### CONTENTS

#### PAGE

| EN<br>TH<br>AC<br>CC<br>LIS<br>LIS | IGLISH ABSTRACT<br>IAI ABSTRACT<br>CKNOWLEDGEMENTS<br>ONTENTS<br>ST OF TABLES<br>ST OF FIGURES | ii<br>iii<br>v<br>vi<br>viii<br>x |
|------------------------------------|--|-----------------------------------|
| CH                                 | HAPTER   |                                   |
| 1.                                 | INTRODUCTION   | 1                                 |
|                                    | 1.1 Background   | 1                                 |
|                                    | 1.2 Cojectives   | 1                                 |
|                                    | 1.4 Expected Benefits  | 2                                 |
| 2.                                 | THEORIES AND LITERATURE REVIEW   | 3                                 |
|                                    | 2.1 Membranes Process  | 3                                 |
|                                    | 2.2 Pervaporation Process, PV  | 4                                 |
|                                    | 2.3 Vapor Permeation, VP   | 5                                 |
|                                    | 2.4 Membrane Performance Evaluation  | 5                                 |
|                                    | 2.5 Mechanism of Mass Transfer through the Membrane  | 6                                 |
|                                    | 2.6 The effects of Operating Parameters  | 9                                 |
|                                    | 2.7 Kapton <sup>®</sup> Polyimide  | 9                                 |
|                                    | 2.8 Pyrolysis Process  | 10                                |
|                                    | 2.9 Literature Review  | 11                                |
| 3.                                 | EXPERIMENT   | 17                                |
|                                    | 3.1 Equipment and Materials  | 17                                |
|                                    | 3.2 Experimental Procedures  | 19                                |
| 4.                                 | RESULTS AND DISCUSSION   | 21                                |
|                                    | 4.1 Single-component permeation  | 21                                |
|                                    | 4.2 Bi-component permeation  | 25                                |
| 5.                                 | CONCLUSIONS AND RECOMMENDATIONS  | 34                                |
|                                    | 5.1 Conclusions  | 34                                |
|                                    | 5.2 Recommendations  | 34                                |

#### REFERENCES

| APPEN | DIX |
|-------|-----|
|-------|-----|

| A. Calibration Curve  | 37 |
|---|----|
| B. GC Conditions for Analyzed Vapor Organics Concentration    | 45 |
| C. Partial Pressure of Vapor Organic compounds in Permeate    | 50 |
| D. Partial Pressure of Vapor Organic compounds in Feed for VP | 58 |
| E. Data from Aspen Engineering Suite 2006                     | 65 |
| F. Calculations   | 72 |
| G. Experimental Data  | 78 |
| RRICULUM VITAE  | 95 |

#### **CURRICULUM VITAE**

35

### LIST OF TABLES

| TABLE |   | PAGE |
|-------|---|------|
| 2.1   | Properties of organic compounds   | 9    |
| 4.1   | Molecular weight, Molecular diameter, and dipole moment of                  | 24   |
|       | pure organic compounds.   |      |
| 4.2   | Fluxes and permeabilities of single-component permeation                    | 24   |
|       | for PV and VP   |      |
| 4.3   | Fluxes and permeabilities of methanol/ethanol obtained                      | 27   |
|       | from bi-component feed  |      |
| 4.4   | Fluxes and permeabilities of acetone/IPA obtained                           | 29   |
|       | from bi-component feed  |      |
| 4.5   | Fluxes and permeabilities of acetone/methanol obtained                      | 31   |
|       | from bi-component feed  |      |
| 4.6   | Fluxes and permeabilities of acetone/ethanol obtained                       | 33   |
|       | from bi-component feed  |      |
| A.1   | Data for calibration curve of vapor methanol, sample volume 1.50 ml         | 38   |
| A.2   | Data for calibration curve of vapor methanol, sample volume 3.00 ml         | 39   |
| A.3   | Data for calibration curve of vapor ethanol, sample volume 3.00 ml          | 40   |
| A.4   | Data for calibration curve of vapor isopropanol, sample volume 3.00 ml      | 41   |
| A.5   | Data for calibration curve of vapor acetone, sample volume 3.00 ml          | 42   |
| A.6.1 | Calibration curve of vapor acetone for sample volume 3.00 ml                | 43   |
| A.6.2 | Calibration curve of vapor ethanol for sample volume 3.00 ml                | 44   |
| C.1   | Data for partial pressure of methanol, sample volume 1.50 ml                | 51   |
| C.2   | Data for partial pressure of methanol, sample volume 3.00 ml                | 52   |
| C.3   | Data for partial pressure of ethanol, sample volume 3.00 ml                 | 53   |
| C.4   | Data for partial pressure of isopropanol, sample volume 3.00 ml             | 54   |
| C.5   | Data for partial pressure of acetone, sample volume 3.00 ml                 | 55   |
| C.6.1 | Data for permeate pressure of acetone                                       | 56   |
| C.6.2 | Data for permeate pressure of ethanol                                       | 57   |
| D.1   | Data for partial pressure of methanol in feed                               | 59   |
| D.2   | Data for partial pressure of ethanol in feed                                | 60   |
| D.3   | Data for partial pressure of isopropanol in feed                            | 61   |
| D.4   | Data for partial pressure of acetone in feed                                | 62   |
| D.5.1 | Data for partial pressure of acetone in feed                                | 63   |
| D.5.2 | Data for partial pressure of ethanol in feed                                | 64   |
| G.1   | The physical characteristics of the membrane carbonized at 600 $^{\circ}$ C | 79   |
| G.2.1 | Fluxes and permeability of pure methanol (100 wt %) as a feed for PV        | 80   |
| G.2.2 | Fluxes and permeability of pure methanol (100 wt %) as a feed for VP        | 80   |

## LIST OF TABLES (Con't.)

TABLE

| G.3.1 | Fluxes and permeability of pure ethanol (99.5 wt %) as a feed for PV                 | 81 |
|-------|--|----|
| G.3.2 | Fluxes and permeability of pure ethanol (99.5 wt %) as a feed for VP                 | 81 |
| G.4.1 | Fluxes and permeability of pure isopropanol (99.8 wt %) as a feed for PV             | 82 |
| G.4.2 | Fluxes and permeability of pure isopropanol (99.8 wt %) as a feed for VP             | 82 |
| G.5.1 | Fluxes and permeability of pure acetone (99.99 wt %) as a feed for PV                | 83 |
| G.5.2 | Fluxes and permeability of pure acetone (99.99 wt %) as a feed for VP                | 83 |
| G.6.1 | Fluxes and permeability of methanol/ethanol (20:80 wt %) mixture<br>as a feed for PV | 84 |
| G.6.2 | Fluxes and permeability of methanol/ethanol (20:80 wt %) mixture<br>as a feed for VP | 85 |
| G.7.1 | Fluxes and permeability of acetone/IPA (20:80 wt %) mixture as a feed for PV         | 86 |
| G.7.2 | Fluxes and permeability of acetone/IPA (20:80 wt %) mixture as a feed for VP         | 86 |
| G.8.1 | Fluxes and permeability of methanol/acetone (20:80 wt %) mixture as a feed for PV    | 87 |
| G.8.2 | Fluxes and permeability of methanol/acetone (20:80 wt %) mixture as a feed for VP    | 89 |
| G.9.1 | Fluxes and permeability of acetone/ethanol (50:50 wt %) mixture as a feed for PV     | 91 |
| G.9.2 | Fluxes and permeability of acetone/ethanol (50:50 wt %) mixture as a feed for VP     | 93 |

#### PAGE

### LIST OF FIGURES

| FIGURE |   |      |
|--------|---|------|
| 2.1    | Principle of membranes process  | 3    |
| 2.2    | Schematic diagram of the pervaporation process                          | 4    |
| 2.3    | Schematic diagram of the vapor permeation                               | 5    |
| 2.4    | The separation mechanism in carbon membrane                             | 7    |
| 2.5    | Structural formula of Kapton <sup>®</sup> polyimide                     | 10   |
| 2.6    | Structure and pyrolysis process of Kapton <sup>®</sup> polyimide        | 10   |
| 3.1    | Schematic diagrams of the pervaporation apparatus                       | 17   |
| 3.2    | Schematic diagrams of the vapor permeation apparatus                    | 18   |
| 4.1.   | Pervaporation fluxes as a function of time for                          | 22   |
|        | (a) methanol, ethanol, IPA and acetone and                              |      |
|        | (b) ethanol, IPA and acetone  |      |
| 4.2.   | Vapor fluxes as a function of time for                                  | 23   |
|        | (a) methanol, ethanol, IPA and acetone and                              |      |
|        | (b) ethanol, IPA and acetone  |      |
| 4.3.   | Fluxes as a function of time for methanol/ethanol (20:80 wt. %) mixture | e 26 |
|        | (a) Fluxes from PV and (b) Fluxes from VP                               |      |
| 4.4.   | Fluxes as a function of time for acetone/IPA (20:80 wt %) mixture       | 28   |
|        | (a) Fluxes from PV and (b) Fluxes from VP                               |      |
| 4.5.   | Fluxes as a function of time for methanol/acetone (20:80 wt %) mixture  | e 30 |
|        | (a) Fluxes from PV and (b) Fluxes from VP                               |      |
| 4.6.   | Fluxes as a function of time for acetone/ethanol (50:50 wt %) mixture   | 32   |
|        | (a) Fluxes from PV and (b) Fluxes from VP                               |      |
| A.1    | Calibration curve of vapor methanol for sample volume 1.50 ml           | 38   |
| A.2    | Calibration curve of vapor methanol for sample volume 3.00 ml           | 39   |
| A.3    | Calibration curve of vapor ethanol for sample volume 3.00 ml            | 40   |
| A.4    | Calibration curve of vapor isopropanol for sample volume 3.00 ml        | 41   |
| A.5    | Calibration curve of vapor acetone for sample volume 3.00 ml            | 42   |
| A.6.1  | Calibration curve of vapor acetone for sample volume 3.00 ml            | 43   |
| A.6.2  | Calibration curve of vapor ethanol for sample volume 3.00 ml            | 44   |
| C.1    | Partial pressure of methanol for sample volume 1.50 ml                  | 51   |
| C.2    | Partial pressure of methanol for sample volume 3.00 ml                  | 52   |
| C.3    | Partial pressure of ethanol for sample volume 3.00 ml                   | 53   |
| C.4    | Partial pressure of isopropanol for sample volume 3.00 ml               | 54   |
| C.5    | Partial pressure of acetone for sample volume 3.00 ml                   | 55   |
| C.6.1  | Partial pressure of acetone for sample volume 3.00 ml                   | 56   |
| C.6.2  | Partial pressure of ethanol for sample volume 3.00 ml                   | 57   |

# LIST OF FIGURES (Con't.)

| E                                       | PAGE   |
|---|--|
| Partial pressure of methanol in feed    | 59   |
| Partial pressure of ethanol in feed     | 60   |
| Partial pressure of isopropanol in feed | 61   |
| Partial pressure of acetone in feed     | 62   |
| Partial pressure of acetone in feed     | 63   |
| Partial pressure of ethanol in feed     | 64   |
|   | E<br>Partial pressure of methanol in feed<br>Partial pressure of ethanol in feed<br>Partial pressure of isopropanol in feed<br>Partial pressure of acetone in feed<br>Partial pressure of acetone in feed<br>Partial pressure of ethanol in feed |