rheology on the Structure of Hollow Fiber Membranes Used for $CO_2$ Capture. *Journal of Membrane Science*, 281(1), 334–344.

Ribeiro Filho, J. L., Treleaven, P. C. & Alippi, C. (1994). Genetic Algorithm Programming Environments. *Computer*, 27(6), 28–43.

Ripon, K. S. N., Siddique, N. H. & Torresen, J. (2011). Improved Precedence Preservation Crossover for Multi-Objective Job Shop Scheduling Problem. *Evolving Systems*, 2(2), 119–129.

Rogers, D. F. & Kulkarni, S. S. (2005). Optimal Bivariate Clustering and a Genetic Algorithm with an Application in Cellular Manufacturing. *European Journal of Operational Research*, 160(2), 423–444.

Saadatseresht, M., Mansourian, A. & Taleai, M. (2009). Evacuation Planning Using Multiobjective Evolutionary Optimization Approach. *European Journal of Operational Research*, 198(1), 305–314.

Sait, S. M. & Youssef, H. (1999). *Iterative Computer Algorithms with Applications in Engineering: Solving Combinatorial Optimization Problems* (1st ed.). Los Alamitos, CA, USA: IEEE Computer Society Press.

Saljoughi, E., Amirilargani, M. & Mohammadi, T. (2010). Effect of PEG Additive and Coagulation Bath Temperature on the Morphology, Permeability and Thermal/Chemical Stability of Asymmetric CA Membranes. *Desalination*, 262(1), 72–78.

Saljoughi, E., Sadrzadeh, M. & Mohammadi, T. (2009). Effect of Preparation Variables on Morphology and Pure Water Permeation Flux Through Asymmetric Cellulose Acetate Membranes. *Journal of Membrane Science*, 326(2), 627–634.

Santoso, Y. E., Chung, T. S., Wang, K. Y. & Weber, M. (2006). The Investigation of Irregular Inner Skin Morphology of Hollow Fiber Membranes at High-Speed Spinning and the Solutions to Overcome It. *Journal of Membrane Science*, 282(1), 383–392.

Schmeling, N., Konietzny, R., Sieffert, D., Rölling, P. & Staudt, C. (2010). Functionalized Copolyimide Membranes for the Separation of Gaseous and Liquid Mixtures. *Beilstein Journal of Organic Chemistry*, 6(1), 789–800.

Scholes, C. A., Kentish, S. E. & Stevens, G. W. (2008). Carbon Dioxide Separation through Polymeric Membrane Systems for Flue Gas Applications. *Recent Patent on Chemical Engineering*, 1(1), 52–66.

Sekman, E., Top, S., Uslu, E., Varank, G. & Bilgili, M. S. (2011). Treatment of Oily Wastewater From Port Waste Reception Facilities by Electrocoagulation. *International Journal of Environmental Research*, 5(4), 1079–1086.

Seng, O., Bauer, M., Biehl, M. & Pache, G. (2005). Search-Based Improvement of Subsystem Decompositions. *Proceedings of the 7th Annual Conference on Genetic and Evolutionary Computation*. 25–29 June. Washington, DC, USA: ACM, 1045–1051.

Senthilkumar, C., Ganesan, G. & Karthikeyan, R. (2011). Parametric Optimization of Electrochemical Machining of Al/15% SiCp Composites Using NSGA-II. *Transactions of Nonferrous Metals Society of China*, 21(10), 2294–2300.

Setiawan, L., Wang, R., Li, K. & Fane, A. G. (2011). Fabrication of Novel Poly(amide-imide) Forward Osmosis Hollow Fiber Membranes with a Positively Charged Nanofiltration-Like Selective Layer. *Journal of Membrane Science*, 369(1), 196–205.

Sharma, N. & Anupama, K. R. (2011). On the Use of NSGA-II for Multi-Objective Resource Allocation in MIMO-OFDMA Systems. *Wireless Networks*, 17(5), 1191–1201.

Sharpe, I. D., Ismail, A. F. & Shilton, S. J. (1999). A Study of Extrusion Shear and Forced Convection Residence Time in the Spinning of Polysulfone Hollow Fiber Membranes for Gas Separation. *Separation and Purification Technology*, 17(2), 101–109.

Shi, L., Wang, R. & Cao, Y. (2009). Effect of the Rheology of Poly(vinylidene Fluoride-Co-Hexafluropropylene) (PVDF-HFP) Dope Solutions on the Formation of Microporous Hollow Fibers Used as Membrane Contactors. *Journal of Membrane Science*, 344(1), 112–122.

Shi, L., Wang, R., Cao, Y., Feng, C., Liang, D. T. & Tay, J. H. (2007). Fabrication of Poly(vinylidene Fuoride-Co-Hexafluropropylene) (PVDF-HFP) Asymmetric

Microporous Hollow Fiber Membranes. *Journal of Membrane Science*, 305(1), 215–225.

Shieh, J. J. & Chung, T. S. (1998). Effect of Liquid-Liquid Demixing on the Membrane Morphology, Gas Permeation, Thermal and Mechanical Properties of Cellulose Acetate Hollow Fibers. *Journal of Membrane Science*, 140(1), 67–79.

Shilton, S. J., Bell, G. & Ferguson, J. (1994). The Rheology of Fibre Spinning and the Properties of Hollow-Fibre Membranes for Gas Separation. *Polymer*, 35(24), 5327–5335.

Shin, S. J., Kim, J. P., Kim, H. J., Jeon, J. H. & Min, B. R. (2005). Preparation and Characterization of Polyethersulfone Microfiltration Membranes by a 2-Methoxyethanol Additive. *Desalination*, 186(1), 1–10.

Shokrian, M., Sadrzadeh, M. & Mohammadi, T. (2010). $C_3H_8$ Separation from $CH_4$ and $H_2$ using a Synthesized PDMS Membrane: Experimental and Neural Network Modeling. *Journal of Membrane Science*, 346(1), 59–70.

Sivakumar, M., Annadurai, G. & Mohan, D. (1999). Studies on Box-Behnken Design Experiments: Cellulose Acetate-Polyurethane Ultrafiltration Membranes for BSA Separation. *Bioprocess Engineering*, 21(1), 65–68.

Soleimani, R., Shoushtari, N. A., Mirza, B. & Salahi, A. (2013). Experimental Investigation, Modeling and Optimization of Membrane Separation Using Artificial Neural Network and Multi-Objective Optimization Using Genetic Algorithm. *Chemical Engineering Research and Design*, 91(5), 883–903.

Sourirajan, S. & Matsuura, T. (1985). *Reverse Osmosis/Ultrafiltration Process Principles* ($6^{th}$ ed.). Ottawa: National Research Council Canada.

Srinivas, N. & Deb, K. (1995). Multiobjective Optimization Using Nondominated Sorting in Genetic Algorithms. *Evolutionary Computation*, 2(3), 221–248.

Strathman, H., Bell, C. M. & Kimmerle, K. (1986). Development of Synthetic Membranes for Gas and Vapor Separation. *Pure and Applied Chemistry*, 58(12), 1663–1668.

Subramanian, R., Subramanian, K. & Subramanian, B. (2009). Application of a Fast and Elitist Multi-Objective Genetic Algorithm to Reactive Power Dispatch. *Serbian Journal of Electrical Engineering*, 6(1), 119–133.

Sukitpaneenit, P. & Chung, T. S. (2009). Molecular Elucidation of Morphology and Mechanical Properties of PVDF Hollow Fiber Membranes from Aspects of

Phase Inversion, Crystallization and Rheology. *Journal of Membrane Science*, 340(1), 192–205.

Sutherland, K. (2004). *Profile of the International Membrane Industry: Market Prospects to 2008* (3rd ed.). Oxford, UK: Elsevier Advanced Technology.

Tamilarasi, A. & Anantha Kumar, T. (2010). An Enhanced Genetic Algorithm with Simulated Annealing for Job-Shop Scheduling. *International Journal of Engineering, Science and Technology*, 2(1), 144–151.

Tan, M., He, G., Li, X., Liu, Y., Dong, C. & Feng, J. (2012). Prediction of the Effects of Preparation Conditions on Pervaporation Performances of Polydimethylsiloxane (PDMS)/Ceramic Composite Membranes by Backpropagation Neural Network and Genetic Algorithm. *Separation and Purification Technology*, 89, 142–146.

Tan, M., He, G., Nie, F., Zhang, L. & Hu, L. (2014). Optimization of Ultrafiltration Membrane Fabrication Using Backpropagation Neural Network and Genetic Algorithm. *Journal of the Taiwan Institute of Chemical Engineers*, 45(1), 68–75.

Tan, X., Liu, N., Meng, B. & Liu, S. (2011). Morphology Control of the Perovskite Hollow Fibre Membranes for Oxygen Separation Using Different Bore Fluids. *Journal of Membrane Science*, 378(1), 308–318.

Tan, X., Liu, Y. & Li, K. (2005). Mixed Conducting Ceramic Hollow-Fiber Membranes for Air Separation. *AIChE Journal*, 51(7), 1991–2000.

Tascan, M. (2014). Optimization of Process Parameters of Wet-Spun Solid PVDF Fibers for Maximizing the Tensile Strength and Applied Force at Break and Minimizing the Elongation at Break Using the Taguchi Method. *Journal of Engineered Fibers & Fabrics*, 9(1), 165–173.

Tasselli, F., Jansen, J. C., Sidari, F. & Drioli, E. (2005). Morphology and Transport Property Control of Modified Poly(ether ether ketone) (PEEKWC) Hollow Fiber Membranes Prepared from PEEKWC/PVP Blends: Influence of the Relative Humidity in the Air Gap. *Journal of Membrane Science*, 255(1), 13–22.

Torrestiana-Sanchez, B., Ortiz-Basurto, R. I. & Brito-De La Fuente, E. (1999). Effect of Nonsolvents on Properties of Spinning Solutions and Polyethersulfone Hollow Fiber Ultrafiltration Membranes. *Journal of Membrane Science*, 152(1), 19–28.

Tsai, H. A., Hong, M. J., Huang, G. S., Wang, Y. C., Li, C. L., Lee, K. R. & Lai, J. Y. (2002). Effect of DGDE Additive on the Morphology and Pervaporation Performances of Asymmetric PSf Hollow Fiber Membranes. *Journal of Membrane Science*, 208(1), 233–245.

Tsai, H. A., Huang, D. H., Fan, S. C., Wang, Y. C., Li, C. L., Lee, K. R. & Lai, J. Y. (2002). Investigation of Surfactant Addition Effect on the Vapor Permeation of Aqueous Ethanol Mixtures through Polysulfone Hollow Fiber Membranes. *Journal of Membrane Science*, 198(2), 245–258.

Tsai, H. A., Kuo, C. Y., Lin, J. H., Wang, D. M., Deratani, A., Pochat-Bohatier, C., Lee, K. R. & Lai, J. Y. (2006). Morphology Control of Polysulfone Hollow Fiber Membranes via Water Vapor Induced Phase Separation. *Journal of Membrane Science*, 278(1), 390–400.

Tsai, H. A., Ma, L. C., Yuan, F., Lee, K. R. & Lai, J. Y. (2008). Investigation of Post-Treatment Effect on Morphology and Pervaporation Performance of PEG Added PAN Hollow Fiber Membranes. *Desalination*, 234(1), 232–243.

Ulbricht, M. (2006). Advanced Functional Polymer Membranes. *Polymer*, 47(7), 2217–2262.

Valliyappan, S. & Simpson, T. W. (2006). Exploring Visualization Strategies to Support Product Family Design Optimization. *11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*. 6–8 September. Portsmouth, Virginia: American Institute of Aeronautics and Astronautics, 1–14.

Van Veldhuizen, D. A. (1999). *Multiobjective Evolutionary Algorithms: Classifications, Analyses, and New Innovations*. Doctor of Philosophy, Air Force Institute of Technology, Hobson Way.

Van Veldhuizen, D. A. & Lamont, G. B. (2000). Multiobjective Evolutionary Algorithms: Analyzing the State-of-the-Art. *Evolutionary Computation*, 8(2), 125–147.

Vandezande, P., Gevers, L. E. M., Weyens, N. & Vankelecom, I. F. J. (2009). Compositional Optimization of Polyimide-Based SEPPI Membranes Using a Genetic Algorithm and High-Throughput Techniques. *Journal of Combinatorial Chemistry*, 11(2), 243–251.

Vergidis, K., Tiwari, A., Majeed, B. & Roy, R. (2007). Optimisation of Business Process Designs: An Algorithmic Approach with Multiple Objectives. *International Journal of Production Economics*, 109(1), 105–121.

Wagner, J. (2001). *Membrane Filtration Handbook: Practical Tips and Hints* (2nd ed.). Minnetonka, MN: Osmonics.

Wan, L. S., Xu, Z. K., Huang, X. J., Che, A. F. & Wang, Z. G. (2006). A Novel Process for the Post-Treatment of Polyacrylonitrile-Based Membranes: Performance Improvement and Possible Mechanism. *Journal of Membrane Science*, 277(1), 157–164.

Wang, D., Li, K. & Teo, W. K. (1996). Polyethersulfone Hollow Fiber Gas Separation Membranes Prepared from NMP/Alcohol Solvent Systems. *Journal of Membrane Science*, 115(1), 85–108.

Wang, D., Li, K. & Teo, W. K. (1998). Preparation and Characterization of Polyetherimide Asymmetric Hollow Fiber Membranes for Gas Separation. *Journal of Membrane Science*, 138(2), 193–201.

Wang, D., Li, K. & Teo, W. K. (1999). Preparation and Characterization of Polyvinylidene Fluoride (PVDF) Hollow Fiber Membranes. *Journal of Membrane Science*, 163(2), 211–220.

Wang, D., Li, K. & Teo, W. K. (2000a). Highly Permeable Polyethersulfone Hollow Fiber Gas Separation Membranes Prepared Using Water as Non-Solvent Additive. *Journal of Membrane Science*, 176(2), 147–158.

Wang, D., Li, K. & Teo, W. K. (2000b). Porous PVDF Asymmetric Hollow Fiber Membranes Prepared with the Use of Small Molecular Additives. *Journal of Membrane Science*, 178(1), 13–23.

Wang, K. Y. & Chung, T. S. (2005). The Characterization of Flat Composite Nanofiltration Membranes and Their Applications in the Separation of Cephalexin. *Journal of Membrane Science*, 247(1), 37–50.

Wang, K. Y., Li, D. F., Chung, T. S. & Chen, S. B. (2004). The Observation of Elongation Dependent Macrovoid Evolution in Single- and Dual-Layer Asymmetric Hollow Fiber Membranes. *Chemical Engineering Science*, 59(21), 4657–4660.

Wang, K. Y., Matsuura, T., Chung, T. S. & Guo, W. F. (2004). The Effects of Flow Angle and Shear Rate within the Spinneret on the Separation Performance of

Poly(ethersulfone) (PES) Ultrafiltration Hollow Fiber Membranes. *Journal of Membrane Science*, 240(1), 67–79.

Wang, R. & Chung, T. S. (2001). Determination of Pore Sizes and Surface Porosity and the Effect of Shear Stress within a Spinneret on Asymmetric Hollow Fiber Membranes. *Journal of Membrane Science*, 188(1), 29–37.

Wang, R., Shi, L., Tang, C. Y., Chou, S., Qiu, C. & Fane, A. G. (2010). Characterization of Novel Forward Osmosis Hollow Fiber Membranes. *Journal of Membrane Science*, 355(1), 158–167.

Wang, S. Y. & Tai, K. (2005). Structural Topology Design Optimization using Genetic Algorithms with a Bit-Array Representation. *Computer Methods in Applied Mechanics and Engineering*, 194(36), 3749–3770.

Wen, X. & Tresco, P. A. (2006). Fabrication and Characterization of Permeable Degradable Poly(DL-lactide-co-glycolide) (PLGA) Hollow Fiber Phase Inversion Membranes for Use as Nerve Tract Guidance Channels. *Biomaterials*, 27(20), 3800–3809.

Whitley, D. L. (1989). The GENITOR Algorithm and Selection Pressure: Why Rank-Based Allocation of Reproductive Trials is Best. *Proceeding of the 3rd International Conference on Genetic Algorithms*. 4–7 June. San Fracisco, CA, USA: Morgan Kaufnmann Publisher Inc. 116–123.

Widjojo, N., Chung, T. S., Arifin, D. Y., Weber, M. & Warzelhan, V. (2010). Elimination of Die Swell and Instability in Hollow Fiber Spinning Process of Hyperbranched Polyethersulfone (HPES) via Novel Spinneret Designs and Precise Spinning Conditions. *Chemical Engineering Journal*, 163(1), 143–153.

Wienk, I. M., Olde Scholtenhuis, F. H. A., Van Den Boomgaard, T. & Smolders, C. A. (1995). Spinning of Hollow Fiber Ultrafiltration Membranes from a Polymer Blend. *Journal of Membrane Science*, 106(3), 233–243.

Wiesner, M. R. & Chellam, S. (1999). Peer Reviewed: The Promise of Membrane Technology. *Environmental Science & Technology*, 33(17), 360A–366A.

Wu, B., Li, K. & Teo, W. K. (2007). Preparation and Characterization of Poly(vinylidene fluoride) Hollow Fiber Membranes for Vacuum Membrane Distillation. *Journal of Applied Polymer Science*, 106(3), 1482–1495.

Xiangli, F., Wei, W., Chen, Y., Jin, W. & Xu, N. (2008). Optimization of Preparation Conditions for Polydimethylsiloxane (PDMS)/Ceramic Composite

Pervaporation Membranes Using Response Surface Methodology. *Journal of Membrane Science*, 311(1), 23–33.

Xu, J. & Xu, Z. L. (2002). Poly(vinyl chloride) (PVC) Hollow Fiber Ultrafiltration Membranes Prepared from PVC/Additives/Solvent. *Journal of Membrane Science*, 208(1), 203–212.

Xu, Z. L. & Qusay, F. A. (2004). Polyethersulfone (PES) Hollow Fiber Ultrafiltration Membranes Prepared by PES/Non-Solvent/NMP Solution. *Journal of Membrane Science*, 233(1), 101–111.

Xue, S., Liu, F. & Xu, X. (2014). An Improved Algorithm Based on NSGA-II for Cloud PDTs Scheduling. *Journal of Software*, 9(2), 443–450.

Yang, Q., Chung, T. S. & Santoso, Y. E. (2007). Tailoring Pore Size and Pore Size Distribution of Kidney Dialysis Hollow Fiber Membranes via Dual-Bath Coagulation Approach. *Journal of Membrane Science*, 290(1), 153–163.

Yeow, M. L., Liu, Y. T. & Li, K. (2004). Morphological Study of Poly(vinylidene fluoride) Asymmetric Membranes: Effects of the Solvent, Additive, and Dope Temperature. *Journal of Applied Polymer Science*, 92(3), 1782–1789.

Yi, S., Su, Y., Qi, B., Su, Z. & Wan, Y. (2010). Application of Response Surface Methodology and Central Composite Rotatable Design in Optimizing the Preparation Conditions of Vinyltriethoxysilane Modified Silicalite/Polydimethylsiloxane Hybrid Pervaporation Membranes. *Separation and Purification Technology*, 71(2), 252–262.

Yuan, Q. & Dai, G. (2015). Research on the Features of NSGA-II and RM-MEDA. *Journal of Computational Information Systems*, 18, 6735–6745.

Zhu, J., Cai, X., Pan, P. & Gu, R. (2014). Multi-Objective Structural Optimization Design of Horizontal-Axis Wind Turbine Blades Using the Non-Dominated Sorting Genetic Algorithm II and Finite Element Method. *Energies*, 7(2), 988–1002.

Zhu, L. P., Yu, J. Z., Xu, Y. Y. & Zhu, B. K. (2009). The Effects of Spinning Temperature on Morphologies and Properties of Polyethersulfone Hollow Fiber Membranes. *Journal of Applied Polymer Science*, 113(3), 1701–1709.

Zilouchian, A. & Jafar, M. (2001). Automation and Process Control of Reverse Osmosis Plants Using Soft Computing Methodologies. *Desalination*, 135(1), 51–59.

Zitzler, E., Deb, K. & Thiele, L. (2000). Comparison of Multiobjective Evolutionary Algorithms: Empirical Results. *Evolutionary Computation*, 8(2), 173–195.

Zitzler, E. & Thiele, L. (1999). Multiobjective Evolutionary Algorithms: A Comparative Case Study and the Strength Pareto Approach. *IEEE Transactions on Evolutionary Computation*, 3(4), 257–271.