


การรีฟอร์มมีเทนด้วยไอน้ำเพื่อเป็นแก๊สสังเคราะห์บนตัวเร่งปฏิกิริยา  
สารละลายของแข็งนิกเกิลแมกนีเซียมออกไซด์



นายวีระพงษ์ วิริยะปัญญา

ศูนย์วิทยทรัพยากร

จุฬาลงกรณ์มหาวิทยาลัย

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต  
สาขาวิชาปิโตรเคมีและวิทยาศาสตร์พอลิเมอร์ หลักสูตรปิโตรเคมีและวิทยาศาสตร์พอลิเมอร์

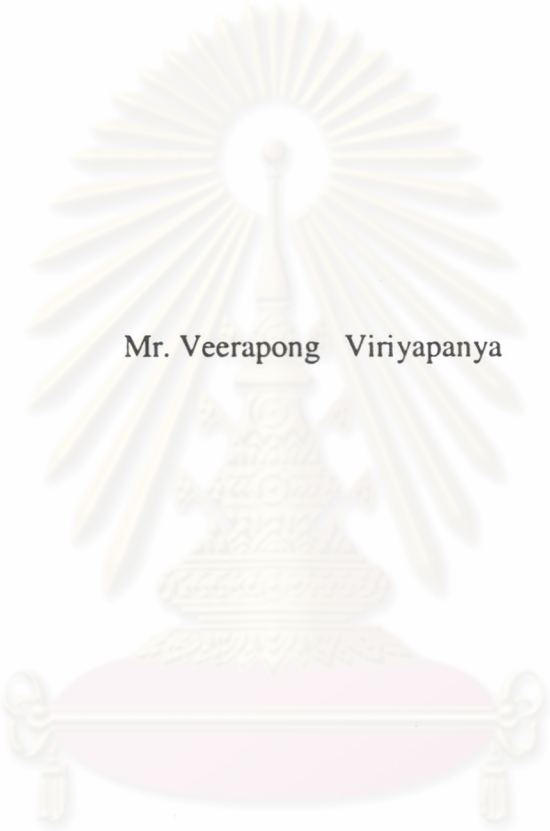
คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

ปีการศึกษา 2545

ISBN 974-17-3015-2

ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย

STEAM REFORMING OF METHANE TO SYNTHETIC GAS  
ON  $\text{Ni}_{0.03}\text{Mg}_{0.97}\text{O}$  SOLID SOLUTION CATALYST



Mr. Veerapong Viriyapanya

ศูนย์วิทยทรัพยากร  
จุฬาลงกรณ์มหาวิทยาลัย

A Thesis Submitted in Partial Fulfillment of the Requirements  
for the Degree of Master of Science in Petrochemistry and Polymer Science

Program of Petrochemistry and Polymer Science

Faculty of Science

Chulalongkorn University

Academic Year 2002

ISBN 974-17-3015-2

Thesis Title           STEAM REFORMING OF METHANE TO SYNTHETIC GAS  
                                  ON Ni<sub>0.03</sub>Mg<sub>0.97</sub>O SOLID SOLUTION CATALYST

By                         Mr. Veerapong Viriyapanya

Program                 Petrochemistry and Polymer Science

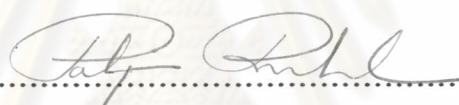
Thesis Advisor         Associate Professor Tharapong Vitidsant, Ph.D.

---

Accepted by the Faculty of Science, Chulalongkorn University in Partial  
Fulfillment of the Requirements for the Master 's Degree


  
..... Dean of Faculty of Science  
(Associate Professor Wanchai Phothiphichitr, Ph.D.)

THESIS COMMITTEE

  
..... Chairman  
(Professor Pattarapan Prasassarakich, Ph.D.)

  
..... Thesis Advisor  
(Associate Professor Tharapong Vitidsant, Ph.D.)

  
..... Member  
(Associate Professor Thirasak Rirksomboon, Ph.D.)

  
..... Member  
(Associate Professor Wimonrat Trakarnpruk, Ph.D.)

วีระพงษ์ วีริยะปัญญา: การรีฟอร์มมีเทนด้วยไอน้ำเพื่อเป็นแก๊สสังเคราะห์บนตัวเร่งปฏิกิริยาสารละลายของแข็งนิกเกิลแมกนีเซียมออกไซด์ (STEAM REFORMING OF METHANE TO SYNTHETIC GAS ON  $\text{Ni}_{0.03}\text{Mg}_{0.97}\text{O}$  SOLID SOLUTION CATALYST) อ.ที่ปรึกษา: รศ.ดร. ธีรพงษ์ วิทิตสานต์; 85 หน้า, ISBN 974-17-3015-2.

วัตถุประสงค์ของงานวิจัยนี้ คือการศึกษาจลนพลศาสตร์ของการรีฟอร์มมีเทนด้วยไอน้ำบนตัวเร่งปฏิกิริยาสารละลายของแข็งนิกเกิลแมกนีเซียมออกไซด์ในเครื่องปฏิกรณ์แบบเบดนิ่งทรงกระบอก ตัวเร่งปฏิกิริยารูปร่างทรงกลมที่มีพื้นที่จำเพาะ 22 ตารางเมตรต่อกรัม ความหนาแน่น 589.64 กิโลกรัมต่อลูกบาศก์เมตร ถูกบรรจุในเครื่องปฏิกรณ์ทรงกระบอกขนาดเส้นผ่านศูนย์กลาง 3 เซนติเมตร สูง 66 เซนติเมตร นอกจากนี้ยังศึกษาอิทธิพลของอุณหภูมิ อัตราส่วนของ  $\text{H}_2\text{O}/\text{CH}_4$  อัตราการป้อนของแก๊สมีเทน อัตราการป้อนของไอน้ำ และน้ำหนักของตัวเร่งปฏิกิริยา ที่มีผลต่อการเปลี่ยนแปลงของแก๊สมีเทน และอัตราเร็วในการเกิดปฏิกิริยา โดยพบว่าสมการอัตราเร็วในการเกิดปฏิกิริยาการรีฟอร์มด้วยไอน้ำในกรณีการใช้ไอน้ำที่มีปริมาณมากเกินพอให้อันดับปฏิกิริยาของแก๊สมีเทนเป็น 1 สำหรับการใช้อไอน้ำในปริมาณน้อยให้สมการอัตราเร็วในการเกิดปฏิกิริยาที่มีอันดับปฏิกิริยาของแก๊สมีเทนเป็น 1 และไอน้ำเป็น 0.5 นอกจากนี้ปฏิกิริยาการรีฟอร์มมีเทนด้วยไอน้ำเป็นปฏิกิริยาอันดับหนึ่งของแก๊สมีเทนซึ่งอธิบายโดยแบบจำลองของ Langmuir – Hinshelwood และปฏิกิริยาเคมีเป็นขั้นตอนในการควบคุมอัตราเร็วในการเกิดปฏิกิริยาเมื่อเปรียบเทียบข้อมูลการทดลองกับสมดุลทางเทอร์โมไดนามิกส์พบว่าสอดคล้องกัน โดยมีแบบจำลองของปฏิกิริยาทางเทอร์โมไดนามิกส์ คือปฏิกิริยาการรีฟอร์มมีเทนด้วยไอน้ำ และปฏิกิริยาออกเตอร์ – แก๊สซิฟท์

## ศูนย์วิทยทรัพยากร จุฬาลงกรณ์มหาวิทยาลัย

หลักสูตร ปิโตรเคมีและวิทยาศาสตร์พอลิเมอร์ ลายมือชื่อนิสิต.....  
สาขาวิชา ปิโตรเคมีและวิทยาศาสตร์พอลิเมอร์ ลายมือชื่ออาจารย์ที่ปรึกษา.....  
ปีการศึกษา.....2545.....ลายมือชื่ออาจารย์ที่ปรึกษาร่วม.....

# # 437 24201 23: MAJOR PETROCHEMISTRY AND POLYMER SCIENCE

KEY WORD: METHANE STEAM REFORMING / SYNTHESIS GAS / WATER-GAS SHIFT / SOLID SOLUTION CATALYST

VEERAPONG VIRIYAPANYA: STEAM REFORMING OF METHANE TO SYNTHETIC GAS ON  $\text{Ni}_{0.03}\text{Mg}_{0.97}\text{O}$  SOLID SOLUTION CATALYST  
 THESIS ADVISOR: ASSOC. PROF. THARAPONG VITIDSANT, Ph.D.,  
 85 pp. ISBN 974-17-3015-2.

The objective of this research was to study the kinetics of methane steam reforming on  $\text{Ni}_{0.03}\text{Mg}_{0.97}\text{O}$  solid solution catalyst in fixed bed cylindrical reactor. The spherical catalyst of  $22 \text{ m}^2/\text{g}$  specific area and  $589.64 \text{ kg}/\text{m}^3$  density were packed in cylindrical reactor of 3 cm. diameter and 66 cm. long. The effect of temperature,  $\text{H}_2\text{O}/\text{CH}_4$  ratio, methane feed rate, steam feed rate and catalyst weight on methane conversion and reaction rate was investigated. The rate equation of steam reforming in case of excess steam was expressed in first order of methane. Non-excess steam showed the rate equation of reaction, which was expressed in order of 1 for methane and 0.5 for steam. The methane steam reforming was first order of methane explained by Langmuir – Hinshelwood model and the chemical reaction was controlling step of reaction rate. Comparison of the experimental data with thermodynamics equilibrium was consistent. The thermodynamics model of reaction could be proposed in methane steam reforming and water - gas shift reactions.

ศูนย์วิจัยทรัพยากร  
 จุฬาลงกรณ์มหาวิทยาลัย

Program Petrochemistry and Polymer Science Student's signature *Ornara Sinyat*  
 Field of Study Petrochemistry and Polymer Science Advisor's signature *T. Vitidsant*  
 Academic year 2002 Co-advisor's signature.....-.....

## ACKNOWLEDGEMENT

The author would like to express sincere thanks to many people who has participated and supported him during the course of study, in particular his advisor, Associate Professor Tharapong Vitidsant, Ph.D., for the encouraging guidance, supervision and helpful suggestion throughout this research. In addition, he is also grateful to Professor Pattarapan Prasassarakich, Ph.D., Associate Professor Thirasak Rirksomboon, Ph.D., and Associate Professor Wimonrat Trakarnpruk, Ph.D. for serving as chairman and members of the thesis committee, respectively, and for their valuable comments.

The author is also thankful for research financial supports from Chulalongkorn University and Scientific and Technological Research Equipment Center, Chulalongkorn University for their help to determine percent by weight of carbon by CHNS/O Analyzer in the catalyst characterization.

Gratitude is expressed towards everyone, whose names are not mentioned here, who has contributed suggestions and support throughout this research. Finally, the author would like to express thankfulness to his family for their support and encouragement throughout the course.

ศูนย์วิจัยทรัพยากร  
จุฬาลงกรณ์มหาวิทยาลัย

## CONTENTS

|                                                           | PAGE |
|-----------------------------------------------------------|------|
| ABSTRACT (IN THAI).....                                   | iv   |
| ABSTRACT (IN ENGLISH).....                                | v    |
| ACKNOWLEDGEMENT.....                                      | vi   |
| CONTENTS.....                                             | vii  |
| LIST OF TABLES.....                                       | x    |
| LIST OF FIGURES.....                                      | xii  |
| LIST OF ABBREVIATIONS.....                                | xiv  |
| CHAPTER I : INTRODUCTION.....                             | 1    |
| 1.1. Background of the Utilization of Natural Gas.....    | 1    |
| 1.2. Objectives.....                                      | 3    |
| 1.3. Scope of the Research.....                           | 3    |
| 1.4. Expected Results.....                                | 4    |
| CHAPTER II : THEORY AND LITERATURE REVIEWS.....           | 5    |
| 2.1. Introduction of Synthesis Gas.....                   | 5    |
| 2.1.1. The Manufacture of Synthesis Gas.....              | 5    |
| 2.1.2. The Utilization of Synthesis Gas.....              | 10   |
| 2.1.2.1. Synthesis Gas.....                               | 10   |
| 2.1.2.2. Carbon Monoxide.....                             | 10   |
| 2.1.2.3. Hydrogen.....                                    | 11   |
| 2.2. Theory of Reforming Reaction.....                    | 15   |
| 2.2.1. Raw Material.....                                  | 15   |
| 2.2.2. Reforming Reaction.....                            | 15   |
| 2.2.2.1. Steam Reforming Reaction.....                    | 17   |
| 2.2.2.2. Carbon Dioxide Reforming Reaction.....           | 20   |
| 2.2.3. Reaction Mechanism of Methane Steam Reforming..... | 21   |
| 2.2.4. Formation of Carbon Deposition.....                | 22   |
| 2.3. Chemical Reaction Rate.....                          | 24   |
| 2.3.1. Rate Law.....                                      | 24   |
| 2.3.2. Order of Reaction.....                             | 26   |
| 2.3.3. Rate Constant.....                                 | 26   |

## CONTENTS (Continued)

|                                                                                                                                                            | PAGE      |
|------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| 2.3.4. The Measurement of Reaction Rate by Differential Method                                                                                             | 27        |
| 2.3.5. The Effect of Factors on Rate of Reaction.....                                                                                                      | 29        |
| 2.4. Catalyst.....                                                                                                                                         | 30        |
| 2.4.1. Classification of Catalysts.....                                                                                                                    | 30        |
| 2.4.2. Heterogeneous Catalysis.....                                                                                                                        | 31        |
| 2.4.2.1. The Mechanism of Heterogeneous Catalytic<br>Reaction.....                                                                                         | 31        |
| 2.4.2.2. Supported Metal Catalyst.....                                                                                                                     | 32        |
| 2.5. Literature Reviews.....                                                                                                                               | 34        |
| <b>CHAPTER III : EXPERIMENTAL.....</b>                                                                                                                     | <b>37</b> |
| 3.1. Materials and Chemicals.....                                                                                                                          | 37        |
| 3.2. Instruments and Apparatus.....                                                                                                                        | 37        |
| 3.2.1. Cylindrical Fixed Bed Reactor.....                                                                                                                  | 38        |
| 3.2.2. Temperature Controller.....                                                                                                                         | 40        |
| 3.2.3. Steam Generator.....                                                                                                                                | 42        |
| 3.2.4. Mass Flow Controller.....                                                                                                                           | 43        |
| 3.2.5. Moisture Trap.....                                                                                                                                  | 43        |
| 3.2.6. Gas Analyzer.....                                                                                                                                   | 44        |
| 3.3. Experimental Procedure.....                                                                                                                           | 46        |
| 3.3.1. Experimental Procedure before the Reaction.....                                                                                                     | 46        |
| 3.3.2. Operation of the Reaction Procedure.....                                                                                                            | 47        |
| 3.4. The Influence of Operating Parameters on the Performance of<br>Reaction at Atmospheric Pressure and Determination of<br>Kinetics of the Reaction..... | 47        |
| 3.4.1. Reaction in Case of Excess Steam.....                                                                                                               | 47        |
| 3.4.2. Reaction in Case of Non-Excess Steam.....                                                                                                           | 48        |
| 3.4.3. The Effect of Catalyst Weight.....                                                                                                                  | 48        |
| 3.5. Reaction Mechanism and Determination of Rate<br>Equation by Langmuir-Hinshelwood Model.....                                                           | 48        |
| 3.6. The Influence of Diffusion on the Rate of Reaction.....                                                                                               | 49        |



## CONTENTS (Continued)

|                                                                                                                       | PAGE |
|-----------------------------------------------------------------------------------------------------------------------|------|
| 3.7. Determination of Thermodynamics Model of Reaction.....                                                           | 49   |
| CHAPTER IV : RESULTS AND DISCUSSION.....                                                                              | 50   |
| 4.1. The Effect of Operating Parameters and Determination of<br>Kinetics of the Reaction at Atmospheric Pressure..... | 50   |
| 4.1.1. Excess Steam Condition.....                                                                                    | 50   |
| 4.1.2. Non-Excess Steam Condition.....                                                                                | 53   |
| 4.1.3. The Effect of Catalyst Weight.....                                                                             | 56   |
| 4.2. Reaction Mechanism and Determination of Rate Equation by<br>Langmuir-Hinshelwood Model.....                      | 58   |
| 4.3. The Effect of Diffusion on the Rate of Reaction.....                                                             | 61   |
| 4.4. Determination of Thermodynamics Model of Reaction.....                                                           | 62   |
| 4.5. Literature Comparison.....                                                                                       | 63   |
| CHAPTER V : CONCLUSIONS AND SUGGESTION.....                                                                           | 65   |
| 5.1. Conclusions.....                                                                                                 | 65   |
| 5.2. Suggestion.....                                                                                                  | 66   |
| REFERENCES.....                                                                                                       | 67   |
| APPENDICES.....                                                                                                       | 71   |
| APPENDIX A.....                                                                                                       | 72   |
| APPENDIX B.....                                                                                                       | 76   |
| APPENDIX C.....                                                                                                       | 78   |
| APPENDIX D.....                                                                                                       | 84   |
| VITA.....                                                                                                             | 85   |

## LIST OF TABLES

| TABLE                                                                                                                                                                                                                                                                              | PAGE |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 1.1. The utilization of synthesis gas.....                                                                                                                                                                                                                                         | 2    |
| 2.1. The ratio of synthesis gas from the producing processes.....                                                                                                                                                                                                                  | 6    |
| 2.2. The utilization of synthesis gas in petrochemical industry.....                                                                                                                                                                                                               | 8    |
| 2.3. The technology of synthesis gas generation.....                                                                                                                                                                                                                               | 9    |
| 2.4. The hydrogen production with several processes.....                                                                                                                                                                                                                           | 12   |
| 2.5. The utilization of global hydrogen in 2000.....                                                                                                                                                                                                                               | 13   |
| 3.1. The optimum condition of gas chromatograph.....                                                                                                                                                                                                                               | 46   |
| 4.1. Values of rate constant, order of reaction for methane<br>and activation energy.....                                                                                                                                                                                          | 53   |
| 4.2. Values of rate constant, order of reaction for methane<br>and steam, and activation energy.....                                                                                                                                                                               | 55   |
| 4.3. Comparison of rate equation and activation energy in each literature.....                                                                                                                                                                                                     | 64   |
| C1 The experiment for determination of rate equation at excess steam<br>condition, catalyst weight of 2 g and atmospheric pressure.....                                                                                                                                            | 78   |
| C2 The experiment for determination of rate equation at non-excess steam<br>condition, catalyst weight of 2 g and atmospheric pressure.....                                                                                                                                        | 79   |
| C3 The experiment about the effect of steam to methane ratio on methane<br>conversion and reaction rate at 850 °C, non-excess steam condition,<br>catalyst weight of 2 g and atmospheric pressure.....                                                                             | 80   |
| C4 The experiment about the mechanism of reaction and determination of<br>rate equation by Langmuir-Hinshelwood model at 850 °C, catalyst weight<br>of 2 g and atmospheric pressure.....                                                                                           | 81   |
| C5 Calculation of variables for determination of rate equation at excess steam<br>condition, catalyst weight of 2 g and atmospheric pressure.....                                                                                                                                  | 82   |
| C6 Calculation of variables for determination of rate equation at non-excess<br>steam condition, catalyst weight of 2 g and atmospheric pressure.....                                                                                                                              | 82   |
| C7 The experiment about the effect of catalyst weight on methane conversion,<br>hydrogen to carbon monoxide ratio and product gas composition at 850 °C,<br>$1.27 \times 10^{-4}$ mole/min of methane feed rate, 0.15 mole/min of steam feed<br>rate and atmospheric pressure..... | 82   |

## LIST OF TABLES (Continued)

| TABLE                                                                                                                                                                                                                                                                                                           | PAGE |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| C8 Calculation of Thiele modulus ( $\Phi$ ) in the effect of diffusion on rate of reaction.....                                                                                                                                                                                                                 | 83   |
| C9 The experiment for determination of thermodynamics model of reaction at 700- 850 °C, steam to methane ratio of 4.0, $1.27 \times 10^{-4}$ to $1.46 \times 10^{-4}$ mole/min of methane feed rate, $5.07 \times 10^{-4}$ to $5.86 \times 10^{-4}$ mole/min of steam feed rate and catalyst weight of 5 g..... | 83   |



ศูนย์วิทยทรัพยากร  
จุฬาลงกรณ์มหาวิทยาลัย

## LIST OF FIGURES

| FIGURE                                                                                       | PAGE |
|----------------------------------------------------------------------------------------------|------|
| 2.1. Partial oxidation process.....                                                          | 7    |
| 2.2. Coal gasification process.....                                                          | 7    |
| 2.3. The production of primary products from synthesis gas.....                              | 13   |
| 2.4. The utilization of primary products.....                                                | 14   |
| 2.5. Sources of the hydrogen production.....                                                 | 14   |
| 2.6. Temperature dependence of the equilibrium constants of the<br>conversion reactions..... | 17   |
| 2.7. The diagram of hydrogen and syngas production.....                                      | 20   |
| 2.8. The reaction mechanism of methane steam reforming.....                                  | 22   |
| 2.9. The deactivation by coke formation in a supported metal catalyst.....                   | 24   |
| 2.10. Concentration of reactant and product at several times.....                            | 25   |
| 2.11. Concentration of reactant versus time at several concentrations.....                   | 28   |
| 2.12. Plot between $\log C$ and $\log r$ .....                                               | 29   |
| 2.13. Steps of heterogeneous catalytic reaction mechanism.....                               | 32   |
| 3.1. Schematic of the instruments and apparatus.....                                         | 38   |
| 3.2. Flow diagram of the methane steam reforming process.....                                | 39   |
| 3.3. Cylindrical fixed bed reactor.....                                                      | 38   |
| 3.4. Tubular furnace.....                                                                    | 40   |
| 3.5. Type-K thermocouple.....                                                                | 41   |
| 3.6. Temperature recorder.....                                                               | 41   |
| 3.7. Boiler.....                                                                             | 42   |
| 3.8. Peristaltic pump.....                                                                   | 42   |
| 3.9. Mass flow controller.....                                                               | 43   |
| 3.10. Moisture trap.....                                                                     | 44   |
| 3.11. Gas chromatograph.....                                                                 | 45   |
| 3.12. The operation and configuration of gas chromatograph.....                              | 45   |
| 4.1. $\Delta X_{CH_4}$ vs. $W/F_{CH_4}$ at several temperatures.....                         | 51   |
| 4.2. $\ln(-r_{CH_4})$ vs. $\ln(P_{CH_4})$ at several temperatures.....                       | 52   |
| 4.3. $\ln k$ vs. $(1/T)$ at excess steam.....                                                | 52   |
| 4.4. $\Delta X_{CH_4}$ vs. $W/F_{CH_4}$ at several steam-methane ratios.....                 | 54   |

## LIST OF FIGURES (Continued)

| FIGURE                                                                                                                          | PAGE |
|---------------------------------------------------------------------------------------------------------------------------------|------|
| 4.5. $\ln k$ vs. $(1/T)$ at non-excess steam.....                                                                               | 55   |
| 4.6. Methane conversion vs. catalyst weight.....                                                                                | 56   |
| 4.7. Hydrogen-carbon monoxide ratio vs. catalyst weight.....                                                                    | 57   |
| 4.8. Product gas composition and methane conversion vs. catalyst weight....                                                     | 57   |
| 4.9. Reaction rate of methane vs. partial pressure of methane or steam<br>at excess and non-excess steam.....                   | 61   |
| 4.10. Comparison of product gas composition from the experiment with<br>thermodynamics equilibrium at various temperatures..... | 63   |
| B1 Chromatogram of gas composition using thermal conductivity<br>detector (TCD).....                                            | 76   |
| B2 Chromatogram of gas composition using flame ionization<br>detector (FID).....                                                | 77   |


  
 ศูนย์วิจัยทรัพยากร  
 จุฬาลงกรณ์มหาวิทยาลัย

## LIST OF ABBREVIATIONS

|               |                                                                  |
|---------------|------------------------------------------------------------------|
| $C_i$         | Concentration of component i                                     |
| $C_{as}^s$    | Concentration at outside particle surface (mole/m <sup>3</sup> ) |
| °C            | Degree of Celsius                                                |
| $D_{eff}$     | Effective diffusivity (m <sup>2</sup> /sec)                      |
| $E_a$         | Activation energy (cal/mole)                                     |
| $F_{CH_4}$    | Methane feed rate (mole/min)                                     |
| FID           | Flame ionization detector                                        |
| °F            | Degree of Fahrenheit                                             |
| I.D           | Inside diameter (cm.)                                            |
| I-S           | Chemisorption of component I at active sites of catalyst         |
| k             | Rate constant                                                    |
| $k_i$         | Adsorption constant of component i                               |
| $k_o$         | Frequency factor                                                 |
| $k_s$         | Rate constant at surface of catalyst                             |
| $k'_i$        | Desorption constant of component i                               |
| $k'_s$        | Reverse rate constant at surface of catalyst                     |
| kPa           | Kilo Pascal                                                      |
| K             | Kelvin                                                           |
| $K_i$         | Adsorption equilibrium constant of component i                   |
| $K_p$         | Equilibrium constant                                             |
| L             | Pore length (m)                                                  |
| m             | Order of reaction for methane (no unit)                          |
| MPa           | Mega Pascal                                                      |
| n             | Order of reaction for steam (no unit)                            |
| O.D           | Outside diameter (cm.)                                           |
| pA            | Pico ampere                                                      |
| psig          | Pound per square inch gauge                                      |
| $P_i$         | Partial pressure of component i (atm)                            |
| $P_T$         | Total pressure (atm)                                             |
| $(r_a)_{obs}$ | Observed reaction rate (mole/kg * sec)                           |
| $r_{ads i}$   | Adsorption rate of component i                                   |

### LIST OF ABBREVIATIONS (Continued)

|                   |                                                                 |
|-------------------|-----------------------------------------------------------------|
| $r_{des\ i}$      | Desorption rate of component i                                  |
| $r_{rls}$         | Rate limiting step (or rate determining step)                   |
| $-r_{CH_4}$       | Reaction rate of methane (mole/kg * min)                        |
| R                 | Gas constant (cal/mole * K)                                     |
| S                 | Active sites of catalyst                                        |
| SCCM              | Standard cubic centimeters per minute                           |
| T                 | Temperature (K)                                                 |
| TCD               | Thermal conductivity detector                                   |
| wt. %             | Percent by weight                                               |
| W                 | Catalyst weight (kg)                                            |
| $\Delta X_{CH_4}$ | Methane conversion (no unit)                                    |
| $y_i$             | Mole fraction of component i (no unit)                          |
| $\Phi$            | Thiele modulus (no unit)                                        |
| $(\rho_s)_{obs}$  | Observed particle density (kg/m <sup>3</sup> )                  |
| $\theta_i$        | Fraction of surface covered component i on the catalyst         |
| $\theta_v$        | Fraction of no surface coverage on the catalyst (void fraction) |

ศูนย์วิจัยทรัพยากร  
จุฬาลงกรณ์มหาวิทยาลัย