



A FEASIBILITY STUDY ON HYDROGEN PRODUCTION FROM RENEWABLE ENERGY SOURCES FOR PEMFC APPLICATIONS

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Abstract : The world energy demand is being increased in recent years. Today's world needs highly efficient system that can fulfill the growing demand for energy. There is strong need for alternative energy source, which is environmental benign and can be produced renewably. Hydrogen is receiving renewed attention driven by growing concerns about climate change, air quality, integration of variable renewable energy sources and rapid technical progress in fuel cell systems. Hydrogen is recognized as a potential fuel, clean energy carrier and a carbon free element for fuel cell systems for the generation of electricity and heat. But currently storage and transportation of hydrogen is research challenge. On-board production of hydrogen from renewable hydrocarbon source can be possible solution to this problem. Mainly proton exchange membrane fuel cell (PEMFC) gained attention of researchers for power generation, which will operate at both elevated as well as lower temperature. PEMFC involves the conversion of the chemical energy stored in fuel cell to electrical energy with minimal or no pollution. PEMFCs are the most significant technology in fuel cell system and high energy conversion efficiency. This article brings together and examines the latest research on hydrogen production via steam reforming and auto thermal reforming from various energy sources like Methanol, Ethanol, Glycerol, Alkanes, Alkenes, Alkynes etc and its integration with PEMFC. In this research the hydrogen production for PEMFC integrated systems were analyzed and the effect of operating parameters like temperature, steam-to-carbon molar ratio and oxygen-to-carbon molar ratio were investigated on electrical and/or thermal efficiency of PEMFC system.

Keywords: Hydrogen production, Biomass, Steam Reforming, Auto Thermal Reforming, PEM Fuel Cell.

I. INTRODUCTION

An alternative fuel must be technically feasible, economically viable, easily convert to another energy form when combusted, be safe to use and be potentially harmless to the environment. Hydrogen is the most abundant element on earth.[1] At standard temperature and pressure, hydrogen is a colourless, odorless, tasteless, highly combustible diatomic gas, nontoxic and non-metallic. Hydrogen is the simplest element known to exist. [1,2,3] Hydrogen has the highest energy content of any common fuel by weight, but the lowest energy content by volume.[3] Hydrogen can transform our fossil fuels dependent economy into hydrogen energy economy which can provide an emission free transportation fuel. Hydrogen is also the most abundant gas in the universe and the source of all the energy which we receive from the sun. [1,2] Hydrogen as a gas H₂, however it doesn't exist naturally on earth it is found only in compound form. Combined with oxygen it forms water H₂O. [4,5] Combined with carbon it forms organic compounds such as methane CH₄, Coal and petroleum. It is found in all growing things Biomass. Hydrogen is one of the most promising energy carriers for the future electricity generation and in fuel cell. It is high efficiency fuel and low polluting carbon free fuel that can be used for transportation, heating and power generation in places where it is difficult to use electricity. [6,7]

II. SIMULATION PROCEDURE

The commercial Aspen plus V10 is used in order to analyse the thermodynamic behaviour of hydrogen production to calculate product composition throughout the plant as well as energy requirement of each unit. The system consists of Steam Reformer, Auto Thermal Reformer, Partial oxidation reactor, High temperature and low temperature shift reactor, Separator, Burner etc. for various process include Steam Reforming, Auto Thermal Reforming Process for Bio-butanol integrated with PEMFC. The choice to employ a commercial package is motivated by the need to perform a large number of simulations on a complex flow-sheet, where a high number of units and interconnections to maximize heat recovery. Moreover, the optimum operating conditions is investigated and at these conditions, the energy utilization in the system is obtaining economical process. Development of process flow sheet for Bio-butanol, 40 kg/hr of Bio-butanol feed contain 24 kg Butanol, 12 kg Acetone and 4 kg Ethanol and remaining is water flow rate which is calculated based on steam-to-carbon molar ratio at Temperature 25 °C and 1 atm Pressure.

2.1 FUEL PROCESSOR- PEMFC SYSTEM FOR STEAM REFORMING

Steam Reforming Process is divided mainly in three sections involves Reforming section, CO clean-up section and Hydrogen production. Figure 1.1 reports the flow-sheet of steam reforming-based fuel processor coupled with a PEMFC. It consists of a reforming and a CO clean-up section. System feed consists of Bio-butanol, water at 25°C and 1 atm. The reforming section is an isothermal reactor modelled by using model library RGIBBS. The CO clean-up section consists of a high temperature shift (HTS) reactor and low temperature shift (LTS) reactor followed by a PROX reactor which is modelled by using model library RGIBBS; the reactor is considered as an adiabatic and methane is considered as an inert in order to eliminate the undesired methanation reaction.

The PROX reactor is modelled as an isothermal stoichiometric reactor, RSTOIC in which two reactions take place: oxidation of CO to CO₂ and H₂ to H₂O. The AIR-PROX (air fed to PROX reactor) is calculated in order to achieve 50% oxygen excess with stoichiometric amount required to convert all CO into CO₂. The PEMFC is simulated as the sequence of anode, modelled as an ideal separator, SEP, and the cathode, modelled as an isothermal stoichiometric reactor, RSTOIC. The hydrogen split fraction in the stream H₂ at the outlet of SEP is fixed at 0.75, another component is taken as 0. The oxidation reaction occurring in the fuel cell, AIR-FC (inlet air to cathode) fed at 1 atm. The anode-off-gas is fed to a burner, modelled as an adiabatic R-STOIC.

All the reactors in the CO clean-up sections work at different temperatures, therefore a heat exchanger is provided at each reactor inlet. H- SR is considered equal to SR, H-HTS is fixed at 350°C, H- LTS at 200°C, H-PROX at 90°C, H- PEMFC in order to cool the product stream to 80°C and exhaust gases temperature is fixed at 100°C.

The heat required to sustain the reforming reactor is furnished by the BURNER. The heat produced for cooling the process streams involved H-HTS, H-LTS, H-PROX, H-PEMFC, as well as the heat recoverable by the H-EX, is provided into the reforming section.

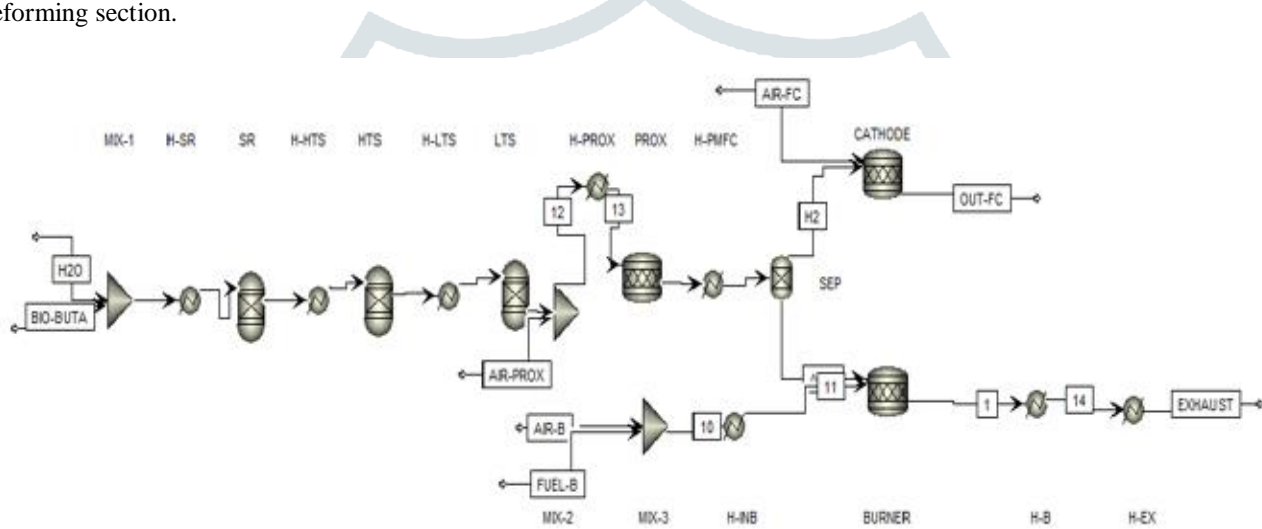


Figure 1 Flow sheet of Bio-butanol Steam Reforming coupled with a PEMFC

2.2 FUEL PROCESSOR- PEMFC SYSTEM FOR AUTO THERMAL REFORMING

In this the system consists of Auto thermal Reformer, Preferential oxidation reactor, High Temperature and low Temperature shift reactor, Separator etc. for Auto thermal Reforming. The PEMFC system based on the ATR process is simulated similar way to the system based on SR. Therefore, only difference is that the reforming reactor in the ATR is modelled as an adiabatic equilibrium reactor with change in temperature 400 °C to 900 °C in the heat-exchanger H-ATR. Since the reactor is adiabatic so that the gases from the burner are directly sent to the heat exchanger H-EX, the heat exchanger H-B is not present in the ATR system.

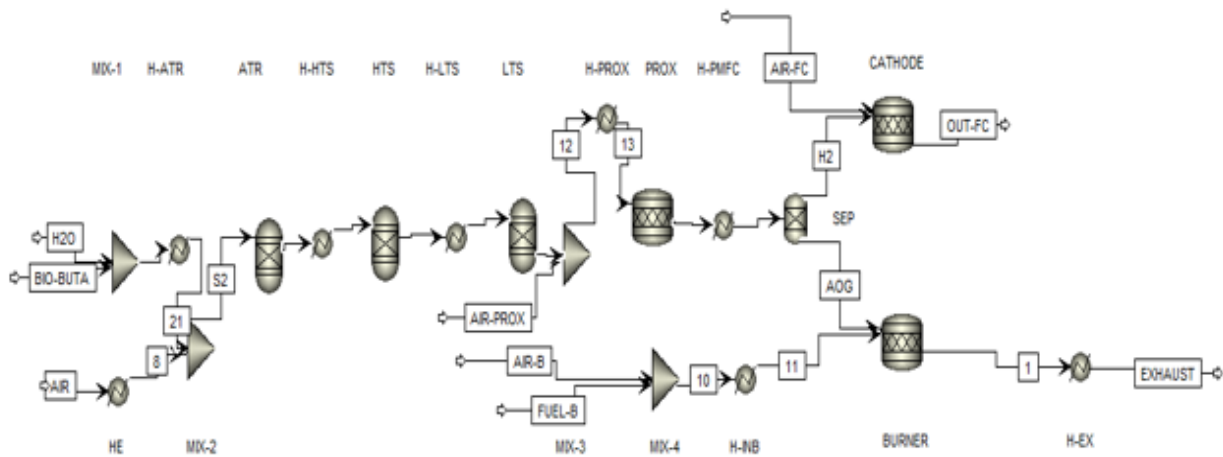


Figure 2.2 Flow sheet of Bio-butanol Auto Thermal Reforming coupled with a PEMFC

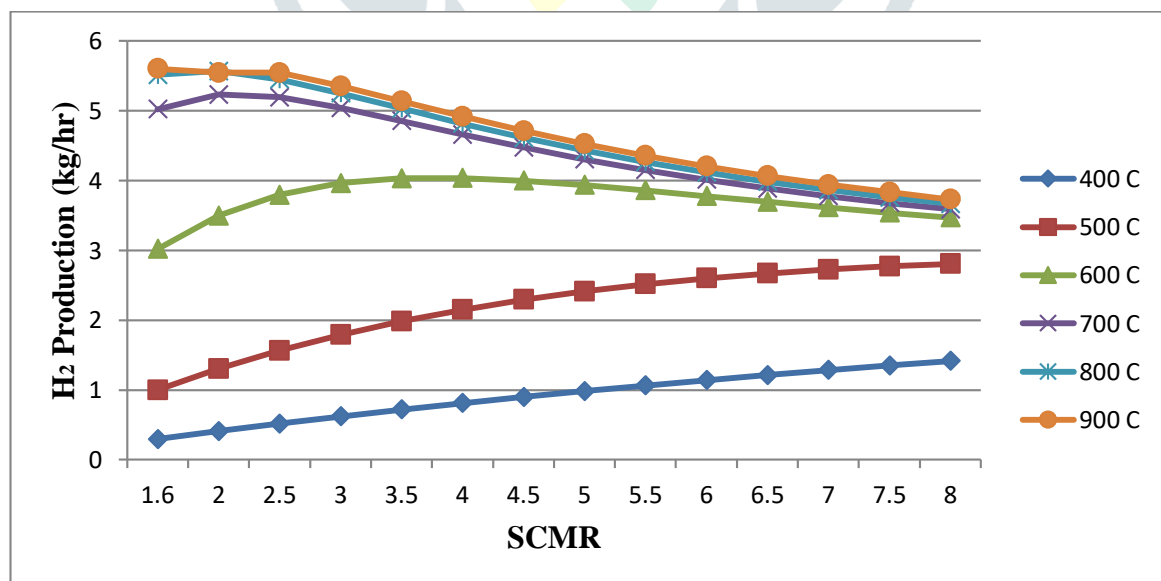
III. RESULT AND DISCUSSION:

3.1 PARAMETER VARIATION STUDY FOR STEAM REFORMING

In Steam reforming process effect of reformer operating conditions, i.e. temperature and SCMR, a parametric study was conducted. Reformer temperature was varied in the range of 400°C to 900°C, whereas SCMR was varied in the range of 1.6 to 8. Effect of SCMR and temperature on hydrogen production rate is shown in Graph 1.1. As observed from the graph that increase in SCMR always increases hydrogen production rate in lower temperature range, i.e. 400 - 500°C. This is due to the increased activity of the water-gas shifted steam reforming reactions by an additional amount of water in the feed.

Table 3.1 Hydrogen Production rate at different reformer Temperature and SCMR (SR)

SCMR	1.6	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Temp	Hydrogen Production Rate (kg/hr)													
400 °C	0.29	0.41	0.52	0.62	0.7	0.81	0.9	0.98	1.1	1.14	1.21	1.28	1.4	1.4
500 °C	1	1.3	1.56	1.79	2	2.15	2.3	2.41	2.5	2.6	2.67	2.73	2.8	2.8
600 °C	3.02	3.5	3.79	3.96	4	4.04	4	3.94	3.9	3.78	3.7	3.62	3.5	3.5
700 °C	5.02	5.23	5.19	5.04	4.9	4.66	4.5	4.3	4.1	4.01	3.89	3.78	3.7	3.6
800 °C	5.51	5.57	5.45	5.25	5	4.81	4.6	4.43	4.3	4.12	3.98	3.86	3.8	3.7
900 °C	5.6	5.55	5.55	5.35	5.1	4.92	4.7	4.53	4.4	4.2	4.07	3.94	3.8	3.7

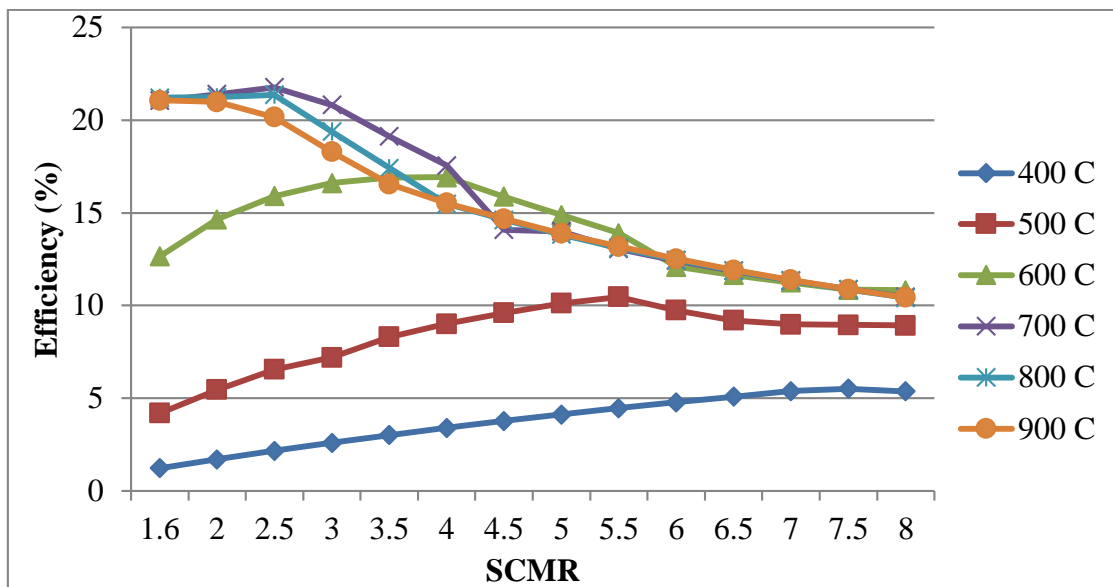


Graph 3.1 Effect of Reformer temperature and SCMR on hydrogen production

As shown on graph temperatures greater than 500 °C, it was found that hydrogen production rate reached to maxima at a certain value of SCMR depending upon reformer temperature. Thereafter a further increase in SCMR reduced hydrogen production rate. This trend can be justified by the enhanced activity of endothermic steam reforming and water-gas shift reactions up to maximum H₂ production. Thereafter reverse water-gas shift reactions dominate over steam reforming and water-gas shift reactions, which is taking place at elevated temperatures and reduces the hydrogen production rate

Table 3.2 System Efficiency at different reformer Temperature and SCMR (SR)

SCMR	1.6	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Temp	Efficiency (%)													
400 °C	1.23	1.71	2.17	2.6	3.01	3.4	3.77	4.12	4.46	4.78	5.09	5.38	5.52	5.37
500 °C	4.19	5.46	6.55	7.2	8.31	9.01	9.61	10.12	10.5	9.74	9.2	8.99	8.96	8.93
600 °C	12.7	14.7	15.91	16.6	16.9	16.92	15.9	14.88	13.9	12.1	11.7	11.2	10.9	10.8
700 °C	21.1	21.9	21.77	20.8	19.1	17.56	14.1	14	13.1	12.4	11.9	11.4	10.9	10.5
800 °C	21.7	21.6	21.37	19.4	17.4	15.49	14.6	13.84	13.1	12.5	11.9	11.4	10.9	10.4
900 °C	21.1	21	20.17	18.3	16.6	15.53	14.7	13.89	13.2	12.5	11.9	11.4	10.9	10.4



Graph 3.2 Effect of Reformer temperature and SCMR on hydrogen production

For steam reforming, maximum system efficiency of **21.77%** was obtained at **700 °C** reformer temperature and **2.5** SCMR. These reformer conditions also correspond to the highest hydrogen production of **5.19** kg/hr.

3.1.1 Heat integration

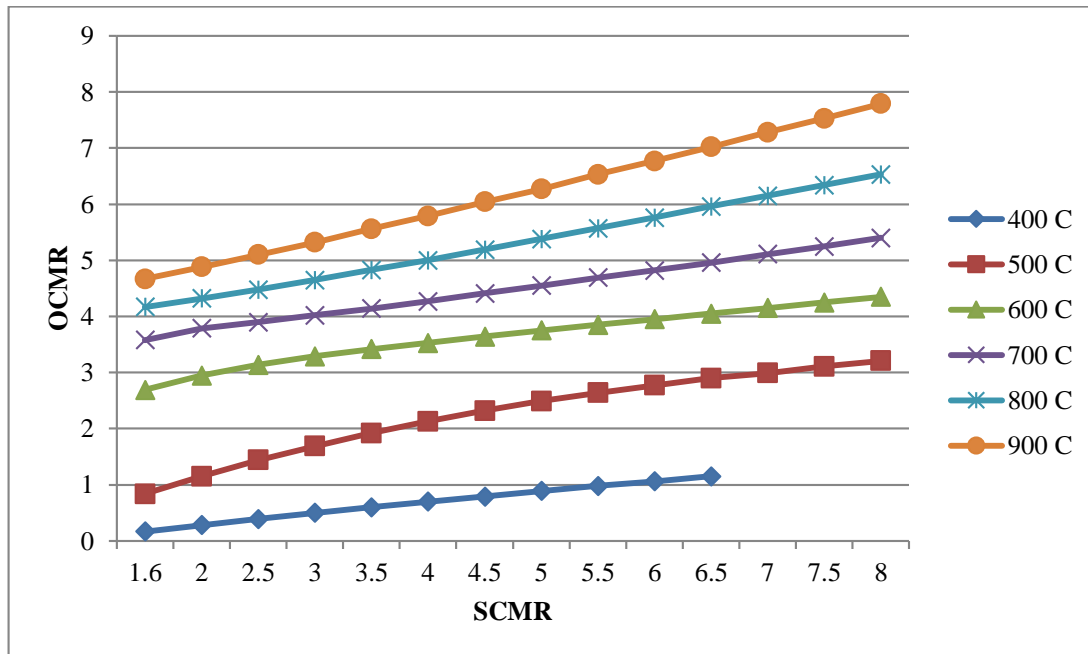
Heat integration is done by using HINT software to calculate the heating and cooling requirement for each process. In heat integration heating and cooling utility requirements for steam reforming process is calculated. Minimum temperature approach of (ΔT_{min}) 25°C is considered. Sample parameter for temperature 700°C and SCMR 2.5, is observed when heating and cooling utility is 0 kW and 47.24 kW.

3.2 PARAMETER VARIATION STUDY FOR AUTO THERMAL REFORMING

In Auto thermal reforming process three parameter variation study was conducted for three parameters namely SCMR, OCMR and reformer temperature. Reformer temperature was varied between 400°C-900°C and SCMR from 1.6 to 8. The relation between SCMR and OCMR with reformer temperature at thermo-neutral condition as shown in Graph 1.3. As observed from the graph increase in SCMR always increase OCMR. Because of the addition energy requirement for additional amount of water in feed, which is only possible by promoting exothermic partial oxidation reactions by adding more amount of oxygen in reformer.

Table 3.2 SCMR and OCMR at different reformer temperature

SCMR	1.6	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Temp	OCMR													
400 °C	-	-	-	0.17	0.28	0.4	0.5	0.6	0.7	0.79	0.9	0.98	1.1	1.2
500 °C	0.84	1.15	1.44	1.69	1.92	2.1	2.3	2.5	2.64	2.77	2.9	2.99	3.1	3.2
600 °C	2.69	2.95	3.14	3.29	3.42	3.5	3.6	3.8	3.85	3.95	4.1	4.15	4.3	4.4
700 °C	3.58	3.79	3.79	4.02	4.14	4.3	4.4	4.6	4.69	4.82	5	5.11	5.3	5.4
800 °C	4.17	4.32	4.48	4.65	4.83	5	5.2	5.4	5.57	5.76	6	6.15	6.3	6.5
900 °C	4.67	4.88	5.1	5.32	5.56	5.8	6	6.3	6.53	6.53	7	7.28	7.5	7.8

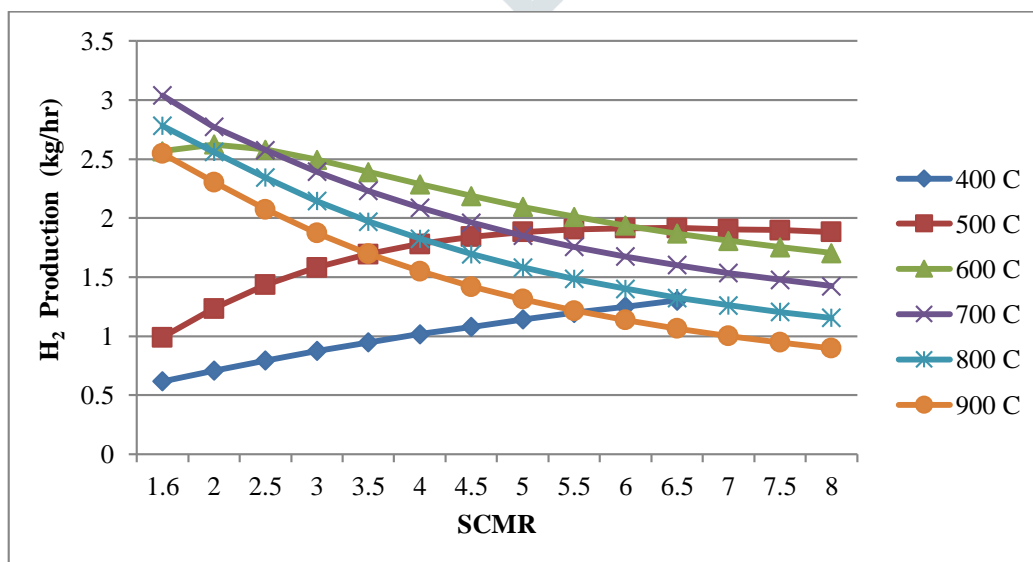


Graph 3.2 Relation between SCMR and OCMR at different reformer temperature at thermo-neutral conditions

For Reformer temperature 400 °C with increase in SCMR H₂ production rate is increased. Whereas at temperature of 500 °C and 600 °C h H₂ yield is reached to maxima with SCMR. Thereafter further increase in SCMR hydrogen yield is reduced. At reformer temperature greater than 600 °C, H₂ production rate always decrease with increase in temperature for the entire range of SCMR. This trend can be justified by the fact that at lower temperature addition of steam promotes endothermic steam reforming reaction and forward water gas shift reaction. At high temperature addition of steam reduced H₂ production rate due to the reverse exothermic water gas shift reaction and consumption of hydrogen to meet the energy requirement for water vaporization.

Table 3.3 Hydrogen production rate at different reformer temperature and SCMR (ATR)

SCMR	1.6	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Temp	Hydrogen production rate (kg/hr)													
400 °C	-	-	-	0.62	0.71	0.8	0.9	0.9	1.02	1.08	1.1	1.2	1.2	1.3
500 °C	0.99	1.23	1.43	1.58	1.7	1.8	1.8	1.9	1.9	1.91	1.9	1.91	1.9	1.9
600 °C	2.57	2.62	2.58	2.49	2.39	2.3	2.2	2.1	2.01	1.94	1.9	1.81	1.8	1.7
700 °C	3.04	2.77	2.58	2.39	2.23	2.1	2	1.9	1.76	1.68	1.6	1.53	1.5	1.4
800 °C	2.78	2.56	2.34	2.15	1.97	1.8	1.7	1.6	1.49	1.4	1.3	1.26	1.2	1.2
900 °C	2.55	2.3	2.07	1.87	1.7	1.6	1.4	1.3	1.22	1.14	1.1	1	0.9	0.9

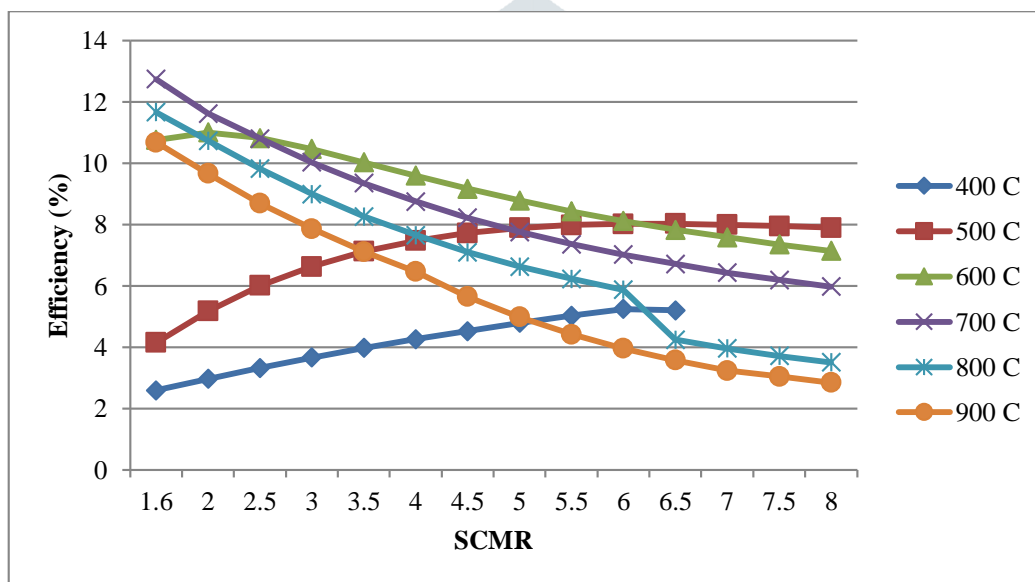


Graph 3.3 Effect of SCMR and reformer temperature for hydrogen production rate

This trend can be justified as increased hydrogen production rate due to the endothermic steam reforming process and forward water gas shift reaction system efficiency is improved in lower temperature range, which is responsible for initial improvement in efficiency at lower temperatures. In lower temperature range after reaching to maxima for efficiency, utility requirements become predominant over power generation thereby reducing overall efficiency of the system. For higher temperature range between 600°C -900°C hydrogen production rate is reduced with SCMR and greater amount of utility requirements are responsible for decrease in the system efficiency.

Table 3.4 System efficiency at different reformer temperature and SCMR

SCMR	1.6	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Temp	Efficiency (%)													
400 °C	-	-	-	2.59	2.96	3.3	3.7	4	4.26	4.52	4.8	5.03	5.2	5.2
500 °C	4.15	5.17	6.01	6.63	7.12	7.5	7.7	7.9	7.98	8.02	8	7.99	8	7.9
600 °C	10.8	11	10.8	10.5	10	9.6	9.2	8.8	8.43	8.11	7.8	7.58	7.4	7.1
700 °C	12.7	11.6	10.8	10	9.35	8.8	8.2	7.8	7.36	7.02	6.7	6.43	6.2	6
800 °C	11.7	10.7	9.82	8.99	8.26	7.7	7.1	6.6	6.23	5.87	4.2	3.96	3.7	3.5
900 °C	10.7	9.66	8.69	7.86	7.11	6.5	5.6	5	4.42	3.96	3.6	3.23	3	2.8



Graph 3.4 Effect of SCMR and reformer temperature on PEMFC efficiency at thermo-neutral conditions

For auto thermal reforming, maximum system efficiency of **12.74%** was obtained at **700 °C** reformer temperature, **3.58** OCMR and **1.6** SCMR. These reformer conditions also correspond to the highest hydrogen yield of **3.0399** kg/hr.

3.2.1 Heat integration

In heat integration heating and cooling utility requirements for Auto thermal reforming process is calculated. Minimum temperature approach of (ΔT_{min}) 25°C is considered. Sample parameter for temperature 700°C, OCMR 3.03 and SCMR 1.6, is observed when heating and cooling utility is 0 kW and 210. 837 Kw.

IV. CONCLUSION:

Feasibility study for Bio-butanol to produce Hydrogen with high purity CO and H₂ for low temperature fuel cell application PEMFC is done by using Aspen plus V10. Hydrogen is produced by two different reforming process involves Steam Reforming and Auto Thermal Reforming. Favorable Reformer condition for Steam reforming of Bio-butanol gives **21.77%** PEMFC efficiency with 700 °C reformer temperature and SCMR 2.5. Similarly for Auto thermal reforming of Bio-butanol gives **12.74%** PEMFC efficiency with 700 °C reformer temperature, 3.03 OCMR and SCMR 1.6. So, we can conclude that the Steam Reforming process obtained highest PEMFC efficiency for hydrogen production from Bio-butanol. Thermodynamic analysis and parametric study indicate that hydrogen produced via steam reforming of bio-butanol for PEMFC application is sustainable option.

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