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

NOOR ADILA BINTI ALUWI SHAKIR

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

NOOR ADILA BINTI ALUWI SHAKIR

A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

JUNE 2016
To my beloved mother and father
ACKNOWLEDGEMENTS

Alhamdulillahi rabbil‘alamin,

First and foremost, I would like to extend my profound sense of gratitude to my dedicated supervisors, Professor Dr. Wong Kuan Yew, Professor Dr. Noordin Bin Mohd Yusof and Professor Dr. Izman Bin Sudin for their continuous support, keen effort, excellent advice, great concern and insightful comments throughout this research.

In addition, I would like to extend my sincere appreciation to all Advanced Membrane Technology Research Centre (AMTEC), UTM members especially to Mr. Sohaimi Abdullah and Mr. Ng Be Cheer for their outstanding help and guidance. I would like to take this opportunity to express my sincere appreciation to all those people and organizations who contributed to this research as well as to those who have directly or indirectly assisted me in the preparation of this thesis.

Finally, I want to express my gratitude to my beloved mother, Zaiton Binti Mohamed and my father, Aluwi Shakir Bin Hj. Abdullah for their undivided support, inspiration, and encouragement during my study duration. Thanks also to my siblings for being so supportive towards throughout my study duration. May Allah reward all of you in Hereafter. Above all, I thank Allah the almighty for His grace, love, mercy and guidance throughout my life.
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 cm³/min, AGL of 0 cm, CBT of 30 °C, BFR (NMP/H₂O) 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. Walau bagaimanapun, 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 penelitian dikajikan untuk mengkaji keadaan pintalan secara serentak. Untuk menangani isu ini, kajian ini menggunakan metodologi algoritma genetik tidak terdominasi-II (NSGA-II) untuk mengoptimalkan keadaan pintalan dalam pembuatan membran gentian geronggang ultrapenurasan polietersulfon (PES) untuk rawatan air sisa berminyak bagi memaksimalkan 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 diperoleh 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 cm²/min, AGL 0 cm, CBT 30 °C, BFR (NMP/H₂O) 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 peneliti membuat keputusan pengoptimuman pintalan secara lebih baik dalam proses pembuatan membran.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td></td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td></td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td></td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td></td>
<td>v</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td></td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td></td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td></td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td></td>
<td>xvi</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td></td>
<td>xxii</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td></td>
<td>xxiv</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td></td>
<td>xxvi</td>
</tr>
</tbody>
</table>

1 INTRODUCTION 1
1.1 Background of the Research 1
1.2 Problem Statement 4
1.3 Research Questions 8
1.4 Objective of the Research 8
1.5 Scope of the Research 9
1.6 Significance of the Research 9
1.7 Structure of the Thesis 11

2 LITERATURE REVIEW 12
2.1 Introduction 12
3 RESEARCH METHODOLOGY 82
3.1 Introduction 82
3.2 Experimental Procedures 83
  3.2.1 Material Selection 83
  3.2.2 Multi-Component Solution Preparation 87
  3.2.3 Preparation of PES Hollow Fiber Membranes 89
  3.2.4 Preparation of Hollow Fiber Module 92
3.3 Characterization Methods of Ultrafiltration Hollow Fiber Membrane Module 93
  3.3.1 Performance Measurement of Flux and Rejection 93
  3.3.2 Morphology Study by Scanning Electron Microscopy 96
3.4 Design of Experiments 97
  3.4.1 Experimental Design Setup 97
  3.4.2 Response Surface Methodology 100
3.5 Development of the Proposed Non-Dominated Sorting Genetic Algorithm-II 101
  3.5.1 Spinning Problem Introduction 102
    3.5.1.1 Objective Functions 103
    3.5.1.2 Variable Constraints 104
    3.5.1.3 Model Formulation 104
  3.5.2 Floating-Point Chromosome Representation 105
  3.5.3 NSGA-II Parameter Tuning 107
    3.5.3.1 Performance Criteria 108
    3.5.3.2 Range of Each Parameter Tested 108
    3.5.3.3 Description of Pilot Test 109
  3.5.4 Population Initialization 110
  3.5.5 Crowded Tournament Selection 111
  3.5.6 NSGA-II Operators 115
    3.5.6.1 Arithmetic Crossover 115
    3.5.6.2 Gaussian Mutation 117
  3.5.7 Recombination and Selection 119
4 DESIGN OF EXPERIMENTS AND REGRESSION MODELING

4.1 Introduction 125
4.2 Experimental Results 125
4.3 Development of First-Order Model for Spinning Process 127
  4.3.1 ANOVA Analysis 127
  4.3.2 Model Adequacy Checking 131
    4.3.2.1 Normal Probability Plot 131
    4.3.2.2 Plot of Residuals versus Predicted Values 132
4.4 Development of Second-Order Model for Spinning Process 134
  4.4.1 ANOVA Analysis 135
  4.4.2 Model Adequacy Checking 144
    4.4.2.1 Normal Probability Plot 144
    4.4.2.2 Plot of Residuals versus Predicted Values 144
  4.4.3 Model Graph Analysis for Flux 145
  4.4.4 Model Graph Analysis for Rejection 154
4.5 Optimal Parameter Combination 162
4.6 Effect of Process Variables on the Performance of PES Hollow Fiber Membranes for Ultrafiltration 163
  4.6.1 Effect of Dope Extrusion Rate 164
4.6.2 Effect of Air Gap Length 168
4.6.3 Effect of Coagulation Bath Temperature 171
4.6.4 Effect of Bore Fluid Ratio 175
4.6.5 Effect of Post-Treatment Time 177

4.7 Summary 179

5 OPTIMIZATION USING NSGA-II 181
5.1 Introduction 181
5.2 Codification of NSGA-II 182
5.3 NSGA-II Parameter Setting 183
5.4 NSGA-II Optimization Parameters for Spinning Condition 190
  5.4.1 Pareto Optimal Set 190
  5.4.2 Optimal Spinning Condition Values 197
5.5 Summary 202

6 VALIDATION AND EVALUATION OF RESULTS 203
6.1 Introduction 203
6.2 Validation of Regression Model for the Spinning Process 203
6.3 Validation of NSGA-II Optimization for the Spinning Process 204
  6.3.1 Confirmation Run 204
  6.3.2 Substitution Method 205
6.4 Evaluation of Flux and Rejection for NSGA-II in the Spinning Process 207
6.5 Evaluation of Optimal Solutions for NSGA-II in the Spinning Process 211
6.6 Summary 211

7 CONCLUSIONS AND RECOMMENDATIONS 212
7.1 Introduction 212
7.2 Research Findings 212
7.3 Research Contributions 214
7.4 Limitations of Research and Recommendations for Future Work 216

REFERENCES 219
Appendices A–E 246–278
### LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Various types of membrane processes (Baker, 2002)</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>Comparison of membrane processes (Wagner, 2001)</td>
<td>17</td>
</tr>
<tr>
<td>2.3</td>
<td>Application of statistical regression technique in modeling related to flux and rejection prediction</td>
<td>45</td>
</tr>
<tr>
<td>3.1</td>
<td>Materials used in the spinning solution</td>
<td>85</td>
</tr>
<tr>
<td>3.2</td>
<td>Physical, mechanical and thermal properties of PES</td>
<td>86</td>
</tr>
<tr>
<td>3.3</td>
<td>Composition of materials</td>
<td>87</td>
</tr>
<tr>
<td>3.4</td>
<td>Experimental parameters of PES ultrafiltration hollow fiber membrane spinning</td>
<td>91</td>
</tr>
<tr>
<td>3.5</td>
<td>Setting of spinning condition values for the real spinning process</td>
<td>98</td>
</tr>
<tr>
<td>3.6</td>
<td>Experimental design for spinning conditions in membrane fabrication</td>
<td>99</td>
</tr>
<tr>
<td>3.7</td>
<td>Experimental design for spinning conditions in membrane fabrication (after adding axial point plus center point)</td>
<td>101</td>
</tr>
<tr>
<td>3.8</td>
<td>Encoding scheme</td>
<td>107</td>
</tr>
<tr>
<td>3.9</td>
<td>Range of values investigated for NSGA-II parameters during pilot test</td>
<td>109</td>
</tr>
<tr>
<td>3.10</td>
<td>Example initial population of 5 random chromosomes and their corresponding objective functions, rank and crowding distance</td>
<td>114</td>
</tr>
<tr>
<td>3.11</td>
<td>Current population after crowded tournament selection</td>
<td>114</td>
</tr>
<tr>
<td>4.1</td>
<td>Experimental results for spinning experiments</td>
<td>126</td>
</tr>
</tbody>
</table>
4.2 ANOVA table for the linear model of flux
4.3 ANOVA table for the linear model of rejection
4.4 Flux and rejection predicted values of regression modeling for first-order model
4.5 Sequential model sum of squares for flux model
4.6 Sequential model sum of squares for rejection model
4.7 Lack of fit tests for flux model
4.8 Lack of fit tests for rejection model
4.9 Model summary statistics for flux model
4.10 Model summary statistics for rejection model
4.11 Sequential model sum of squares for flux model
4.12 Resulting ANOVA table (partial sum of squares) for reduced quadratic model for flux
4.13 Sequential model sum of squares for rejection model
4.14 Resulting ANOVA table (partial sum of squares) for reduced quadratic model for rejection
4.15 Flux and rejection predicted values of regression modeling
4.16 Optimal parameter combinations for flux using RSM
4.17 Optimal parameter combinations for rejection using RSM
4.18 Dimensions of PES hollow fiber membranes prepared at different DERs
4.19 Dimensions of PES hollow fiber membranes prepared at different AGLs
4.20 Dimensions of PES hollow fiber membranes prepared at different CBTs
4.21 Dimensions of PES hollow fiber membranes prepared at different BFRs
5.1 Results obtained for NSGA-II for different $N_p$ parameters
5.2 Results obtained for NSGA-II for different $P_c$ parameters
5.3 Results obtained for NSGA-II for different $P_m$ parameters
5.4 Best parameters of NSGA-II for spinning process optimization
5.5 Non-dominated Pareto optimal solutions obtained from NSGA-II in the spinning process
5.6 Spinning solution for 50-50% flux-rejection case
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7</td>
<td>Optimal solutions of NSGA-II for spinning conditions</td>
<td>202</td>
</tr>
<tr>
<td>6.1</td>
<td>Confirmation experiments for regression modeling</td>
<td>206</td>
</tr>
<tr>
<td>6.2</td>
<td>Confirmation experiments for NSGA-II optimization</td>
<td>206</td>
</tr>
<tr>
<td>6.3</td>
<td>Comparison of the spinning process results</td>
<td>210</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Basic concept of membrane separation process (Hunger <em>et al.</em>, 2012; Schmeling <em>et al.</em>, 2010)</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>Cross-section of hollow fiber membrane (Mustaffar, 2004)</td>
<td>22</td>
</tr>
<tr>
<td>2.3</td>
<td>Specifications to fabricate high performance and effective ultrafiltration hollow fiber membranes</td>
<td>23</td>
</tr>
<tr>
<td>2.5</td>
<td>Hollow fiber membrane spinning methods</td>
<td>26</td>
</tr>
<tr>
<td>2.6</td>
<td>Die swell schematic diagram of nascent membrane extruding spinneret (Qin <em>et al.</em>, 2001)</td>
<td>31</td>
</tr>
<tr>
<td>2.7</td>
<td>Modeling techniques in solving spinning process problems</td>
<td>42</td>
</tr>
<tr>
<td>2.8</td>
<td>Optimization methods in solving spinning process problems</td>
<td>49</td>
</tr>
<tr>
<td>2.9</td>
<td>Standard procedure of GA (Nagasawa and Irohara, 2013)</td>
<td>59</td>
</tr>
<tr>
<td>2.10</td>
<td>Pareto front of a set of solutions in a bi-objective space</td>
<td>65</td>
</tr>
<tr>
<td>2.11</td>
<td>The goal for MOEAs is to i) Find close to the Pareto optimal set and then ii) Creating diversity along it (Ayala and Coelho, 2008)</td>
<td>67</td>
</tr>
</tbody>
</table>
2.12 Selection strategy with tournament mechanism (Razali and Geraghty, 2011)

2.13 Crowding distance calculation (Deb et al., 2002)

2.14 NSGA-II procedure (Deb et al., 2002)

2.15 Flow chart of NSGA-II (Zhu et al., 2014)

3.1 Overall flow of the determination of optimal spinning conditions in PES ultrafiltration hollow fiber membrane fabrication

3.2 Molecular structure of PES (Alaei Shahmirzadi et al., 2015)

3.3 Apparatus for polymer solution preparation

3.4 Schematic diagram of spinneret (Ismail, 1997)

3.5 Schematic diagram of hollow fiber module

3.6 Schematic diagram of ultrafiltration hollow fiber membrane: 1) Feed tank, 2) Pump, 3) Pressure gauge, 4) Control valve, 5) Flow meter, 6) Hollow fiber membrane module and 7) Measuring cylinder (Ghasem et al., 2012)

3.7 Plot of absorbance versus oil concentration (Ong et al., 2015)

3.8 Pareto front of a set of solutions in the flux and rejection objective space

3.9 Crowding distance for spinning process optimization

3.10 Gaussian mutation for spinning process optimization

4.1 Half normal probability plot of main effects and interactions for a) Flux and b) Rejection

4.2 Normal probability plot of residuals for a) Flux and b) Rejection

4.3 Residuals vs. predicted plot for a) Flux and b) Rejection

4.4 Normal probability plot of residuals for a) Flux and b) Rejection

4.5 Residuals vs. predicted plot for a) Flux and b) Rejection

4.6 Plots for flux between DER and AGL: a) Contour, b) 3D surface and c) Interaction

4.7 Plots for flux between DER and BFR: a) Contour, b) 3D surface and c) Interaction

4.8 Plots for flux between DER and PT: a) Contour, b) 3D surface and c) Interaction

4.9 Plots for flux between AGL and BFR: a) Contour, b) 3D surface and c) Interaction
4.10 Plots for flux between CBT and BFR: a) Contour, b) 3D surface and c) Interaction

4.11 Plots for flux between CBT and PT: a) Contour, b) 3D surface and c) Interaction

4.12 Plots for flux between BFR and PT: a) Contour, b) 3D surface and c) Interaction

4.13 Plots for rejection between DER and AGL: a) Contour, b) 3D surface and c) Interaction

4.14 Plots for rejection between DER and CBT: a) Contour, b) 3D surface and c) Interaction

4.15 Plots for rejection between DER and BFR: a) Contour, b) 3D surface and c) Interaction

4.16 Plots for rejection between AGL and CBT: a) Contour, b) 3D surface and c) Interaction

4.17 Plots for rejection between AGL and BFR: a) Contour, b) 3D surface and c) Interaction

4.18 Plots for rejection between CBT and BFR: a) Contour, b) 3D surface and c) Interaction

4.19 Overall cross-section of PES hollow fiber membranes at different DERs (magnification: 120x): a) 2 cm$^3$/min; trial 21, b) 4 cm$^3$/min; trial 17 and c) 6 cm$^3$/min; trial 22 (AGL fixed at 1 cm, CBT fixed at 24 °C, BFR (NMP/H$_2$O) fixed at 35/65 wt.% and PT fixed at 4 h)

4.20 Cross-section of PES hollow fiber membranes at different DERs (magnification: 500x): a) 2 cm$^3$/min; trial 21, b) 4 cm$^3$/min; trial 17 and c) 6 cm$^3$/min; trial 22 (AGL fixed at 1 cm, CBT fixed at 24 °C, BFR (NMP/H$_2$O) fixed at 35/65 wt.% and PT fixed at 4 h)

4.21 Outer surface of PES hollow fiber membranes at different DERs (magnification: 10kx): a) 2 cm$^3$/min; trial 21, b) 4 cm$^3$/min; trial 17 and c) 6 cm$^3$/min; trial 22 (AGL fixed at 1 cm, CBT fixed at 24 °C, BFR (NMP/H$_2$O) fixed at 35/65 wt.% and PT fixed at 4 h)

4.22 Effect of DER on flux and rejection for PES hollow fiber
4.23 Cross-section of PES hollow fiber membranes at different AGLs (magnification: 500x): a) 0 cm; trial 23, b) 1 cm; trial 20 and c) 2 cm; trial 24 (DER fixed at 4 cm$^3$/min, CBT fixed at 24 °C, BFR (NMP/H$_2$O) fixed at 35/65 wt.% and PT fixed at 4 h)

4.24 Effect of AGL on flux and rejection for PES hollow fiber membranes

4.25 Outer surface of PES hollow fiber membranes at different AGLs (magnification: 10kx): a) 0 cm; trial 23, b) 1 cm; trial 20 and c) 2 cm; trial 24 (DER fixed at 4 cm$^3$/min, CBT fixed at 24 °C, BFR (NMP/H$_2$O) fixed at 35/65 wt.% and PT fixed at 4 h)

4.26 Cross-section of PES hollow fiber membranes at different CBTs (magnification: 500x): a) 18 °C; trial 25, b) 24 °C; trial 20 and c) 30 °C; trial 26 (DER fixed at 4 cm$^3$/min, AGL fixed at 1 cm, BFR (NMP/H$_2$O) fixed at 35/65 wt.% and PT fixed at 4 h)

4.27 Outer surface of PES hollow fiber membranes at different CBTs (magnification: 10kx): a) 18 °C; trial 25, b) 24 °C; trial 20 and c) 30 °C; trial 26 (DER fixed at 4 cm$^3$/min, AGL fixed at 1 cm, BFR (NMP/H$_2$O) fixed at 35/65 wt.% and PT fixed at 4 h)

4.28 Effect CBT on flux and rejection for PES hollow fiber membranes

4.29 Overal cross-section (magnification: 120x) and inner skin layer (magnification: 1.0kx) of PES hollow fiber membranes at different BFRs (NMP/H$_2$O) a) 0/100 wt.%; trial 27 and b) 70/30 wt.%; trial 28 (DER fixed at 4 cm$^3$/min, AGL fixed at 1 cm, CBT fixed at 24 °C and PT fixed at 4 h)

4.30 Effect of BFR on flux and rejection for PES hollow fiber membranes

4.31 Overall cross-section (magnification: 120x) and cross-section (magnification: 500x) of PES hollow fiber membranes at different PTs a) 2 h; trial 29, b) 4 h; trial 20 and c) 6 h; trial 30 (DER fixed at 4 cm$^3$/min, AGL fixed at 1 cm, CBT fixed at 24 °C and BFR (NMP/H$_2$O) fixed at 35/65 wt.%)

4.32 Effect of PT on flux for PES hollow fiber membranes
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Pareto optimal fronts obtained using NSGA-II with $N_p = 50$</td>
<td>185</td>
</tr>
<tr>
<td>5.2</td>
<td>Pareto optimal fronts obtained using NSGA-II with different $N_p$</td>
<td>185</td>
</tr>
<tr>
<td>5.3</td>
<td>Pareto optimal fronts obtained using NSGA-II with different $P_c$</td>
<td>187</td>
</tr>
<tr>
<td>5.4</td>
<td>Pareto optimal fronts obtained using NSGA-II with different $P_m$</td>
<td>189</td>
</tr>
<tr>
<td>5.5</td>
<td>Pareto optimal front for conflicting objective functions of flux and rejection</td>
<td>196</td>
</tr>
<tr>
<td>6.1</td>
<td>Experimental vs. regression for flux values</td>
<td>207</td>
</tr>
<tr>
<td>6.2</td>
<td>Experimental vs. regression for rejection values</td>
<td>208</td>
</tr>
</tbody>
</table>
**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td>Artificial bee colony algorithm</td>
</tr>
<tr>
<td>ACO</td>
<td>Ant colony optimization</td>
</tr>
<tr>
<td>AGL</td>
<td>Air gap length</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial intelligence</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial neural network</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>BFT</td>
<td>Bore fluid temperature</td>
</tr>
<tr>
<td>BFR</td>
<td>Bore fluid ratio</td>
</tr>
<tr>
<td>BFFR</td>
<td>Bore fluid flow rate</td>
</tr>
<tr>
<td>BSA</td>
<td>Bovine serum albumin</td>
</tr>
<tr>
<td>CA</td>
<td>Cellulose acetate</td>
</tr>
<tr>
<td>CBT</td>
<td>Coagulation bath temperature</td>
</tr>
<tr>
<td>CCD</td>
<td>Central composite design</td>
</tr>
<tr>
<td>DCMD</td>
<td>Direct contact membrane distillation</td>
</tr>
<tr>
<td>DER</td>
<td>Dope extrusion rate</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of experiments</td>
</tr>
<tr>
<td>DP</td>
<td>Dynamic programming</td>
</tr>
<tr>
<td>DT</td>
<td>Dope temperature</td>
</tr>
<tr>
<td>EA</td>
<td>Evolutionary algorithm</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic algorithm</td>
</tr>
<tr>
<td>GFR</td>
<td>Gas flushing rate</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical user interface</td>
</tr>
<tr>
<td>HMWC</td>
<td>High molecular weight component</td>
</tr>
<tr>
<td>HQ</td>
<td>Hydroquinone</td>
</tr>
<tr>
<td>HT</td>
<td>High throughput</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>ID</td>
<td>Inner diameter</td>
</tr>
<tr>
<td>LMWC</td>
<td>Low molecular weight component</td>
</tr>
<tr>
<td>LP</td>
<td>Linear programming</td>
</tr>
<tr>
<td>MATLAB</td>
<td>Matrix laboratory</td>
</tr>
<tr>
<td>MED</td>
<td>Multiple effect distillation</td>
</tr>
<tr>
<td>MF</td>
<td>Microfiltration</td>
</tr>
<tr>
<td>MINLP</td>
<td>Mixed-integer non-linear programming</td>
</tr>
<tr>
<td>MOEA</td>
<td>Multi-objective evolutionary algorithm</td>
</tr>
<tr>
<td>MOGA</td>
<td>Multi-objective genetic algorithm</td>
</tr>
<tr>
<td>MOP</td>
<td>Multi-objective optimization problem</td>
</tr>
<tr>
<td>MPDA</td>
<td>m-Phenylenediamine</td>
</tr>
<tr>
<td>MWCO</td>
<td>Molecular weight cut-off</td>
</tr>
<tr>
<td>NF</td>
<td>Nanofiltration</td>
</tr>
<tr>
<td>NLP</td>
<td>Non-linear programming</td>
</tr>
<tr>
<td>NMP</td>
<td>N-methyl-2-pyrrolidone</td>
</tr>
<tr>
<td>NP</td>
<td>Non-deterministic polynomial</td>
</tr>
<tr>
<td>NPF</td>
<td>Number of Pareto front</td>
</tr>
<tr>
<td>NPGA</td>
<td>Niched Pareto genetic algorithm</td>
</tr>
<tr>
<td>NSGA</td>
<td>Non-dominated sorting genetic algorithm</td>
</tr>
<tr>
<td>NSGA-II</td>
<td>Non-dominated sorting genetic algorithm-II</td>
</tr>
<tr>
<td>OD</td>
<td>Outer diameter</td>
</tr>
<tr>
<td>P</td>
<td>Post-treatment</td>
</tr>
<tr>
<td>PAES</td>
<td>Pareto-archieved evolution strategy</td>
</tr>
<tr>
<td>PAI</td>
<td>Polyamide-imide</td>
</tr>
<tr>
<td>PAN</td>
<td>Polyacrylonitrile</td>
</tr>
<tr>
<td>PBI</td>
<td>Polybenzimidazole</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>PEEKWC</td>
<td>Modified poly(ether ether ketone)</td>
</tr>
<tr>
<td>PEI</td>
<td>Polyetherimide</td>
</tr>
<tr>
<td>PEG</td>
<td>Poly(ethylene) glycol</td>
</tr>
<tr>
<td>PES</td>
<td>Polyethersulfone</td>
</tr>
<tr>
<td>PI</td>
<td>Polyimide</td>
</tr>
<tr>
<td>PLGA</td>
<td>Poly(lactic-co-glycolic acid)</td>
</tr>
<tr>
<td>Abbr.</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>PRESS</td>
<td>Predicted residual sum of squares</td>
</tr>
<tr>
<td>PSF</td>
<td>Polysulfone</td>
</tr>
<tr>
<td>PSO</td>
<td>Particle swarm optimization</td>
</tr>
<tr>
<td>PT</td>
<td>Post-treatment time</td>
</tr>
<tr>
<td>PU</td>
<td>Polyurethane</td>
</tr>
<tr>
<td>PVDF</td>
<td>Polyvinylidene fluoride</td>
</tr>
<tr>
<td>PVDF-HFP</td>
<td>Poly (vinylidene fluoride-co-hexafluoropropylene)</td>
</tr>
<tr>
<td>PVP</td>
<td>Polyvinylpyrrolidone</td>
</tr>
<tr>
<td>PWP</td>
<td>Pure water permeability</td>
</tr>
<tr>
<td>RDGA</td>
<td>Rank-density based genetic algorithm</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity</td>
</tr>
<tr>
<td>RO</td>
<td>Reverse osmosis</td>
</tr>
<tr>
<td>RSM</td>
<td>Response surface methodology</td>
</tr>
<tr>
<td>RT</td>
<td>Residence time</td>
</tr>
<tr>
<td>RWGA</td>
<td>Random weighted genetic algorithm</td>
</tr>
<tr>
<td>SA</td>
<td>Simulated annealing</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>SEPPI</td>
<td>Solidification of emulsified polymer solutions via phase inversion</td>
</tr>
<tr>
<td>SPEA</td>
<td>Strength Pareto evolutionary algorithm</td>
</tr>
<tr>
<td>SS</td>
<td>Spinneret size</td>
</tr>
<tr>
<td>ST</td>
<td>Spinneret temperature</td>
</tr>
<tr>
<td>TBAB</td>
<td>Tetrabutylammonium bromide</td>
</tr>
<tr>
<td>TMP</td>
<td>Transmembrane pressure</td>
</tr>
<tr>
<td>TS</td>
<td>Take-up speed</td>
</tr>
<tr>
<td>UF</td>
<td>Ultrafiltration</td>
</tr>
<tr>
<td>VEGA</td>
<td>Vector evaluated genetic algorithm</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

A - Surface area of hollow fiber membrane

Cf - Concentration of solute area of feed

Cp - Concentration of solute area of permeate

D - Outer diameter of hollow fiber membrane

Fj(x) - Function of flux

Fr(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

Np - Population size

Pc - Probability of crossover

Pm - Probability of mutation

Pt - Population

P* - Pareto optimal set

PF* - Pareto front

Q - Water flux reading

Qt - Population after selection, crossover and mutation

R - Rejection

Rt - Combined population

t - Time

Ts - Tournament size
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$</td>
<td>Permeate volume</td>
</tr>
<tr>
<td>$w$</td>
<td>Pseudo-weight</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Difference of pressure between feed area and permeation area</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Decision space</td>
</tr>
<tr>
<td>$\infty$</td>
<td>Infinity</td>
</tr>
<tr>
<td>$\prec_n$</td>
<td>Crowded comparison operator</td>
</tr>
<tr>
<td>$\mathbb{R}^a$</td>
<td>Decision variable space</td>
</tr>
<tr>
<td>$\mathbb{R}^k$</td>
<td>Objective function space</td>
</tr>
</tbody>
</table>
## LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Summary of spinning condition parameters for membranes fabrication</td>
<td>246</td>
</tr>
<tr>
<td>B</td>
<td>Reviews of method used in optimizing spinning conditions in membranes fabrication</td>
<td>250</td>
</tr>
<tr>
<td>C</td>
<td>NSGA-II parameters tuning</td>
<td>255</td>
</tr>
<tr>
<td>D</td>
<td>MATLAB codes for optimization of spinning condition parameters for membranes fabrication using NSGA-II</td>
<td>270</td>
</tr>
<tr>
<td>E</td>
<td>Validation of NSGA-II MATLAB codes</td>
<td>278</td>
</tr>
</tbody>
</table>
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 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.


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


