SIMULATION AND OPTIMIZATION OF PROPANE AUTOTHERMAL REFORMER FOR FUEL CELL APPLICATIONS

HENRY INSIONG

UNIVERSITI TEKNOLOGI MALAYSIA

To my beloved father and mother

ACKNOWLEDGEMENTS

I am deeply grateful to my thesis supervisor Engr. Mohd. Kamaruddin Bin Abd. Hamid for his continuous guidance, support and enthusiasm throughout this work, and being an inspiring teacher for me.

I would like to express my most sincere thanks to Prof. Madya Dr. Maketab Mohamed for co-supervising my work and invaluable suggestion and advice.

I am also would like to thank to all my friends for their assistance in giving opinion during the course of my study.

Finally, I would express my gratitude to my mother, father and to all my siblings for their endless love and support.

ABSTRACT

Autothermal reforming (ATR) is one of the leading methods for hydrogen production from hydrocarbons. Liquefied petroleum gas, with propane as the main component, is a promising fuel for on-board hydrogen producing systems in fuel cell vehicles and for domestic fuel cell power generation devices. In this research, autothermal reforming of propane process is studied and operation conditions were optimized using Aspen HYSYS 2004.1 for proton exchange membrane fuel cell application. Furthermore, heat integration process also applied after the existed stream from the ATR reactor. Besides that water gas shift (WGS) which included High Temperature Shift (HTS), Medium Temperature Shift (MTS) and Low Temperature Shift (LTS) reactor, preferential oxidation (PrOx) were used for the clean up system to reduce the concentration of carbon monoxide. Then, optimization for the ATR, WGS and PrOx reactor were done to get the highest hydrogen produced with the lowest CO. Temperature and component's profile were also investigated for every unit's operations. Based on the final result, 100 kgmole/hr or propane with the ratio of air and water 1 : 7 : 4.3, produced 41.62% of hydrogen with CO concentration lower than 10 ppm, and 83.14% fuel processor efficiency.

ABSTRAK

ATR merupakan salah satu kaedah yang terbaik untuk menghasilkan hidrogen daripada hidrokarbon. Ceacir gas petroleum dimana propana dijadikan sebagai bahan utama menjanjikan bahan mentah utama untuk menghasilkan system hidrogen untuk kenderaan *fuel cell* dan untuk kegunaan kuasa jana *fuel cell* peralatan domestik. Dalam kajian ini, reactor ATR mengunakan propana adalah dikaji dan operasi sistemnya dioptimumkan mengunakan Aspen HYSYS 2004.1 untuk *fuel cell* aplikasi. Selain itu, integrasi haba juga diterapkan dan diaplikasi selepas aliran keluar daripada reaktor ATR. Di samping itu, WGS dan PrOx proses dijalankan untuk proses pembersihan bagi merendahkan kepekatan CO. Proses pengoptimum dilakukan untuk setiap reaktor bagi menghasilkan hidrogen yang paling tinggi dan pada masa yang sama kepekatan CO terendah. Butiran yang lebih terperinci bagi suhu dan komposisi bahan turut dikaji pada setiap unit operasi. Berdasarkan kepada keputusan akhir yang diperolehi daripada proses simulasi didapati bahawa sebanyak 100 kgmol/j propana dengan nisbah kepada air dan udara sebanyak 1 : 7 : 4.3 telah menghasilkan sebanyak 41.62% hidrogen dengan kepekatan CO dibawah 10 ppm,dan kecekapan sistem penjana adalah 83.14%

LIST OF CONTENTS

CHAPTER	SUBJECT	PAGE
	TITLE PAGE	i
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	LIST OF CONTENTS	vii
	LIST OF TABLES	xi
	LIST OF FIGURES	xii
	LIST OF ABBREVIATIONS	Xii
	LIST OF APPENDICES	xv
I	**INTRODUCTION**	**1**
	1.1 Background Research	1
	1.2 Problem Statement and Importance of Study	3
	1.3 Objective and Scopes of Study	3
	1.4 Thesis Organization	4
II	**LITERATURE REVIEW**	**6**
	2.1 Hydrogen Production for Fuel Cell Application.	6
	2.1.1 Natural Gas	7
	2.1.1.1 Methane	8

	2.1.1.2 Ethane	9
	2.1.1.3 Propane	9
	2.1.1.4 Butane	10
	2.1.2 Alcohol	10
	2.1.2.1 Methanol	10
	2.1.2.2 Ethanol	11
	2.1.2.3 Propanol	12
	2.1.3 Naphtha	13
	2.1.3.1 Gasoline	13
	2.1.3.2 Diesel	13
	2.1.3.3 Kerosene	14
	2.2 Propane as Input for Hydrogen Production	14
	2.2.1 Partial Oxidation and Oxidative Steam Reforming	15
	2.2.2 Authothermal Reforming	16
	2.2.3 Steam Reforming	17
	2.2.4 Cracking Method	17
	2.2.5 Indirect Partial Oxidation	18
	2.3 Steam Reforming of Propane	18
	2.4 Simulation of hydrogen Production for Fuel cell Application using Propane.	20
	2.5 Summary	21
III	**METHODOLOGY**	**22**
	3.1 Research Tools	22
	3.1.1 Aspen HYSYS 2004.1	22
	3.2 Research Activities	23
	3.2.1 Data Collection	23
	3.2.2 Steady State Model Development	23
	3.2.3 Stoichiometry Mathematical Calculation	24
	3.2.4 Validation of the Steady State Process	26

3.2.5 Heat Integration between Processes 26
3.2.6 Clean up Model Development 27
3.2.6.1 Water Gas Shift Processes (WGS) 27
3.2.6.2 Preferential Oxidation Processes (PrOx) 28
3.2.7 Plan wide Optimization 28
3.2.8 Temperature and Components Profile 29
3.2.9 Fuel Processor Efficiency 29
3.3 Summary 30

IV OPTIMIZATION AND SIMULATION OF HYDROGEN PRODUCTION FROM PROPANE FOR FUEL CELL APPLICATIONS 32

4.1 Optimization and Simulation Of Hydrogen Production from Propane 32
4.1.1 Physical Properties 33
4.1.2 Thermodynamic Properties 34
4.1.3 Integration Algorithm 37
4.1.4 Mathematical Modelling of the Reactor Operating 37
4.1.5 Degree of Freedom Analysis 39
4.1.6 Steady State Simulation 39
4.1.7 Optimization Model Simulation 40
4.1.8 Summary 40

V RESULTS AND DISCUSSIONS 42

5.1 Base Case of Simulation 42
5.2 Validation of Base Case 44
5.3 ATR Reactor Optimization 45
5.4 Heat Integration 48
5.5 Water Gas Shift (WGS) 49
5.51 Optimization of WGS 49

	5.6 Preferential Oxidation (PrOx)	52
	5.6.1 Optimization of PrOx Reactor	53
	5.7 Components and Temperature Profile of the Fuel Processor System	55
	5.7.1 Components Profile	56
	5.7.2 Temperature Profile	58
	5.8 Fuel Processor Efficiency	59
	5.9 Summary	60
VI	**CONCLUSIONS AND RECOMMENDATIONS**	**61**
	6.1 Introduction	61
	6.2 Summary of Results	62
	6.3 Conclusions	63
	6.4 Recommendations	63
	6.4.1 Purification of Hydrogen	63
	6.4.2 Water Management	64
	REFERENCES	65
	Appendices (A1-G1)	71-87

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Feed composition for the steam reforming experiments	19
2.2	Stoichiometry for the "full" steam reforming reaction and the corresponding of ΔH° and thermal efficiency	19
3.1	Lower heating value	30
4.1	Physical property of the component	34
5.1	Result for base case	43
5.2	Comparison between molar flow rate calculated and simulated	45
5.3	Comparison between before and after optimization at the ATR process	47
5.4	Result after optimization of the WGS reactor	51
5.5	Result for every components at the PrOx reactor	53
5.6	Result of optimization at the PrOx reactor	55
5.7	Components profile for every reactor	56

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
3.1	Algorithm for methodology	31
4.1	HYSYS simulation environment	33
4.2	Block diagram of the simulation of hydrogen plant using Aspen HYSYS 2004.1	41
5.1	PFD of the ATR reactor	44
5.2	Temperature of ATR out, molar flow of carbon monoxide (CO) and hydrogen (H_2) output from ATR versus molar flow of air	46
5.3	PFD of heat integration process	48
5.4	PFD of water gas shift process	49
5.5	Temperature of HE_3 out , molar flow of carbon monoxide (CO) and hydrogen (H_2) output from WGS reactor versus molar flow of water	50
5.6	PFD of the PrOx process with entire process	52
5.7	Molar flow of carbon monoxide (CO) and hydrogen (H_2) output from PrOx versus molar flow Air_PrOx	54
5.8	Components profile for hydrogen and carbon monoxide	57
5.9	Temperature profile for every units operation	58

LIST OF ABBREVIATIONS

ATR	-	Autothermal reforming
AES	-	Aspentech Engineering Suite
CH_4	-	Methane
C_2H_6	-	Ethane
C_3H_8	-	Propane
C_4H_{10}	-	Butane
CHP	-	Combined Heat and Power
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
CPO	-	Catalytic partial oxidation
CH_3OH	-	Methanol
CMR	-	Compact methanol reformer
CFBMRR	-	Circulating Fluidized Bed Membrane Reformer-Regenerator
ESEM-EDAX	-	Environmental scanning electron microscopy-energy disperse X-ray analysis
GC	-	Gas-chromatographs
H_2	-	Hydrogen
H_2O	-	Water
HSA	-	Highs surface area
IIR-MCFCs	-	Indirect internal reformer molten carbonate fuel cells
IPOX	-	Indirect partial oxidation
LPG	-	Liquefied petroleum gas
MCFC	-	Molten carbonate fuel cell
MR	-	Membrane reactor

MSR	-	Methane steam reforming
OSR	-	Oxidative Steam Reforming
PAFC	-	Phosphoric acid fuel cell
PEMFC	-	Proton exchange membrane fuel cell
POX	-	Partial oxidation
SE-SMR	-	Sorption-enhanced steam methane reforming
SOFC	-	Solid oxide fuel cell
SPFC	-	Solid polymer fuel cell
SR	-	Steam reforming
TRs	-	Traditional reactors
ŋ	-	Thermal efficiency
γ	-	Activity coefficient
WGS	-	Water Gas Shift
PrOx	-	Preferential Oxidation
PFD	-	Process Flow Diagram

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A1	Result of ATR reactor for base case and before optimization	71
A2	Result of ATR reactor after the optimization	72
B	Result of heat integration process	73
C1	Result of WGS reactor before the optimization	75
C2	Result of WGS reactor after the optimization	78
D1	Result of PrOx reactor before the optimization	81
D2	Result of PrOx reactor after the optimization	83
E1	Calculation of concentration of carbon monoxide	86
F1	Calculation of fuel processor efficiency	86
G1	Component profile for all components	87

CHAPTER I

INTRODUCTION

1.0 Background Research

Hydrogen is the most abundant element in the universe. Chemically bound hydrogen is present all over the earth; as part of the Earth's water mass (including fossil substances) (Haussinger et al., 2003). Hydrogen (H_2) is a colourless, odourless, tasteless, flammable and non-toxic gas at atmospheric temperature and pressure. The gas burns in air with a pale blue, almost invisible flame. Hydrogen is the lightest of all gasses, approximately one fifteenth as heavy as air. Hydrogen ignites easily and forms an explosive gas together with oxygen or air.

Hydrogen is used in diverse industries such as a chemical, petrochemical and petroleum refining, metallurgy, glass and ceramics manufacture, electronic and food processing. Hydrogen is used in large quantities as a raw material in the chemical synthesis of ammonia, methanol, hydrogen peroxide, polymers and solvents. It is used in refineries for desulphurization and hydrotreating. It is used in metallurgical industries to provide a reducing atmosphere and in the annealing of steel. The electronic industry uses hydrogen in the manufacture of semiconductor devices. In the food industry, hydrogen is used for hydrogenation of fats and oils. Hydrogen also finds specialty application as a rocket fuel duel to its high combustion energy release per unit of weight.(Newson and Truong, 2001).

Recently, there has been a tremendous interest in the development of hydrogen economy based on hydrogen as the energy carrier. Excitement in this field stems from the fact that hydrogen is a potentially non-polluting, inexhaustible and efficient source of energy. Hydrogen can be used in a fuel cell to produce electricity and heat or even be combusted with oxygen to produce energy and the only by product is water (Chris, 2001).

A fuel cell by definition is an electrical cell, which unlike storage cells can be continuously fed with a fuel so that the electrical power output is sustained indefinitely (Reed, 1995). They convert hydrogen or hydrogen-containing fuels, directly into electrical energy plus heat through the electrochemical reaction of hydrogen and oxygen into water. The process is that of electrolysis in reverse.

Overall reaction:

$$2\,H_2\,(\text{gas}) + O_2\,(\text{gas}) \rightarrow 2\,H_2O + \text{energy} \qquad (1.1)$$

Because hydrogen and oxygen gases are electrochemically converted into water, fuel cells have many advantages over heat engines. These include high efficiency, virtually silent operation and, if hydrogen is the fuel, there are no pollutant emissions. If the hydrogen is produced from renewable energy sources, then the electrical power produced can be truly sustainable. The two principle reactions in the burning of any hydrocarbon fuel are the formation of water and carbon dioxide (Espinal et al., 2005). As the hydrogen content in a fuel increases, the formation of water becomes more significant, resulting in proportionally lower emissions of carbon dioxide. As fuel use has developed through time, the percentage of hydrogen content in the fuels has increased. It seems a natural progression that the fuel of the future will be 100 % hydrogen.

Fuel cells are classified according to the electrolyte use. There are the alkaline fuel cell used in space vehicle power systems, the phosphoric acid fuel cell (PAFC) used in both road transportation and stationary engines, the solid polymer fuel cell (SPFC) also used in both road transportation and stationary engines, the molten carbonate fuel cell (MCFC) used in stationary engines and the solid oxide fuel cell (SOFC) used only in stationary engines (Chen and Elnashaie, 2004)

In general, fuel cells can be used for a wide variety of applications, the most important of which are as a power source for vehicles, as a stationary power source (for example for large-scale power plants generation, power generation in the home or small power plants for larger industrial or residential sites) and as a power sources for portable devices (for example laptops, cameras, mobile phones, for replacement of batteries etc.). Natural gas and propane are attractive for stationary applications since they are low-cost fuels and the infrastructure for their transportation already exists (Wang et al., 2005).

1.1 Problem Statement and Importance of Study

This research aims to develop an optimized model of hydrogen production plant using propane for fuel cell application by autothermal reforming. In order to analyze its performance, well-defined steady state model that will represent the real plant for hydrogen production is required. In order to do that, Aspen HYSYS 2004.1 is utilized. The important to have this optimized model is to analyze design parameter for fuel processor, and also to get preliminary fuel processor efficiency.

1.2 Objective and Scopes of Study

Objective of this study is to develop an optimized model of hydrogen production plant using propane for fuel cell applications by autothermal reforming. In order to achieve that objective, the following scopes have been drawn:

i). Steady-state Model for Base Case

- Steady-state model of hydrogen plant from propane was carried out by stoichiometry mathematical analysis calculation and the simulation using Aspen HYSYS 2004.1.

ii). Steady-state Model Validation for Base Case

- Steady-state model developed within Aspen HYSYS 2004.1 process simulator was validated using data from stoichiometry mathematical analysis calculation

ii). Process Heat Integration Model Development

- Heat integration model was applied for this simulation using Aspen HYSYS 2004.1.

iii). Clean Up Model Development

- Clean up model was applied to reduce the concentration of carbon monoxide at the reformer.

iv). Plant Wide Optimization

- Every reactor had been optimized to achieve the highest hydrogen and the lowest carbon monoxide.

v). Temperature and Components Profile Analysis

- To get the overall overview of the process of the reformer.

1.3 Thesis Organization

The realization of the objective of this thesis involves the culmination of a number of tasks. The first task, introduced in chapter two is to do the literature survey about the synthesis of hydrogen for fuel cell applications. In this chapter, an internal research of hydrogen production using propane by autothermal reforming was been concentrated. This chapter is the most important chapter because we developed the method of hydrogen synthesis are based on the literature survey that we had done.

Chapter three is methodology for this thesis whereby the arrangements for the methods are based on the scopes. Basically, there are five methods that we carried out. Then, chapter four is optimization simulation of hydrogen production plant from propane for fuel cell application. In this chapter we developed the simulation using Aspen HYSYS 2004.1.

Chapter five is the results and discussion whereby the results are based on the methodology that is developed from chapter four. Then, chapter six presents the conclusions and recommendations.

REFERENCES

Aartun, I., Silberova, B., Venvik, H., Pfeifer, P., Gorke, O., Schubert, K. and Holmen, A. (2005). “Hydrogen Production from Propane in Rh-impregnated Metallic Microchannel Reactors and Alumina Foams.” Catalysis Today 105: 469–478.

Aartun, I., Venvik, H. J., Holmen, A., Pfeifer, P., Gorke, O. and Schubert, K. (2005). “Temperature Profiles and Residence Time Effects During Catalytic Partial Oxidation and Oxidative Steam Reforming of Propane in Metallic Microchannel Reactors.” Catalysis Today 110: 98–107.

Aartun, I., Gjervan, T., Venvik, H., Gorke, O., Pfeifer, P., Fathi, M., Holmena, A. and Schubert, K. (2004). “Catalytic Conversion of Propane to Hydrogen in Microstructured Reactors.” Chemical Engineering Journal 101: 93–99.

Agrel, J., Birgersson, H., Boutonnet, M., Melian-Cabrera, I., Navarro, R.M. and Fierro, J. L. G. (2003). “Production of Hydrogen from Methanol over Cu/ZnO Catalysts Promoted by ZrO_2 and Al_2O_3.” Journal of Catalysis 219: 389–403.

Aspen HYSYS 2004.1 Documentation (April 2005), Aspen Technology Inc., Ten Canal Park Cambridge, MA 02141-2201, USA.

Avcı, A. K., Trimm, D. L., Aksoylu, A. E. and Onsan, Z. I. (2004). “Hydrogen Production by Steam Reforming of *n*-butane Over Supported Ni and Pt-Ni Catalysts.” Applied Catalysis A: General 258: 235–240.

Avcı, A. K., Trimm, D. L. and Onsan, Z. I. (2002). “Quantitative Investigation of Catalytic Natural Gas Conversion for Hydrogen Fuel Cell Applications.” Chemical Engineering Journal 90: 77–87.

Avcı, A. K., Onsan, Z. I. and. Trimm, D. L (2001). “On-board Fuel Conversion for Hydrogen Fuel Cells: Comparison of Different Fuels by Computer Simulations.” Applied Catalysis A. General 216: 243–256.

Basile, A., Gallucci, F. and Paturzo, L. (2005). "Hydrogen Production from Methanol by Oxidative Steam Reforming Carried Out in a Membrane Reactor." Catalysis Today 104: 251–259.

Caglayan, B. S., Avcı, A. K., Onsan, Z. I. and Aksoylu, A. E. (2005). "Production of Hydrogen over Bimetallic Pt–Ni/d-Al_2O_3 I. Indirect Partial Oxidation of Propane." Applied Catalysis A: General 280: 181–188.

Cavallaro, S., Chiodo, V., Vitaa, A. and Freni, S. (2003). "Hydrogen Production by Auto-thermal Reforming of Ethanol on Rh/Al_2O_3 Catalyst." Journal of Power Sources 123: 10–16.

Cavallaro, S., Mondello, N. and Freni, S. (2001). "Hydrogen Produced from Ethanol for Internal Reforming Molten Carbonate Fuel Cell." Journal of Power Sources 102: 198–204.

Chen*,* Z. and Elnashaie, S.S.E.H. (2004). "Steady-state Modelling and Bifurcation Behaviour of Circulating Fluidized Bed Membrane Reformer–Regenerator for the Production of Hydrogen for Fuel Cells from Heptane." Chemical Engineering Science 59: 3965–3979.

Chris Spilsbury, Air Products PLC, Hydrogen Production Workshop, University of Glamorgan, 'Hydrogen Production, Supply and Distribution', 14 February 2001.

Dagaut, P. and Nicolle, A. (2005). "Experimental and Detailed Kinetic Modelling Study of Hydrogen-Enriched Natural Gas Blend Oxidation over Extended Temperature and Equivalence Ratio Ranges." Proceedings of the Combustion Institute 30: 2631–2638.

Dehertog, W. J. H. and Fromen, G. F. (1999). "A Catalytic Route for Aromatics Production from LPG." Applied Catalysis A: General 189: 63–75.

Deshmukh, S. R. and Vlachos, D. G., (2005). "Effect of Flow Configuration on the Operation of Coupled Combustor/Reformer Microdevices for Hydrogen Production." Chemical Engineering Science 60: 5718–5728.

Espinal, J. F., Mondragon, F. and Truong, T. N. (2005). "Mechanisms for Methane and Ethane Formation in the Reaction of Hydrogen with Carbonaceous Materials." Carbon 43: 1820–1827.

Ersoz, A., Olgun, H. and Ozdogan, S. (2006). “Reforming Options for Hydrogen Production from Fossil Fuels for PEM Fuel Cells.” Journal of Power Sources 154: 67–73.

Ersoz, A., Olgun, H., Ozdogan, S., Gungora, S., Akguna, F. and Tırıs, M. (2003). “Autothermal Reforming as a Hydrocarbon Fuel Processing Option for PEM Fuel Cell.” Journal of Power Sources 118: 384–392.

Fernandez, E. O., Rusten, H. K., Jakobsen, H. A., Ronning, M., Holmen, A. and Chen, D. (2005). “Sorption Enhanced Hydrogen Production by Steam Methane Reforming using Li_2ZrO_3 as Sorbent: Sorption Kinetics and Reactor Simulation.” Catalysis Today 106: 41–46.

Freni, S., Cavallaro, S., Mondello, N., Spadaro, L. and Frusteri, F. (2003). “Production of Hydrogen for MC Fuel Cell by Steam Reforming of Ethanol over MgO Supported Ni and Co Catalysts.” Catalysis Communications 4: 259–268.

Haussinger, B., Kiwi, M. L. and Renken, A. (2003). “Mathematical Modelling of the Unsteady state oxidation of Nickel Catalysts.” Applied Catalysis A: General 58: 234–247.

Hey, K. L., Kalk, T., Mahlendorf, F., Niemzig, O., Trautman, A. and Roes, J. (2000). “Portable PEFC Generator with Propane as Fuel.” Journal of Power Sources 86: 166–172.

Hoang, D. L. and Chan, S. H. (2004). “Modelling of a Catalytic Autothermal Methane Reformer for Fuel Cell Application.” Applied Catalysis A: General 268: 207–216.

Hohlein, B., Andrian, S. V., Grube, T. and Menzer, R. (2000). “Critical Assessment of Power Trains with Fuel-Cell Systems and Different Fuels.” Journal of Power Sources 86: 243–249.

Kamaruddin, H., Norazana,. I., Kamarul, A. I. and Arshad,. A. (2005). “Simulation Of Hydrogen Production for Mobile Fuel Cell Applications Via Autothermal Reforming of Methane.” Putrajaya, Malaysia: 540-548.

Karagiannakis, G., Kokkofitis, C., Zisekas, S. and Stoukides, M. (2005). “Catalytic and Electrocatalytic Production of H_2 from Propane Decomposition over Pt and Pd in a Proton-Conducting Membrane-Reactor.” Catalysis Today 104: 219–224.

Laosiripojana, N. and Assabumrungrat, S. (2005). “Hydrogen Production from Steam and Autothermal Reforming of LPG over High Surface Area Ceri.” Journal of Power Sources 178: 56-63.

Lenz, B. and Aicher, T. (2005). “Catalytic Aututhermal Reforming of Jet Fuel.” Power Sources 149: 44-52.

Liguras, D. K., Kondarides, D. I. and Verykios, X. E. (2003). “Production of Hydrogen for Fuel Cells by Steam Reforming of Ethanol over Supported Noble Metal Catalysts.” Applied Catalysis B: Environmental 43: 345–354.

Liu, Z. W., Jun, K. W., Roh, H. S. and. Park, S. E. (2002). “Hydrogen Production for Fuel Cells Through Methane Reforming at Low Temperatures.” Journal of Power Sources 111: 283-287.

Lee, D. K., Baek, I. H. and Yoon, W. L. (2004). “Modelling and Simulation for the Methane Steam Reforming Enhanced by in Situ CO_2 Removal Utilizing the CaO Carbonation for H_2 Production.” Chemical Engineering Science 59: 931–942

Mattos, L.V. and Noronha, F. B. (2005). “Hydrogen Production for Fuel Cell Applications by Ethanol Partial Oxidation on Pt/CeO_2 Catalysts: the Effect of the Reaction Conditions and Reaction Mechanism.” Journal of Catalysis 233: 453–463.

Minutillo, M. (2005). “On-board Fuel Processor Modelling for Hydrogen-Enriched Gasoline Fuelled Engine.” International Journal of Hydrogen Energy 30: 1483–1490.

Mizuno, T., Matsumura, Y., Nakajima, T. and Mishima, S. (2003). “Effect of Support on Catalytic Properties of Rh Catalysts for Steam Reforming of 2-Propanol.” International Journal of Hydrogen Energy 28: 1393–1399.

Newson, E. and Truong, T. B. (2001). “Low-temperature Catalytic Partial Oxidation of Hydrocarbons (C1–C10) for Hydrogen Production.” International Journal of Hydrogen Energy 28: 1379–1386.

Otsuka, K., Shigeta, Y. and Takenaka, S. (2002). “Production of Hydrogen from Gasoline Range Alkanes with Reduced CO_2 Emission.” International Journal of Hydrogen Energy 27: 11–18.

Reed R. M., (1995), “The Commercial Production of Pure Hydrogen from Hydrocarbons & Steam”. American Institute of Chemical Engineers: 453-461

Resini, C., Delgado, L. M. C. H., Vargase, M. A. L., Alemany, L. J., Rianic, P., Berardinelli, S., Marazzac, R. and Busca, G. (2006). "Production of Hydrogen by Steam Reforming of C3 Organics over Pd–Cu/ γ -Al_2O_3 Catalyst." International Journal of Hydrogen Energy 31: 13–19.

Resini, C., Delgado, L. M. C. H., Arrighi, L., Alemany, L. J., Marazza, R. and Busca, G. (2005). "Propene versus propane steam reforming for hydrogen production over Pd-based and Ni-based catalysts." Catalysis Communications 6: 441–445.

Richard, M. F. and Ronald, W. R. (2000). " Elementary Principles of Chemical Processes." 3rd edition. USA: John Wiley and Sons, Inc. 15 and 53.

Silberova, B., Venvik, H. J., Walmsley, J. C. and Holmen, A. (2005). "Small-scale Hydrogen Production from Propane." Catalysis Today 100: 457–462.

Silberova, B., Venvik, H. J. and Holmen, A. (2005). "Production of Hydrogen by Short Contact Time Partial Oxidation and Oxidative Steam Reforming of Propane." Catalysis Today 99: 69–76.

Silberova, B., Fathi, M. and Holmen, A. (2004). "Oxidative Dehydrogenation of Ethane and Propane at Short Contact Time." Applied Catalysis A: General 276: 17–28.

Smet, C. R. H., Croon, M. H. J. M., Berger, R. J., Marin, G. B. and Schouten, J. C. (2001). "Design of Adiabatic Fixed-Bed Reactors for the Partial Oxidation of Methane to Synthesis Gas. Application to Production of Methanol and Hydrogen-for-Fuel-Cells." Chemical Engineering Science 56: 4849–4861.

Sun, J., Qiua, X. P., Wuc, F. and Zhu, W. T. (2005). "H_2 from Steam Reforming of Ethanol at Low Temperature over Ni/Y_2O_3, Ni/La_2O_3 and Ni/Al_2O_3 Catalysts for Fuel-Cell Application." International Journal of Hydrogen Energy 30: 437–445.

Suzuki, T., Iwanami, H. I. and Yoshinari, T. (2000). "Steam Reforming of Kerosene on Ru/Al_2O_3 Catalyst to Yield Hydrogen." International Journal of Hydrogen Energy 25: 119-126.

Todorova, S. and Su, B. L. (2004). "Effects of Acidity and Combination of Ga and Pt on Catalytic Behaviour of Ga-Pt Modified ZSM-5 Catalysts in Benzene Alkylation with Pure Propane." Catalysis Today 93–95: 417–424.

Wang, Y. N. and Rodrigues A. E. (2005). “Hydrogen Production from Steam Methane Reforming Coupled with in Situ CO_2 Capture: Conceptual Parametric Study.” Fuel 84: 1778–1789.

Wang, Y. H. and Zhang, J. C. (2005). “Hydrogen Production on Ni–Pd–Ce/g-Al_2O_3 Catalyst by Partial Oxidation and Steam Reforming of Hydrocarbons for Potential Application in Fuel Cells.” Fuel 84: 1926–1932.

Wang, Y., Shah, N. and Huffman, G. P. (2005). “Simultaneous Production of Hydrogen and Carbon Nanostructures by Decomposition of Propane and Cyclohexane over Alumina Supported Binary Catalysts.” Catalysis Today 99: 359–364.