

**T.C.
MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN
PURE AND APPLIED SCIENCES**

**RESIDENTIAL COGENERATION SYSTEMS
BASED ON
PEM FUEL CELLS**

**Halil OSMANOĞLU
(Mechanical Engineering)**

**THESIS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING PROGRAMME**

**SUPERVISOR
Prof. Dr. Sibel ÖZDOĞAN**

İSTANBUL 2007

**T.C.
MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN
PURE AND APPLIED SCIENCES**

**RESIDENTIAL COGENERATION SYSTEMS
BASED ON
PEM FUEL CELLS**

Halil OSMANOĞLU
(Mechanical Engineering)
(141101820050010)

**THESIS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING PROGRAMME**

**SUPERVISOR
Prof. Dr. Sibel ÖZDOĞAN**

İSTANBUL 2007

ACKNOWLEDGEMENT

I am sincerely grateful to my supervisor, Prof. Dr. Sibel Özdoğan, for valuable helps of this thesis study and I would also like to thank to her for sharing her office with me along the thesis study.

Lastly, I would like to thanks my family for their material and spiritual support, encouragement and unconditional love along my life.

January-2007

HALİL OSMANOĞLU

TABLE OF CONTENTS

	PAGE
ABSTRACT	V
ÖZET	VI
LIST OF SYMBOLS	VII
ABBREVIATIONS	X
LIST FO FIGURES	XI
LIST OF TABLES	XV
I. INTRODUCTION	1
II. FUEL CELLS	3
II.1. BRIEF HISTORY OF FUEL CELLS	5
II.2. BASIC PRINCIPLES OF FUEL CELLS	7
II.3. TYPES OF FUEL CELLS	9
II.4. ADVANTAGES OF FUEL CELLS	12
II.5. FUEL CELL APPLICATIONS	14
III. POLYMER ELECTROLYTE MEMBRANE (PEM) FUEL CELLS	16
III.1. OPERATION PRINCIPLES OF PEM FUEL CELL AND ITS COMPONENTS	16
III.1.1. Operation Principles of PEM Fuel Cell	16
III.1.2. Main Cell Components	18
III.1.2.1. Cell Description	18
III.1.2.2. Membrane	20
III.1.2.3. Electrode	21
III.1.2.4. Gas Diffusion Layer	22
III.1.2.5. Bipolar Plates	23

III.1.3. Fuel Requirement	24
III.1.3.1. Technologies of hydrogen production	24
III.2. FUEL CELL BASIC CHEMISTRY AND THERMODYNAMICS	25
III.2.1. Basic Reactions	25
III.2.2. Heat of Reaction	26
III.2.3. Nernst Equation for Reversible Fuel Cell Voltage	27
III.3. FUEL CELL OUTPUT VOLTAGE AND ASSOCIATED LOSSES	31
III.3.1. Activation Losses	32
III.3.1.1. The Tafel Equation	32
III.3.2. Internal Currents and Crossover Losses	33
III.3.3. Ohmic Losses	35
III.3.4. Concentration Losses	36
III.3.5. Fuel Cell Output Voltage	36
III.4. POLARIZATION CURVE AND ITS SENSITIVITY TO OPERATION PARAMETERS	37
III.4.1. Polarization Curve	37
III.4.1.1. Effect of Transfer Coefficient / Tafel Slope	38
III.4.1.2. Effect of Exchange Current Density	38
III.4.1.3. Effect of Internal Resistance	39
III.4.1.4. Effect of Limiting Current Density	39
III.4.1.5. Effect of Operation Pressure	39
III.4.1.6. Effect of Operation Temperature	39
III.4.1.7. Air vs. Oxygen	40
III.5. FUEL CELL EFFICIENCY	40
III.5.1. Effect of Fuel Cell Operation Conditions	42
III.5.1.1. Operation Pressure	42
III.5.1.2. Operation Temperature	43
III.5.1.3. Reactants Flow Rates	45
III.5.2. Second Law Efficiency	48
III.5.2.1. Mathematical Model	48
IV. RESIDENTIAL COGENERATION WITH PEM FUEL CELLS	51
IV.1. BRIEF HISTORY OF COGENERATION	52
IV.2. MICRO-COGENERATION	53
V. METHODOLOGY	55
V.1. PEM FUEL CELL MODELING	55
V.1.1. Model Assumptions and Operation Principles	55
V.1.2. Calculations for PEM Fuel Cell Modeling	57
V.1.2.1. Calculation of Output Voltage	57

V.1.2.1. Calculation of Electrical Power	59
V.1.2.3. Calculation of Heat Generation	59
V.1.2.4. Calculation of Useful Heat Generation	61
V.1.2.5. Calculation of Mass Flow Rates	64
V.1.2.6. Calculation of Exergy Values	67
V.1.2.7. Calculation of Efficiencies	69
V.2. COGENERATION	71
V.2.1. Heating and Cooling Loads	72
V.2.2. Electrical Consumption	74
V.2.3. Domestic Water Heating	75
V.2.4. Calculation of Cogeneration Cases	76
VI. RESULTS AND DISCUSSION	85
VI.1. PEM FUEL CELL MODELING	85
VI.1.1. Temperature Effects	86
VI.1.2. Pressure Effects	110
VI.2. COGENERATION	133
VII. CONCLUSIONS AND RECOMMENDATIONS	154
REFERENCES	156
APPENDIX	158
APPENDIX A. Chemical Exergy Table	159
APPENDIX B. Heating and Cooling Load Parameters and Results	160
APPENDIX C. Electrical Consumptions of the Residential House ...	164
APPENDIX D. Performance of Heat Pump for Different Models ...	172
VITA	176

ÖZET

PEM YAKIT PİLLERİNE DAYALI EVSEL KOJENERASYON SİSTEMLERİ

Yakıt pili teknolojisi; ulaşımda, yerleşik ve taşınabilir uygulamalarda için güç üretiminde kullanılan ve hızla gelişmekte olan bir teknolojidir. Polimer elektrolit yakıt pilleri birçok olumlu özelliklere sahiptir. Diğer yakıt pili modellerine göre düşük sıcaklıkta çalışırlar ve bu durum ısının daha kolay muhafaza edilmesini ve ısı kayıplarının azaltılmasını sağlar. Polimer elektrolit yakıt pilleri temiz ve verimli güç kaynaklarıdır. Bu verimlilik evsel uygulamalar için değişik güç üretim kapasitelerinde çok kullanışlı ve ilgi çekicidir.

Tez kapsamında, kararlı haldeki polimer elektrolit zarlı yakıt pili Matlab yazılımı kullanılarak modellendi. Model sadeleştirilmiş kimyasal ve elektriksel denklemlere dayanılarak oluşturuldu. Performansı etkileyen en önemli özellikler olan çalışma sıcaklığı ve basıncı parametrik olarak incelendi. Değişen sıcaklık ve basınç şartlarında akım yoğunluğuna göre çıkış gerilimi, elektriksel güç üretimi, ısı üretimi, giren ve çıkan maddeler ve termodinamiğin birinci ve ikinci kanununa göre elde edilen verimlerin grafikleri çizildi.

Kojenerasyon bölümünde, yerleşime uygun bir ev tasarlandı. Evin toplam enerji ihtiyacı, ısıtma ve soğutma ihtiyacı, sıcak su kullanımı ve elektrik tüketimidir. Evin ısıtma ve soğutma yükleri inşa ve izolasyon parametreleri seçilerek HVAC-Calc 4.0 Residential yazılım programıyla bulundu. Sıcak su ihtiyacı günlük ortalama dört kişinin sıcak su tüketimine göre hesaplandı. Elektrik tüketimi ise kış ve yaz şartlarına göre her oda için gerekli elektrikli aletler seçilerek hesaplandı. Bu çalışma çerçevesinde modellenen polimer elektrolit yakıt pilinin elektriksel ve termal enerjisi değişik senaryolara göre evin enerji ihtiyacının karşılanmasında kullanıldı.

Ocak-2007

HALİL OSMANOĞLU

ABSTRACT

RESIDENTIAL COGENERATION SYSTEMS BASED ON PEM FUEL CELLS

The fuel cell technology is a developing technology for power generation for stationary, transportation and portable applications. PEM fuel cells in particular have desirable properties. They operate at relatively low temperatures that is easier to conserve heat and reduces thermal losses. PEM fuel cells are environmentally clean and efficient power sources. Their efficiency for different size range applications of residential houses is very useful and attractive.

In the scope of the thesis, a steady-state model of polymer electrolyte membrane fuel cell was made by Matlab. The model was based on simplified chemical and electrical equations. The most important performance related parameters, namely operation temperature and pressure, were parametrically investigated. Output voltage, electrical output power, heat generation, material inputs and outputs, and efficiencies according to first and second law of thermodynamics were plotted by the change of temperature and pressure against current density.

A residential house was designed in cogeneration section. Total energy requirement of the house is space heating and cooling, domestic water heating and electrical consumption. Space heating and cooling loads were found by HVAC-Calc 4.0 Residential software program choosing construction and insulation parameters. Domestic water heating was calculated for daily average hot water consumption of four people. Electric consumption was calculated according to summer and winter options by choosing electrical appliances for each room. Electrical and thermal energy of the PEM fuel cell modeled within the frame of this study were used to satisfy the energy requirements of the residence at different cases.

January-2007

HALİL OSMANOĞLU

LIST OF SYMBOLS

A	: Area (cm^2)
a_c	: Catalyst specific area ($\text{cm}^2\text{mg}^{-1}$)
b	: Tafel slope
CO	: Carbon monoxide
CO₂	: Carbon dioxide
C_p	: Specific heat (kJ/kg-K)
dG	: Differential of Gibbs free energy
E_c	: Activation energy (J/mol)
E_{cell}	: Fuel cell potential (V)
E_{Nernst}	: Reversible voltage of the cell (V)
e	: Specific exergy (kJ/kg)
F	: Faraday's constant (Coulombs/electron-mol)
f	: Shape factor
G	: Gibbs free energy
G₀	: Gibbs free energy at standard temperature and pressure (25°C and 1 atm)
g	: Gravity acceleration (m/s^2)
H	: Enthalpy (kJ)
H₂	: Hydrogen
H₂O	: Water
h	: Heat transfer coefficient ($\text{W/m}^2\text{ }^\circ\text{C}$)
h₀	: Specific enthalpy at standard conditions (kJ/kg)
h_f	: Heat of formation (kJ/kg)
I	: Current (A)
i	: Current density (A/cm^2)
i₀	: Exchange current density (A/cm^2)
i_L	: Limiting current density (A/cm^2)
k	: Thermal conductivity ($\text{W/m}^\circ\text{C}$)
L	: Characteristic length (m)
L_c	: Catalyst loading (mgcm^{-2})
K	: Potassium
KOH	: Potassium hydroxide
Li	: Lithium

M	: Molar mass (g/mol)
m	: Mass flow rate (g/s)
N	: Avogadro's number
\dot{N}	: Molar flow rate (mol/s)
Na	: Sodium
n_{cell}	: Number of cells in the fuel cell
Nu_L	: Nusselt number
O	: Oxygen
OH	: Hydroxide
P	: Pressure (atm)
P_0	: Reference or standard pressure (1 atm)
P_r	: Reactant partial pressure (atm)
Pr	: Prandtl number
Pt	: Platinum
P_{vs}	: Saturation pressure (kPa)
Q	: Heat (W)
R	: Universal gas constant (kJ/kmol-K)
R_C	: Convective thermal resistance (K/W)
R_i	: Total internal resistance (Ωcm^2)
R_R	: Radiative thermal resistance (K/W)
R_{th}	: Thermal resistance (K/W)
Ra_L	: Rayleigh number
Ru	: Ruthenium
S	: Stoichiometric ratio
SO_3	: Sulfide anion
s_0	: Specific entropy at standard conditions
T	: Temperature (K)
t	: Time (h)
UF	: Utilization factor
V	: Voltage (V)
v_m	: Molar volume ($\text{m}^3\text{mol}^{-1}$)
W	: Electrical power (W)
x	: Mole fraction
α	: Charge transfer coefficient
α_{td}	: Thermal diffusivity (m^2/s)
β	: Thermal expansion coefficient
γ	: Pressure coefficient
ϕ	: Relative humidity
η	: Efficiency
σ	: Stefan-Boltzmann constant ($\text{W}/\text{m}^2\text{K}^4$)
ν	: Kinematic viscosity (m^2/s)
$\Delta(g_f)$: Change of formation of Gibbs's free energy
ΔH	: Change of enthalpy
ΔS	: Change of entropy

Subscripts

act	: Activation
ch	: Chemical
conc	: Concentration
cons	: Consumption
cool	: Cooling
dis	: Dissipation
DWH	: Domestic water heating
el	: Electric
ext	: External
gen	: Generation
HHV	: Higher heating value
HP	: Heat pump
in	: Input
OCV	: Open circuit voltage
ohm	: Ohmic
out	: Output
ph	: Physical
react	: Reactant
ref	: Reference
SH	: Space heating
surr_wall	: Surrounding wall
th	: Thermal

ABBREVIATIONS

AFC	: Alkaline fuel cell
CHP	: Combined heat and power
COP	: Coefficient performance of heat pump
DC	: Direct current
DMFC	: Direct methanol fuel cell
EE	: Electrical energy
HHV	: Higher heating value
HP	: Heat pump
HVAC	: Heating ventilating air conditioning
LHV	: Lower heating value
MCFC	: Molten carbonate fuel cell
MEA	: Membrane electrode assembly
NASA	: National aeronautics space administration
PAFC	: Phosphoric acid fuel cell
PEM	: Polymer electrolyte membrane or proton exchange membrane
PEMFC	: Polymer electrolyte membrane (proton exchange membrane) fuel cell
PSA	: Perfluorocarbon-sulfonic acid ionomer
PSEPVE	: Perfluoro-sulfonylfluoride ethyl-propyl-vinyl ether
PV	: Photovoltaic
SOFC	: Solid oxide fuel cell
SPE	: Solid polymer electrolyte
TE	: Thermal energy
TFE	: Tetrafluorethylene

LIST OF FIGURES

	PAGE
Figure II.1 A fuel cell is similar to a battery	3
Figure II.2 A schematic representation of a fuel cell	4
Figure II.3 Fuel cell history timeline	5
Figure II.4 Fuel cell patent publications per year in the world	6
Figure II.5 Basic cathode-electrolyte-anode construction of a fuel cell	7
Figure II.6 Electrode reactions and charge flow for an acid electrolyte fuel cell	8
Figure II.7 Energy diagram for a simple exothermic chemical reaction	9
Figure II.8 Types of fuel cells, their reactions and operating temperatures ...	11
Figure III.1 The basic principle of operation of a PEM fuel cell	17
Figure III.2 Main cell components and processes	19
Figure III.3 Structure of PFSA polymer	21
Figure III.4 Fuel cell with a load a) in open circuit; b) load connected	32
Figure III.5 Voltage losses in the fuel cell	37
Figure III.6 Voltage losses in fuel cell and resulting polarization curve	38
Figure III.7 Effect of operating temperature on fuel cell polarization curve...	40
Figure III.8 Fuel cell operating pressure as a function of reactant gas supply; a) supply from a high pressure tank, b) supply by a mechanical device, a compressor or blower	43
Figure III.9 Modes of reactant supply: a) dead-end mode, b) flow-through mode, c) recirculation mode.	46
Figure IV.1 Cogeneration versus conventional generation	54
Figure V.1 Flow chart of the PEM fuel cell model	57
Figure V.2 The PEM fuel cell with cogeneration options	71
Figure V.3 Schematic representation of the residence	72
Figure VI.1 Polarization curve at different temperatures	86

Figure VI.2	Electrical power at different temperatures	87
Figure VI.3	Heat generation in fuel cell (Hydrogen only) at different temperatures	88
Figure VI.4	Heat generation in fuel cell (All inlets) at different temperatures	89
Figure VI.5	Useful heat generation (Hydrogen only) at different temperatures	90
Figure VI.6	Useful heat generation (All inlets) at different temperatures	91
Figure VI.7	Hydrogen inlet mass flow rate at different temperatures	92
Figure VI.8	Oxygen inlet mass flow rate at different temperatures	93
Figure VI.9	Water vapor in hydrogen inlet at different temperatures	94
Figure VI.10	Water vapor in oxygen inlet at different temperatures	95
Figure VI.11	Unused hydrogen flow rate at different temperatures	96
Figure VI.12	Oxygen outlet flow rate at different temperatures	97
Figure VI.13	Water in hydrogen outlet at different temperatures	98
Figure VI.14	Water in oxygen outlet at different temperatures	99
Figure VI.15	Water production at different temperatures	99
Figure VI.16	Cooling water mass flow rate (Hydrogen only) at different temperatures	100
Figure VI.17	Cooling water mass flow rate (All inlets) at different temperatures	101
Figure VI.18	Electrical efficiency according to thermodynamics first law (Hydrogen only) at different temperatures	102
Figure VI.19	Electrical efficiency according to thermodynamics second law (Hydrogen only) at different temperatures	103
Figure VI.20	Electrical efficiency according to thermodynamics first law (All inlets) at different temperatures	104
Figure VI.21	Electrical efficiency according to thermodynamics second law (All inlets) at different temperatures	105
Figure VI.22	Total efficiency according to thermodynamics first law (Hydrogen only) at different temperatures	106
Figure VI.23	Total efficiency according to thermodynamics second law (Hydrogen only) at different temperatures	107

Figure VI.24	Total efficiency according to thermodynamics first law (All inlets) at different temperatures	108
Figure VI.25	Total efficiency according to thermodynamics second law (All inlets) at different temperatures	109
Figure VI.26	Polarization curve at different pressures	110
Figure VI.27	Electrical power at different pressures	111
Figure VI.28	Heat generation in fuel cell (Hydrogen only) at different pressures	112
Figure VI.29	Heat generation in fuel cell (All inlets) at different pressures	113
Figure VI.30	Useful heat generation (Hydrogen only) at different pressures ...	114
Figure VI.31	Useful heat generation (All inlets) at different pressures	115
Figure VI.32	Hydrogen inlet mass flow rate at different pressures	116
Figure VI.33	Oxygen inlet mass flow rate at different pressures	117
Figure VI.34	Water vapor in hydrogen inlet at different pressures	118
Figure VI.35	Water vapor in oxygen inlet at different pressures	119
Figure VI.36	Unused hydrogen flow rate at different pressures	120
Figure VI.37	Oxygen outlet flow rate at different pressures	121
Figure VI.38	Water in hydrogen outlet at different pressures	122
Figure VI.39	Water in oxygen outlet at different pressures	123
Figure VI.40	Water production at different pressures	123
Figure VI.41	Cooling water mass flow rate (Hydrogen only) at different pressures	124
Figure VI.42	Cooling water mass flow rate (All inlets) at different pressures	125
Figure VI.43	Electrical efficiency according to thermodynamics first law (Hydrogen only) at different pressures	126
Figure VI.44	Electrical efficiency according to thermodynamics second law (Hydrogen only) at different pressures	127
Figure VI.45	Electrical efficiency according to thermodynamics first law (All inlets) at different pressures	128
Figure VI.46	Electrical efficiency according to thermodynamics second law (All inlets) at different pressures	129
Figure VI.47	Total efficiency according to thermodynamics first law (Hydrogen only) at different pressures	130

Figure VI.48	Total efficiency according to thermodynamics second law (Hydrogen only) at different pressures	131
Figure VI.49	Total efficiency according to thermodynamics first law (All inlets) at different pressures	132
Figure VI.50	Total efficiency according to thermodynamics second law (All inlets) at different pressures	133
Figure B.1	Design conditions	160
Figure B.2	Infiltration	161
Figure B.3	Duct	162

LIST OF TABLES

	PAGE
Table II.1 Different types of fuel cell	12
Table VI.1 Cases 1-4 in winter	135
Table VI.2 Efficiencies of cases 1-4 in winter	135
Table VI.3 Cases 1-4 in summer	136
Table VI.4 Efficiencies of cases 1-4 in summer	136
Table VI.5 Cases 5-8 in summer	139
Table VI.6 Efficiencies of cases 5-8 in summer	139
Table VI.7 Cases 5-8 in winter for scenario I	140
Table VI.8 Efficiencies of cases 5-8 in winter for scenario I	140
Table VI.9 Cases 5-8 in winter for scenario II	141
Table VI.10 Efficiencies of cases 5-8 in winter for scenario II	141
Table VI.11 Cases 5-8 in winter for scenario III	142
Table VI.12 Efficiencies of cases 5-8 in winter for scenario III	142
Table VI.13 Cases 5-8 in winter for scenario IV	143
Table VI.14 Efficiencies of cases 5-8 in winter for scenario IV	143
Table VI.15 Case-1 and Cases 9-11 in winter	148
Table VI.16 Efficiencies of case-1 and cases 9-11 in winter	149
Table VI.17 Case-1 and cases 9-11 in summer	150
Table VI.18 Efficiencies of case-1 and cases 9-11 in summer	150
Table VI.19 Cases 8 and 12 in summer	152
Table VI.20 Efficiencies of cases 8 and 12 in summer	152
Table VI.21 Cases 8 and 12 in winter	153
Table VI.22 Efficiencies of cases 8 and 12 in winter	153
Table VII.1 Results of the PEM fuel cell model at different temperatures and pressures	155

Table A.1	Standard molar chemical exergy, (kJ/kmol), of various substances at 298.15 K and P_0	159
Table B.1	HVAC-Calc Residential 4.0 Report	163
Table C.1	Usage hours of electrical appliances in the living room at different times	164
Table C.2	Electrical consumptions of the appliances in the living room at different times	164
Table C.3	Usage hours of electrical appliances in the kitchen at different times	165
Table C.4	Electrical consumptions of the appliances in the kitchen at different times	166
Table C.5	Usage hours of electrical appliances in the bedroom 1 at different times	167
Table C.6	Electrical consumptions of the appliances in the bedroom I at different times	167
Table C.7	Usage hours of electrical appliances in the bedroom II at different times	168
Table C.8	Electrical consumptions of the appliances in the bedroom II at different times	168
Table C.9	Usage hours of electrical appliances in the bathroom at different times	169
Table C.10	Electrical consumptions of the appliances in the bathroom at different times	169
Table C.11	Usage hours of other electrical appliances at different times	170
Table C.12	Electrical consumptions of the other appliances at different times	170
Table C.13	Total electrical consumptions of the house at different times	171
Table D.1	Performance of WH100 model of Whirlpool heat pump	172
Table D.2	Performance of WH200 model of Whirlpool heat pump	173
Table D.3	Performance of WGH100 model of Whirlpool heat pump	174
Table D.4	Performance of WGH200 model of Whirlpool heat pump	175

I. INTRODUCTION

With the ever increasing political and economical indeterminate surrounding a fossil fuel based economy, the search for alternative energy sources has gained momentum in recent years. In addition to renewable sources (such as, wind, solar, micro-hydro), fuel cell technology has received a heightened research focus [5].

Fuel cells can play a leading role in meeting national goals of clean air, climate protection and energy security. Fuel cell systems can meet the toughest of air pollution standards. Fuel cells can also significantly reduce carbon dioxide emissions compared to traditional energy sources are used. Regulated air pollutants such as sulfur and nitrogen oxides, carbon monoxide, and unburned hydrocarbons are nearly absent.

With 10 percent market penetration, carbon dioxide emissions, the major greenhouse gas, would be reduced by 60 million tons a year. Fuel cells emit 40 percent to 60 percent less carbon dioxide than conventional power generation systems when hydrogen is derived from carbon-based fuels. Carbon dioxide emissions can be completely eliminated when hydrogen is produced using solar or wind power. Additionally, since hydrogen is the most abundant element, sources of hydrogen fuel are everywhere such as renewable sources, electrolysis, biomass, hydrocarbons.

Fuel cells are quiet, reliable, easy to maintain and safe. They are also modular, allowing units to be installed according to energy demand. Fuel cells offer a promising solution and provide a way of generating electricity by an electrochemical process and are more reliable, efficient, and effective than a conventional power source. The higher energy efficiency in cogeneration mode, low emission, good transient response, high scalability, and superior durability are some of the favorable factors towards the potential success of this technology.

Various types of fuel cells at different stages of development can be found. The most mature and potential candidate for residential and stationary applications among

different types of fuel cells is the Proton Exchange Membrane (PEM) fuel cell. A proton exchange membrane fuel cell uses a solid polymer based ion exchange membrane as the electrolyte. These cells operate at relatively low temperature (60-100 °C) and have high power density, quick start-up, high efficiency, modularity in construction, and higher specific energy have made PEM fuel cells the most promising solution for many mobile and stationary applications [10].

Residences require electricity for lights, appliances, and space cooling and thermal energy for space and domestic water heating. PEM fuel cell cogeneration systems which provide both electricity and thermal energy can meet these needs more effectively than conventional systems. Because thermal energy rejects during the production of electricity, it can meet the heating loads. Fuel cells can obtain more than 80 percent efficiency using both heat and electricity

Fuel cells can be fabricated in a wide range of sizes without sacrificing either efficiency or environmental performance. This flexibility allows fuel cells to generate power in a clean, efficient manner for automobiles, utilities and buildings. Fuel cell modules can be installed as needed on sites without much investment. They may be remote power plants and new high voltage lines. The power generating capacity of stationary sources can be easily increased by adding more fuel cell modules. Fuel cells have been installed in hotels, hospitals, offices and other buildings to provide their electricity, and space and water heating needs.

II. FUEL CELLS

A fuel cell is an electrochemical energy converter that converts chemical energy of fuel directly into DC electricity. Typically, a process of electricity generation from fuels involves several conversion steps, namely:

1. combustion of fuel converts chemical energy of fuel into heat,
2. this heat is then used to boil water and generate steam,
3. steam is used to run a turbine in a process that converts thermal energy into mechanical energy, and finally
4. mechanical energy is used to run a generator that generates electricity.

A fuel cell circumvents all these processes and generates electricity in a single step without involving any moving parts (Figure 1) [1]. A fuel cell is a mini power plant that produces electricity without combustion. Chemical energy is converted directly into electrical energy and heat when hydrogen fuel is combined with oxygen from the air. Water is the only by-product. No pollutants are produced if pure hydrogen is used. Hydrogen can be produced from water using renewable solar, wind, hydro or geothermal energy. Hydrogen also can be extracted from anything that contains hydrocarbons, including gasoline, natural gas, biomass, landfill gas, methanol, ethanol, methane and coal-based gas [10].

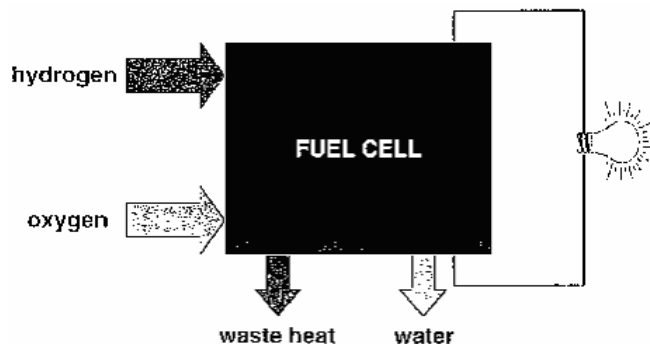


Figure II.1. A fuel cell is similar to a battery

A fuel cell uses electrolyte layer between a porous anode (negative electrode) and cathode (positive electrode) on either side. A schematic representation of a fuel cell with the reactant/product gases and the ion conduction flow directions is shown in the Figure 2. Gaseous fuels such as hydrogen are fed to the anode and an oxidant (i.e., oxygen from air) is fed continuously to the cathode; the electrochemical reactions take place at the electrodes to produce an electric current. The ion species and transport direction, as well as water production and removal, depend on the fuel cell type. The fuel and oxidant gases flow past the surface of the fuel and the electrochemical reduction of the oxidant.

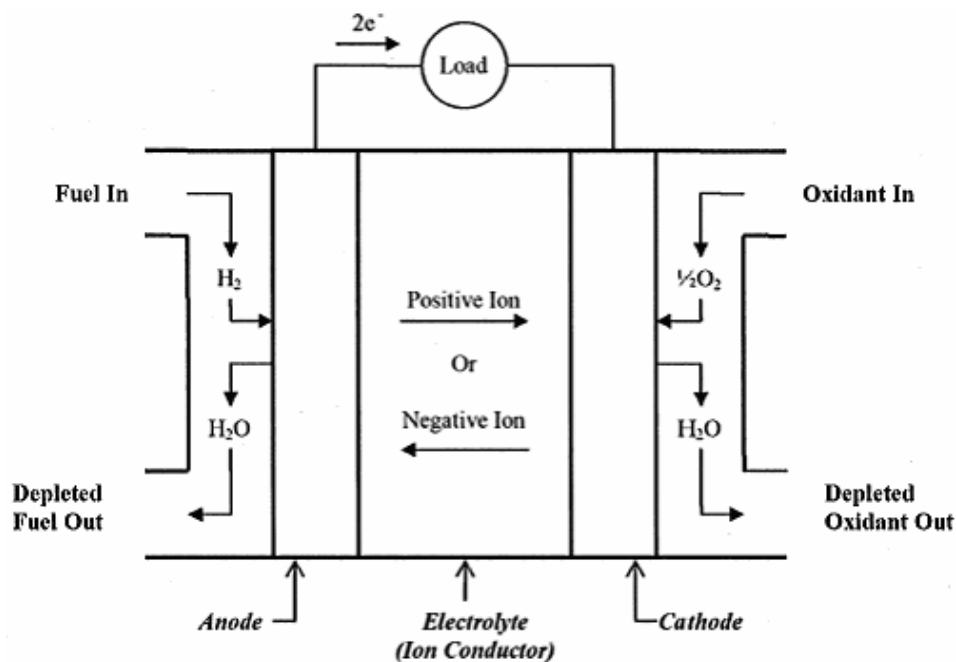


Figure II.2. A schematic representation of a fuel cell

Hydrogen is the choice of fuel for most applications due to its high reactivity with a suitable catalyst, its ability to be produced from wide range of other energy sources, and its high energy density. However, in theory, any substance capable of chemical oxidation can be used as fuel at the anode of a fuel cell. Similarly, the oxidant can be any substance that can be reduced. The oxygen is the most common oxidant as it is economically available in air [4].

A fuel cell is in some aspects similar to a battery. It has an electrolyte, and negative and positive electrodes, and it generates DC electricity through electrochemical reactions. However, unlike a battery, a fuel cell requires a constant supply of fuel and

oxidant. Also, unlike in a battery, the electrodes in a fuel cell do not undergo chemical changes [1].

II.1. BRIEF HISTORY OF FUEL CELLS

The timeline of fuel cell development history is shown in the Figure 3. The discovery of the fuel cell operating principle, the gaseous fuels that generate electricity, is attributed to Sir William Grove in 1839. The fuel cell or the “gaseous voltaic battery” as it was called by Grove, remained nothing more than a scientific curiosity for almost a century. E. Chen, in *Fuel cells Technology Handbook*, provides a very detailed description of these early fuel cell developments. It was another Englishman, Francis T. Bacon, who started working on practical fuel cells in 1937, and he developed a 6 kW fuel cell by the end of the 1950s. However, the first practical fuel cell applications were in the U.S. Space Program. General Electric developed the first polymer membrane fuel cells that were used in the Gemini Program in the early 1960s. This was followed by the Apollo Space Program, which used the fuel cells to generate electricity for life support, guidance, and communications. These fuel cells were built by Pratt and Whitney based on license taken on Bacon’s patents.

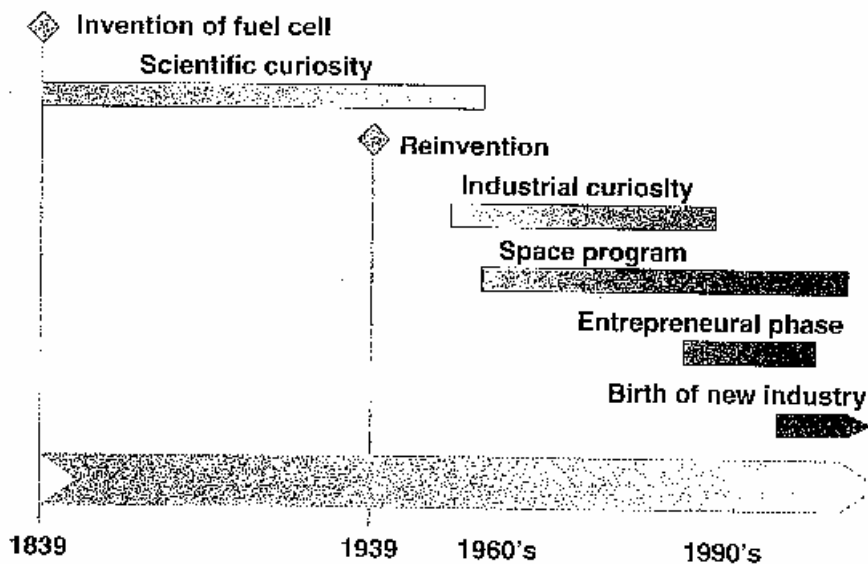


Figure II.3. Fuel cell history timeline

In the mid-1960s General Motors experimented with a fuel cell powered van (these fuel cells were developed by Union Carbide). Although fuel cells have continued to be successfully used in the U.S. Space Program until today, they were again “forgotten” for terrestrial applications until the early 1990s. In 1989, Perry Energy Systems, a division of Perry Technologies, working with Ballard, a then emerging Canadian company, successfully demonstrated a polymer electrolyte membrane (PEM) fuel cell powered submarine. In 1993, Ballard Power Systems demonstrated fuel cell powered buses. Energy Partners, a successor of Perry Energy Systems, demonstrated the first passenger car running on PEM fuel cells in 1993. The car companies, supported by the U.S. Department of Energy, picked up on this activity and by the end of the century almost every car manufacturer had built and demonstrated a fuel cell powered vehicle. A new industry was born. The stocks of fuel cell companies, such as Ballard and Plug Power, soared in early 2000, based on a promise of a new energy revolution (eventually in 2001 they came down with the rest of the market). The number of fuel cell related patents world-wide, but primarily in the United States and Japan, is increasing dramatically (Figure 4), showing continuous interest and involvement of the scientific and engineering community [1].

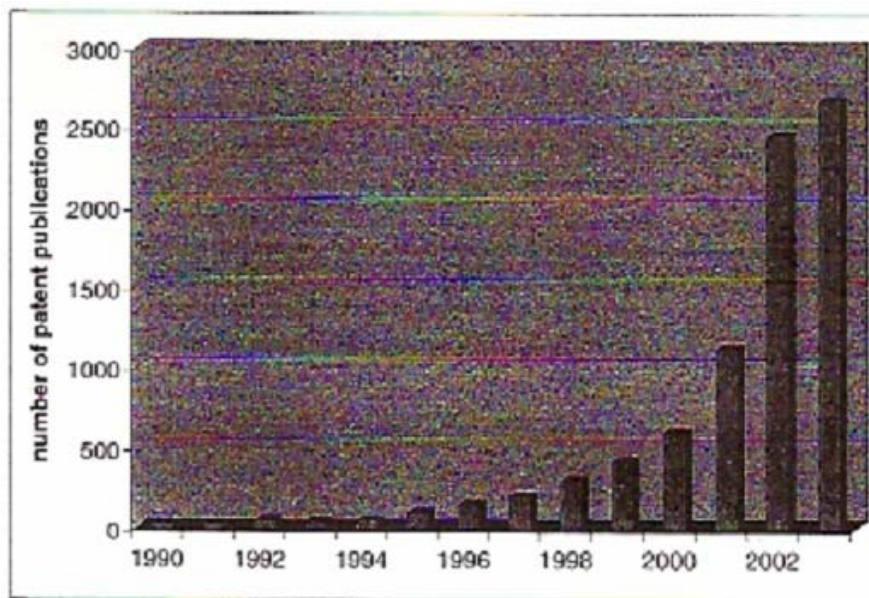


Figure II.4. Fuel cell patent publications per year in the world

II.2. BASIC PRINCIPLES OF HYDROGEN FUEL CELLS

The basic operation of the hydrogen fuel cell is actually uncomplicated. A way of looking at the fuel cell is being burnt or combusted in the simple reaction.



In this chemical reaction the main objective is to produce electrical energy instead of heat energy release. To produce high current the electrodes are usually made flat with a thin layer of electrolyte as in the Figure II.5.

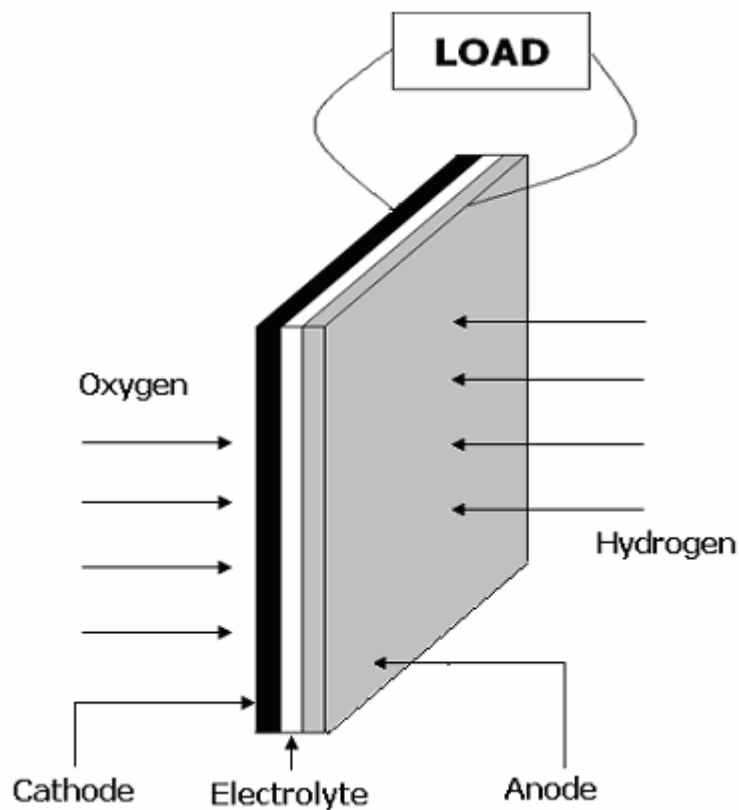


Figure II.5. Basic cathode-electrolyte-anode construction of a fuel cell

Electrode structure is porous. As a result both the electrolyte from one side and the gas from the other side can penetrate it. Thus there occurs maximum possible contact between the electrode, the electrolyte and the gas.

The hydrogen gas ionizes at the anode of an electrolyte. There can be released electrons, H^+ ions and energy.



Oxygen reacts with electrons taken from the electrode and H^+ ions from the electrolyte in order to form water.



These reactions proceed continuously. Electrons produced at the anode must pass through an electrical circuit to cathode. Also, H^+ ions must pass through the electrolyte. Polymers can be made to contain mobile H^+ ions. These materials are named ‘proton exchange membrane’. They allow H^+ ions to pass through them, and not electrons. Otherwise the electrons would go through the electrolyte and they wouldn’t go around the external circuit. This is shown in the Figure II.6.

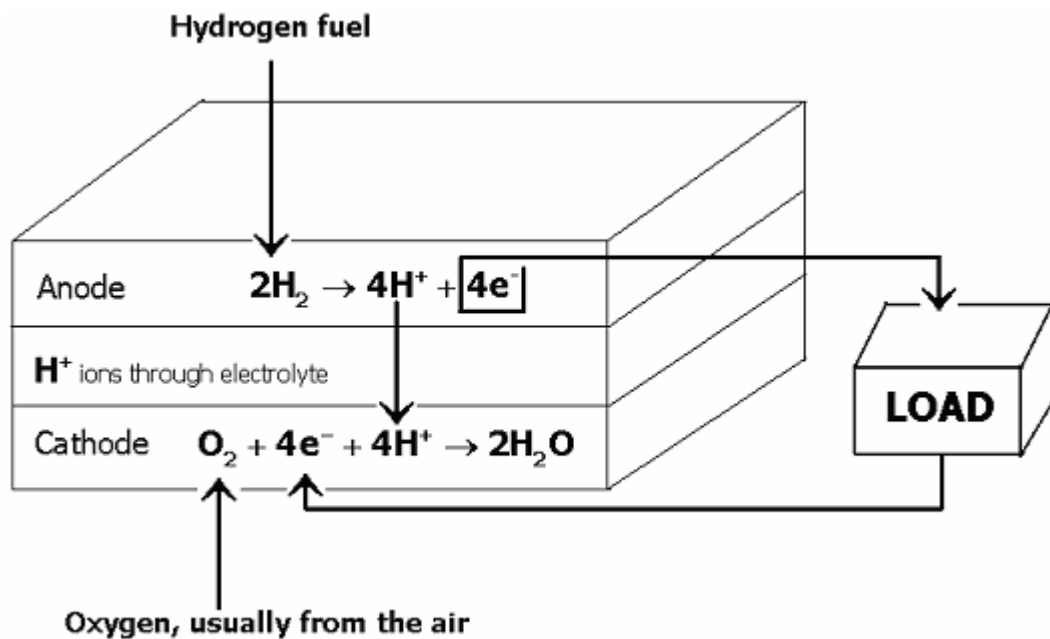


Figure II.6. Electrode reactions and charge flow for an acid electrolyte fuel cell

Although energy is released, the activation energy must be supplied to get over the energy hill (Figure II.7). If a molecule has enough energy but it is low, then the reaction proceeds slowly. At very high temperatures activation energy decreases.

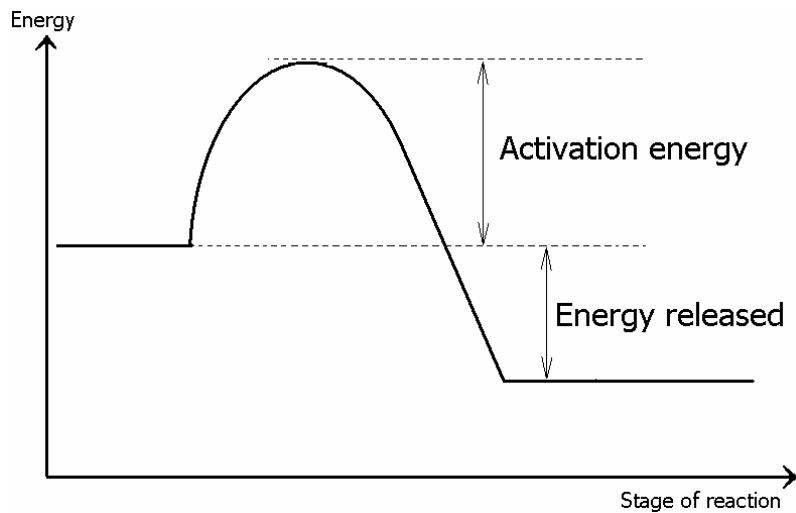


Figure II.7. Energy diagram for a simple exothermic chemical reaction

Three main ways for dealing with the slow reaction are to use catalysts, to raise the temperature and to increase the electrode area. Using catalysts and raising the temperature can be applied to any chemical reaction. However, increasing the electrode area is special to fuel cells and it's very important. Electrode area is such an important issue that the performance of a fuel cell design is often quoted in terms of the current per centimeter square.

The surface area of an electrode is much different than multiplication of its length and width. The electrode is made highly porous. This property increases the effective surface area. Modern fuel cell electrodes have a microstructure which gives them surface areas that can be hundreds of times their straightforward 'length x width'. Thus, the micro-structural design and manufacture of a fuel cell electrode is very important subject for fuel cells [10].

II.3. TYPES OF FUEL CELLS

Fuel cells can be grouped by the type of electrolyte, namely:

- **Alkaline fuel cells (AFC)** use concentrated (85 %) KOH as the electrolyte for high temperature operation (250°C) and less concentrated (35-50 %) for lower temperature operation ($<120^{\circ}\text{C}$). The problem of slow reaction rate is overcome by using highly porous electrodes, with a platinum catalyst, and by

operating at quite high pressures. This fuel cell is intolerant to CO_2 present in either fuel or oxidant. Alkaline fuel cells have been used in the space program (Apollo and Space Shuttle) since the 1960s [1].

- **Polymer electrolyte membrane or proton exchange membrane fuel cells (PEMFC)** have got the essential simplicity of fuel cell. Its electrolyte is a solid polymer and protons are mobile in structure. PEMFC use a thin ($<50 \mu m$) proton conductive polymer membrane (such as perfluorosulfonated acid polymer) as the electrolyte. The catalyst is typically platinum supported on carbon with loadings of about $0.3 mg/cm^2$, or, if the hydrogen feed contains minute amounts of CO, Pt-Ru alloys are used. Thus the cost of the platinum is a small part of the total price of a PEM fuel cell. PEMFC run at quite low temperatures. Operating temperature is typically between 60 and $80^\circ C$. The hydrogen supply is a difficult problem to be solved and quite pure hydrogen must be used in PEM fuel cells. PEM fuel cells are a serious candidate for automotive applications, but also for small-scale distributed stationary power generation, and for portable power applications as well [1].
- **Phosphoric acid fuel cells (PAFC)** were the first to be produced in commercial quantity. PAFC use concentrated phosphoric acid ($\sim 100\%$) as the electrolyte. The electro catalyst in both the anode and the cathode is platinum. Operating temperature is typically between 150 and $220^\circ C$. Phosphoric acid fuel cells are already semi commercially available in container packages (200kW) for stationary electricity generation [1].
- **Molten carbonate fuel cells (MCFC)** have the electrolyte composed of a combination of alkali (Li, Na, K) carbonates. Operating temperatures are between 600 and $700^\circ C$ where the carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. These fuel cells are in the precommercial / demonstration stage for stationary power generation [1].
- **Solid oxide fuel cells (SOFC)** use a solid, nonporous metal oxide as the electrolyte. These cells operate at 800 to $1000^\circ C$ where ionic conduction by oxygen ions takes place. Similar to MCFC, these fuel cells are in the precommercial / demonstration stage for stationary power generation,

although smaller units are being developed for portable power and auxiliary power in automobiles [1].

Figure II.8 summarizes the basic principles and electrochemical reactions in various fuel cell types.

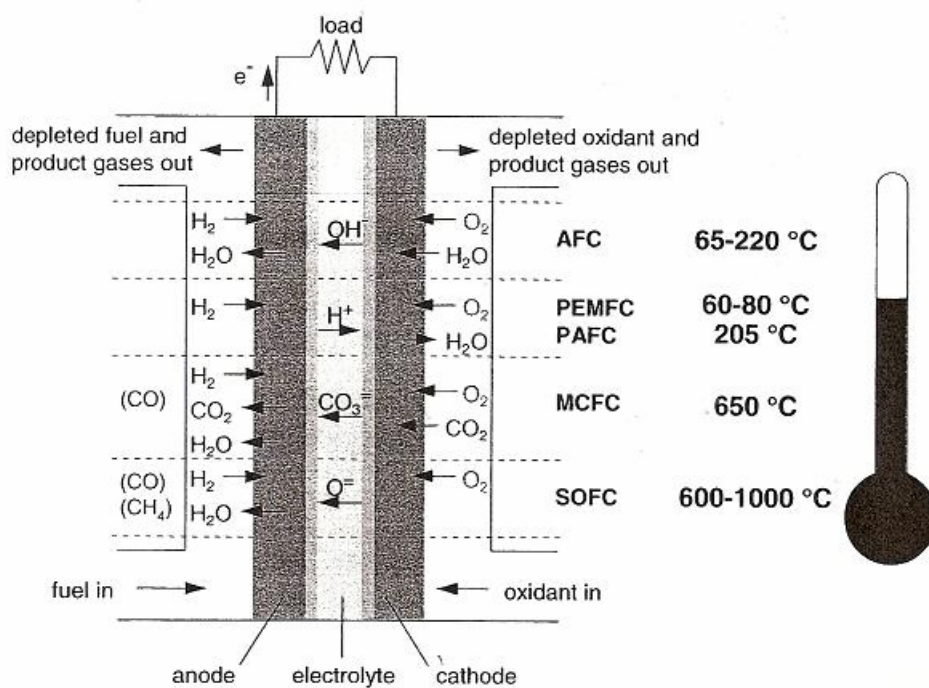


Figure II.8 Types of fuel cells, their reactions and operating temperatures

Sometimes a direct methanol fuel cell (DMFC) is categorized as yet another type of fuel cell; however, according to the previous categorization (based on electrolyte), it is essentially a polymer membrane fuel cell that uses methanol instead of hydrogen as a fuel [1].

Basic information about fuel cell systems is given in Table II.1:

Table II.1. Different types of fuel cell

Fuel Cell Type	Mobile Ion	Operating Temperature	Applications and notes
Alkaline (AFC)	OH^-	50-200 °C	Used in space vehicles, e.g. Apollo, Shuttle
Proton exchange membrane (PEM)	H^+	50-100 °C	Especially suitable for vehicles and mobile applications, but also for lower power CHP systems.
Phosphoric acid (PAFC)	H^+	220 °C	Large number of 200 kW CHP systems in use
Molten carbonate (MCFC)	CO_3^{-2}	650 °C	Suitable for medium to large scale CHP systems, up to MW capacity.
Solid oxide (SOFC)	O^{-2}	500 – 1000 °C	Suitable for all sizes of CHP systems, 2 kW to multi MW.

II.4. THE ADVANTAGES OF FUEL CELLS

The cost is the most important disadvantage of the fuel cells. However, there are many advantages. Fuel cells have many features that make them attractive when compared with the existing, conventional energy conversion technologies. Advantages of fuel cell are, namely [1]:

- **Promise of high efficiency** - Because the fuel cell efficiency is higher than the efficiency of conventional power plants and internal combustion engines. Therefore, fuel cells are attractive for decentralized power generation and automobile applications.
- **Promise of low or zero emissions** - Fuel cells operating on hydrogen generate zero emissions - the only exhaust is unused air/oxygen and water. This may be attractive not only for transportation but also for many indoor applications, as well as submarines. However, hydrogen is not a readily

available fuel, and if a fuel cell is equipped with a fuel processor to generate hydrogen, or if methanol is used instead of hydrogen, some emissions are generated, including carbon dioxide. In general, these emissions are lower than those of comparable conventional energy conversion technologies.

- **Issue of national security** - Fuel cells use hydrogen as fuel. Although hydrogen is not a readily available fuel it may be produced from indigenous sources, either by electrolysis of water or by reforming hydrocarbon fuels. Use of indigenous sources (renewable energy, nuclear, biomass, coal or natural gas) to generate hydrogen may significantly reduce dependence on foreign oil, which would have an impact on national security. However, widespread use of hydrogen would require establishing a hydrogen infrastructure or the so-called hydrogen economy.
- **Simplicity and promise of low cost** - Fuel cells are extremely simple. They are made in layers of repetitive components, and they have no moving parts. Because of this, they have the potential to be mass produced at a cost comparable to that of existing energy conversion technologies or even lower. To date, the fuel cells are still expensive for either automotive or stationary power generation, primarily because of use of expensive materials, such as sulfonated fluoropolymers used as proton exchanged membrane, and noble metals, such as platinum or ruthenium, used as catalysts.
- **No moving parts and promise of long life** - Because a fuel cell does not have any moving parts, it may be expected to exhibit a long life. Current fuel cell technology may reach the lifetime acceptable for automotive applications (3000-5000 hours), but their durability must be improved by an order of magnitude for use in stationary power generation (where the requirement is >40,000-80,000 hours).
- **Modular** - Fuel cells are by their nature modular. More power may be generated simply by adding more cells. Mass produced fuel cells may be significantly less expensive than traditional power plants. Instead of building big power plants, which must be planned well in advance, and whose permitting process may be extremely cumbersome, it may be cost-effective to gradually increase generation capacity by adding smaller fuel cells to the

grid. Such a concept of distributed generation may not only be cost-effective but also may significantly improve reliability of the power supply.

- **Quiet** - Fuel cells are inherently quiet, which may make them attractive for a variety of applications, such as portable power, backup power, and military applications.
- **Size and weight** - Fuel cells may be made in a variety of sizes-from microwatts to megawatts-which make them useful in a variety of applications, from powering electronic devices to powering entire buildings.

II.5. FUEL CELL APPLICATIONS

Because of their attractive properties, fuel cells have already been developed and demonstrated in the following applications:

- **Automobiles** - Almost every car manufacturer has already developed and demonstrated at least one prototype vehicle, and many have already gone through several generations of fuel cell vehicles. Some car manufacturers are working on their own fuel cell technology (General Motors, Toyota, Honda) and some buy fuel cell stacks and systems from fuel cell developers such as Ballard, United Technologies Corporation Fuel Cells, and DeNora (DaimlerChrysler, Ford, Nissan, Mazda, Hyundai, Fiat, Volkswagen) [1].
- **Scooters and bicycles** - Several companies (Palcan, Asian Pacific and Manhattan Scientific) have demonstrated fuel cell-powered scooters and bicycles [1].
- **Golf carts** - Energy Partners demonstrated a fuel cell-powered golf cart in 1994 (it was used in Olympic Village at the 1996 Olympic Games in Atlanta). Schatz Energy Center developed fuel cell-powered golf carts to be used in the city of Palm Desert in California [1].
- **Utility vehicles** - Energy Partners converted three John Deere Gator utility vehicles to fuel cell power and demonstrated them in service at Palm Springs airport (1996). John Deere is working with Hydrogenics Canada, on development of fuel cell-powered electric utility vehicles, including those for lawn maintenance [1].

- **Distributed power generation** - Several companies are working on development of small (1-10kW) fuel cell power systems intended to be used in homes. Some of them are combined with boilers to provide both electricity and heat (Plug Power with Vaillant and Ballard with Ebara) [1].
- **Backup power** - Ballard announced plans to commercialize 1 kW backup power generators in cooperation with Coleman (2000), but then bought back the technology and continued to sell the units (2002). Proton Energy Systems demonstrated regenerative fuel cells combining its own PEM electrolyzer technology with Ballard's Nexa units. A regenerative fuel cell generates its own hydrogen during periods when electricity is available [1].
- **Portable power** - Many companies (MTI, Motorola, NEC, Fuji, Matsushita, Medis, Manhattan Scientific, Polyfuel) are developing; miniature fuel cells as battery replacements for various consumer and military electronic devices. Because of fuel storage issues, most of them use methanol in either direct methanol fuel cells or through micro reformer in regular PEM fuel cells [1].
- **Space** - Fuel cells continue to be used in the U.S. Space Program, providing power on the space orbiters. Although this proven technology is of the alkaline type, NASA announced plans to use PEM fuel cells in the future [1].
- **Airplanes** - In November 2001 Boeing announced that it was modifying a small single-engine airplane by replacing its engine with fuel cells and an electric motor that would turn a conventional propeller. Test flights are scheduled to begin in early 2004, and are being conducted with the intention of using fuel cells as auxiliary power units on jet airliners in the future [1].
- **Locomotives** - Propulsion Research Institute started a consortium that demonstrated a fuel cell-powered locomotive for mining operations (the fuel cell was built by DeNora) [1].
- **Boats** - MTU Friedrichschaffen demonstrated a sailboat on lake Constanze (2004) powered by a 20kW fuel cell, developed jointly with Ballard [1].
- **Underwater vehicles** – In 1989 Perry Technologies successfully tested the first commercial fuel cell powered submarine, the two-person observation submersible PC-1401, using Ballard's fuel cell. Siemens has been successfully providing fuel cell engines for large submarines used by the German, Canadian, Italian, and Greek Navies [1].

III. POLYMER ELECTROLYTE MEMBRANE (PEM) FUEL CELLS

III.1. OPERATION PRINCIPLES OF PEM FUEL CELL AND ITS COMPONENTS

III.1.1. Operation principles of PEM Fuel Cell

PEM stands for polymer electrolyte membrane or proton exchange membrane. Sometimes, they are also called polymer membrane fuel cells, or just membrane fuel cells. In the early days (1960s) they were known as solid polymer electrolyte (SPE) fuel cells. This technology has drawn the most attention because of its simplicity, viability, quick startup, and the fact that it has been demonstrated in almost a conceivable application [1].

At the heart of a PEM fuel cell is a polymer membrane that has some unique capabilities. It is impermeable to gases but it conducts protons (hence the name, proton exchange membrane). The membrane that acts as the electrolyte is squeezed between the two porous, electrically conductive electrodes. These electrodes are typically made out of carbon doth or carbon fiber paper. At the interface between the porous electrode and the polymer membrane there is a layer with catalyst particles, typically platinum supported on carbon [1]. A schematic diagram of cell configuration and basic operating principles is shown in the Figure III.1.

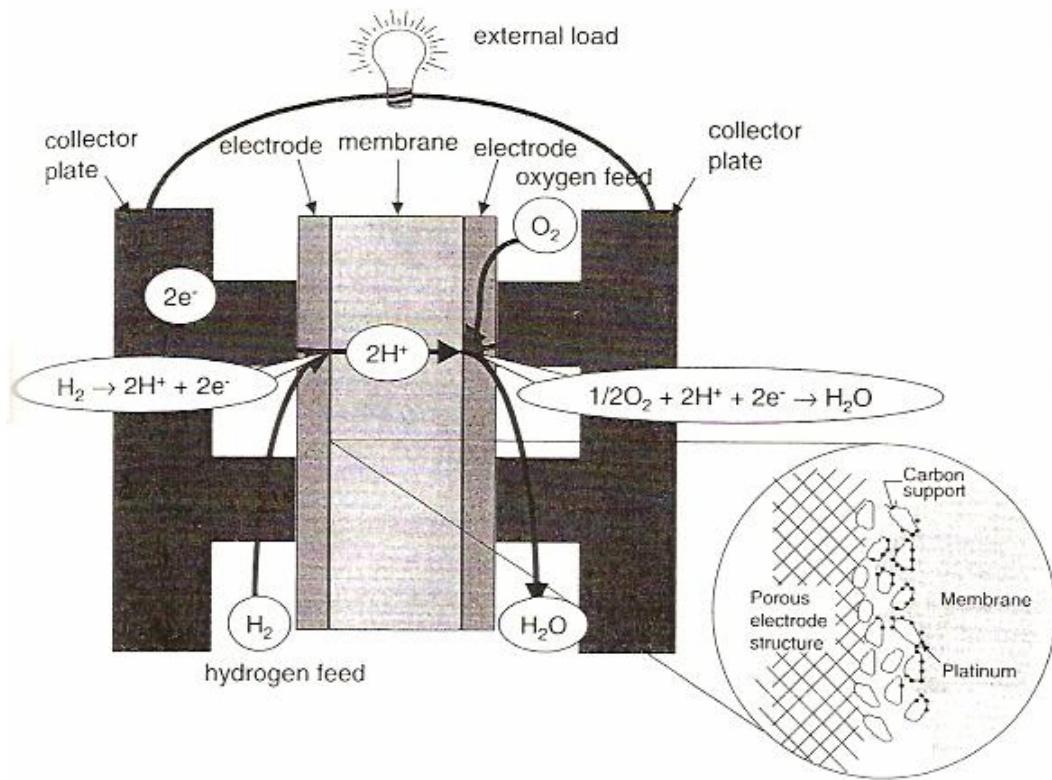


Figure III.1. The basic principle of operation of a PEM fuel cell

Electrochemical reactions happen at the surface of the catalyst at the interface between the electrolyte and the membrane. Hydrogen, which is fed on one side of the membrane, splits into its primary constituents—protons and electrons. Each hydrogen atom consists of one electron and one proton. Protons travel through the membrane, whereas the electrons travel through electrically conductive electrodes, through current collectors, and through the outside circuit where they perform useful work and come back to the other side of the membrane. At the catalyst sites between the membrane and the other electrode they meet with the protons that went through the membrane and oxygen that is fed on that side of the membrane. Water is created in the electrochemical reaction, and then pushed out of the cell with excess flow of oxygen. The net result of these simultaneous reactions is current of electrons through an external circuit—direct electrical current [1].

The hydrogen side is negative and it is called the anode, whereas the oxygen side of the fuel cell is positive and it is called the cathode. Each cell generates about 1 V, so more cells are needed in series to generate some practical voltages. According to application, the output voltage may be between 6 V and 200 V or even more. A fuel cell stack needs a supporting system [1]:

- Handle the supply of reactant gases and their exhaust, including the products;
- Take care of waste heat and maintain the stack temperature;
- Regulate and condition power output;
- Monitor the stack vital parameter; and
- Control the start-up, operation, and shutdown of the stack and system components.

Polymer electrolyte fuel cells have the ability to operate at very low temperatures. This is the main attraction of the PEM. Since they have the ability to deliver such high power densities at this temperature they can be made smaller which reduces overall weight, cost to produce and specific volume. Since the PEM has an immobilized electrolyte membrane there is simplification in the production process that in turn reduces corrosion and provides for longer stack life [10].

Working at low temperature of the polymer electrodes bring the further advantage that a PEMFC can start quickly. The thinness of the MEAs (membrane electrode assemblies) means that compact fuel cells can be made. There are no corrosive fluid hazards and they can work in any orientation. This means that the PEMFC is particularly suitable for use in vehicles and in portable applications [10].

III.1.2. Main Cell Components

III.1.2.1. Cell Description

The heart of a fuel cell is a polymer, proton-conductive membrane. On both sides of the membrane there is a porous electrode. The electrodes must be porous because the reactant gases are fed from the back and must reach the interface between the electrodes and membrane, where the electrochemical reactions take place in the so called catalyst layer, or more precisely, on the catalyst surface. Technically, the catalyst layer may be a part of the porous electrode or part of the membrane, depending on the manufacturing process. The multilayer assembly of the membrane sandwiched between the two electrodes is commonly called the membrane electrode assembly or MEA. The MEA is then sandwiched between the collector/separator plates--"collector" because they collect and conduct electrical current and "separator" because in multicell configuration they separate the gases in the adjacent cells. At the same time, in multicell configuration they physically/electrically connect the cathode

of one cell to the anode of the adjacent cell, and that is why they are called the bipolar plates. They provide the pathways for flow of reactant gases (so-called flow fields), and they also provide the cell structural rigidity [1].

The following processes take place inside the fuel cell (the numbers correspond to those in the Figure III.2):

- 1) Gas flow through the channels; some convective flows may be induced in the porous layers.
- 2) Gas diffusion through porous media.
- 3) Electrochemical reactions, including all the intermediary steps.
- 4) Proton transport through proton-conductive polymer membrane.
- 5) Electron conduction through electrically conductive cell components.
- 6) Water transport through polymer membrane including both electrochemical drag and back diffusion.
- 7) Water transport (both vapor and liquid) through porous catalyst layer and gas diffusion layers.
- 8) Two-phase flow of unused gas carrying water droplets.
- 9) Heat transfer, including both conduction through solid components of the cell and convection to reactant gases and cooling medium.

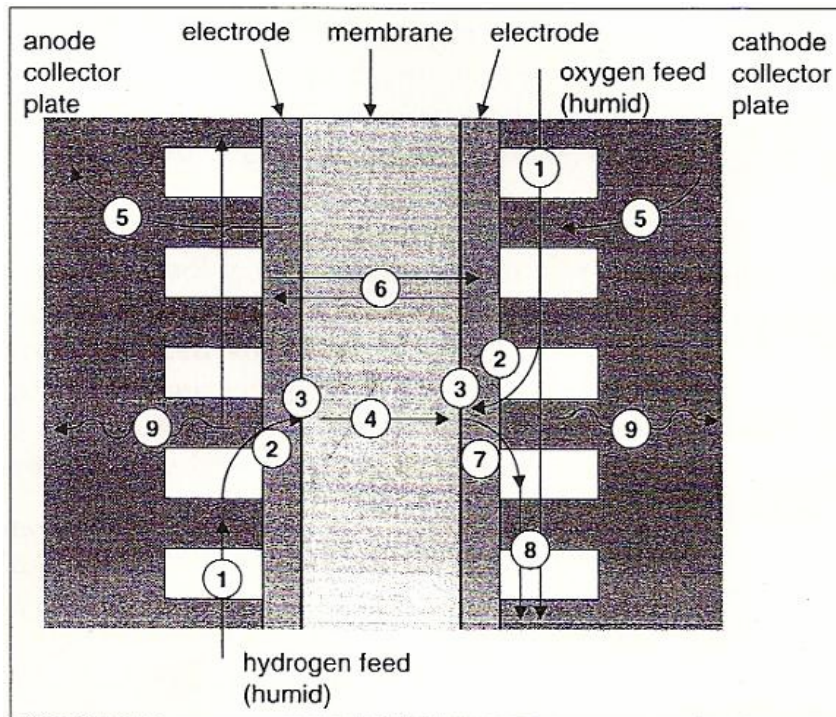


Figure III.2. Main cell components and processes

Obviously, the design of the components and properties of materials must accommodate the above-listed processes with minimum obstruction and losses. Because in some of the components more than one process takes place, very often with conflicting requirements, the properties and the design must be optimized. For example, the gas diffusion layer must be optimized so that the reactant gas may easily diffuse, yet at the same time that water, which travels in the opposite direction, does not accumulate in the pores. On top of that, the diffusion layer (or current collector layer as it is sometimes called) must be both electrically and thermally conductive. Similar requirements may be established for almost every fuel cell component. Although a fuel cell seems to be a very simple device, numerous processes take place simultaneously. It is therefore important to understand those processes, their mutual interdependence, and their dependence on components design and materials properties [1].

III.1.2.2. Membrane

A fuel cell membrane must exhibit relatively high proton conductivity, must present an adequate barrier to mixing of fuel and reactant gases, and must be chemically and mechanically stable in the fuel cell environment. Typically, the membranes for PEM fuel cells are made of perfluorocarbon-sulfonic acid ionomer (PSA). This is essentially a copolymer of tetrafluorethylene (TFE) and various perfluorosulfonate monomers. The best-known membrane material is Nafion made by DuPont, which uses perfluoro-sulfonylfluoride ethyl-propyl-vinyl ether (PSEPVE). The Figure III.3 shows the chemical structure of perfluorosulfonate ionomer such as Nafion. W.L. Gore and Associates have developed a composite membrane made up of a Teflon-like component providing mechanical strength and dimensional stability and a perfluorosulfonic acid component providing protonic conductivity [1].

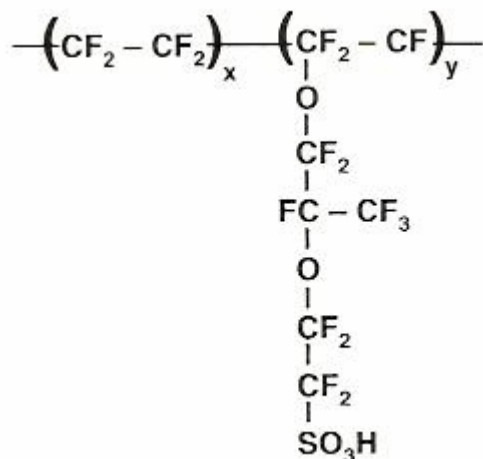


Figure III.3. Structure of PFSA polymer

The SO_3H group is ionically bonded, and so the ends of the side chain - actually an SO_3^- ion with H^+ ion. This is why such structure is called ionomer. Because of their ionic nature, the ends of the side chains tend to cluster within the overall structure of the membrane. Although the Teflon-like backbone is highly hydrophobic, the sulphonic acid at the end of the side chain is highly hydrophilic. The hydrophilic regions are created around the dusters of sulphonated side chains. This is why this kind of material absorbs relatively large amounts of water (in some cases up to 50% by weight). H^+ ions movement within well-hydrated regions makes these materials proton conductive [1].

III.1.2.3. Electrode

A fuel cell electrode is essentially a thin catalyst layer pressed between the ionomer membrane and porous, electrically conductive substrate. It is the layer where the electrochemical reactions take place. More precisely, the electrochemical reactions take place on the catalyst surface. Because there are three kinds of species that participate in the electrochemical reactions, namely gases, electrons and protons, the reactions can take place on a portion of the catalyst surface where all three species have access. Electrons travel through electrically conductive solids, including the catalyst itself, but it is important that the catalyst particles are somehow electrically connected to the substrate. Protons travel through ionomer; therefore the catalyst must be in intimate contact with the ionomer. And finally, the reactant gases travel only through voids; therefore the electrode must be porous to allow gases to travel to

the reaction sites. At the same time, product water must be effectively removed; otherwise the electrode would flood and prevent oxygen access [1].

The most common catalyst in PEM fuel cells for both oxygen reduction and hydrogen oxidation reactions is platinum. In the early days - PEMFC development large amounts of Pt catalyst were used (up to 28 mg cm^{-2}). In the late 1990s, with the use of supported catalyst structure, this was reduced to $0.3\text{-}0.4 \text{ mg cm}^{-2}$. It is the catalyst surface area that matters, not the weight, so it is important to have small platinum particles (4nm or smaller) with large surface area finely dispersed on the surface of catalyst support, typically carbon powders with high porous area .

To minimize the cell potential losses due to the rate of proton transport and reactant gas permeation in the depth of the electro catalyst layer, this layer should be made reasonably thin. At the same time, the metal active surface area should be maximized, for which the Pt particles should be as small as possible [1].

III.1.2.4. Gas Diffusion Layer

A layer between the catalyst layer and bipolar plates is called a gas diffusion layer, electrode substrate, or diffuser/current collector. Although it does not directly participate in the electrochemical reactions, a gas diffusion layer in PEM fuel cells has several important functions [1]:

- It provides a pathway for reactant gases from the flow field channels to the catalyst layer, allowing them access to the entire active area (not just to those adjacent to the channels).
- It provides a pathway for product water from the catalyst layer to the flow field channels.
- It electrically connects the catalyst layer to the bipolar plate, allowing the electrons to complete the electrical circuit.
- It also serves to conduct heat generated in the electrochemical reactions in the catalyst layer to the bipolar plate, which has means for heat removal.
- It provides mechanical support to the MEA, preventing it from sagging into the flow field channels.

The required properties of the gas diffusion layer follow from its functions:

- It must be sufficiently porous to allow flow of both reactant gases and product water. Depending on the design of the flow field, diffusion in both through-plane and in-plane is important.
- It must be both electrically and thermally conductive, again in both through-plane and in-plane. Interfacial or contact resistance is typically more important than bulk conductivity.
- Because the catalyst layer is made of discrete small particles, the pores of the gas diffusion layer facing the catalyst layer must not be too big.
- It must be sufficiently rigid to support the "flimsy" MEA. However, it must have some flexibility to maintain good electrical contacts.

These somewhat conflicting requirements are best met by carbon fiber-based materials such as carbon fiber papers and woven carbon fabrics or cloths.

III.1.2.5. Bipolar Plates

In a single-cell configuration, there are no bipolar plates. The two plates on each side of the membrane electrode assembly may be considered as two halves of a bipolar plate. The fully functioning bipolar plates are essential for multicell configurations (as shown in the Figure 16), by electrically connecting the anode of one cell to the cathode of the adjacent cell.

The bipolar collector/seperator plates have several functions in a fuel cell stack. Their required properties follow from their functions, namely:

- They connect cells electrically in series-therefore, they must be electrically conductive.
- They separate the gases in adjacent cells-therefore, they must be impermeable to gases.
- They provide structural support for the stack-therefore, they must have adequate strength, yet they must be lightweight.
- They conduct heat from active cells to the cooling cells or conduits-therefore, they must be thermally conductive.
- They typically house the flow field channels-therefore, they must be conformable.

III.1.3. Fuel Requirements

The PEM fuel cells run on hydrogen. The sources of hydrogen are vast, being the most abundant element in the universe, despite this abundance it does not appear naturally in a useful form. About half of the world's hydrogen supply, is produced through the steam reforming of natural gas. For residential and commercial applications, natural gas is a logical fuel choice because its distribution is widely developed to date use natural gas as a fuel. Propane may be an alternative fuel for those users that are not connected to the natural gas supply line. Fuel processing of propane and natural gas is similar and usually can be accomplished with the same fuel processing catalysts and hardware. For some applications liquid fuels may be preferable such as fuel oil, gasoline, diesel, methanol, or ethanol. All of these fuels also require fuel processing.

III.1.3.1. Technologies of Hydrogen Production

Production of hydrogen requires feedstock (logical sources being hydrocarbon fuels and water) and energy. The amount of energy required to produce hydrogen is always greater than the energy that can be released by hydrogen utilization.

Presently, hydrogen is mostly being produced from fossil fuels (natural gas, oil, and coal). Hydrogen is used in refineries to upgrade crude oil (hydro treating and hydro cracking), in the chemical industry to synthesize various chemical compounds (such as ammonia, methanol), and in metallurgical processes (as a reduction or protection gas).

Technologies for hydrogen production from fossil fuels have been developed and are used to produce industrial hydrogen. These include steam reforming of natural gas, partial oxidation of hydrocarbons, and coal gasification. Depending on the cost of fuel, hydrogen can be produced for \$6 to \$14 per GJ [6]. However, as mentioned earlier, these technologies will not help reduce dependency on fossil fuels and will not reduce CO₂ generation. The only method that can generate hydrogen from fossil fuels without generation of CO₂ is direct thermal (and catalytic) cracking of hydrocarbons.

Water electrolysis is a mature technology and was developed for hydrogen production capacities ranging from a few cm^3/min to thousands m^3/hr . It is relatively efficient ($>70\%$), but because it needs high-quality energy (electricity), hydrogen produced by water electrolysis is expensive ($>\$20/\text{GJ}$). There is also potential to generate relatively inexpensive hydrogen from hydropower and nuclear plants during off-peak hours.

Water electrolysis is particularly suitable for use in conjunction with photovoltaic (PVs). In general, there is a good match between the polarization curves of PVs and electrolyzers, and experience from a handful of PV/electrolysis pilot plants shows that they can be matched directly (with no power-tracking electronics) with relatively high efficiency ($>93\%$ coupling efficiency) [7]. Electricity produced from photovoltaic is expensive and hydrogen produced from such electricity is even more expensive.

Many other methods for hydrogen production, suitable for coupling with solar or other renewable energy technologies, have been investigated and developed to at least a pilot demonstration stage. These include direct heat method, thermo chemical method and photolytic method. Unfortunately, all of these processes have severe technical difficulties, many of them have been abandoned, and all of them are far from industrial use.

III.2. FUEL CELL BASIC CHEMISTRY AND THERMODYNAMICS

A fuel cell is an electrochemical energy converter. It converts chemical energy of fuel, typically hydrogen, directly into electrical energy. As such, it must obey the laws of thermodynamics.

III.2.1. Basic Reactions

The electrochemical reactions in fuel cells happen simultaneously on both sides of the membrane – the anode and the cathode. The basic fuel cell reactions are:

At the anode:



At the cathode:



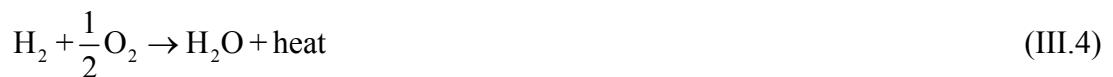
Overall:



These reactions may have several intermediate steps, and there may be some (unwanted) side reactions, but for now these reactions accurately describe the main processes in a fuel cell.

III.2.2. Heat of Reaction

The overall reaction is the same as the reaction of hydrogen combustion. Combustion is an exothermic process, which means that there is energy released in the process:



The heat (or enthalpy) of a chemical reaction is the difference between the heat of formation of products and reactants. For the previous equation this means:

$$\Delta H = (h_f)_{\text{H}_2\text{O}} - (h_f)_{\text{H}_2} - \frac{1}{2}(h_f)_{\text{O}_2} \quad (\text{III.5})$$

Heat of formation of liquid water is -286 kJ mol^{-1} (at 25°C) and heat of formation of elements is by definition equal to zero. Therefore:

$$\Delta H = (h_f)_{\text{H}_2\text{O}} - (h_f)_{\text{H}_2} - \frac{1}{2}(h_f)_{\text{O}_2} = -286 \text{ kJ mol}^{-1} - 0 - 0 = -286 \text{ kJ mol}^{-1} \quad (\text{III.6})$$

Note that the negative sign for enthalpy of a chemical reaction, by convention, means that heat is being released in the reaction, that is, this is an exothermic reaction. Equation III.4 may now be written as:



This equation is valid at 25⁰C only, meaning that both the reactant gases and the product water are at 25⁰C. At 25⁰C, and atmosphere pressure, water is in liquid form.

III.2.3. Nernst Equation for Reversible Fuel Cell Voltage

The reversible voltage of the cell (E_{Nernst}) is the potential of the cell obtained in open circuit thermodynamic balance. The equation takes into account the pressure of oxidant and hydrogen and the concentration of the reactants, which affect the Gibbs free energy [3].

The Nernst equation is derived using the concept of Gibbs free energy. This can be defined as the energy available to do external work, neglecting any work done by changes in pressure and/or volume. In the fuel cell the external work involves moving electrons around an external circuit. Every chemical reaction proceeds in the direction to minimize the Gibbs free energy and it is negative at equilibrium. The definition of the Gibbs's free energy is the enthalpy minus the energy connected with entropy and given by following equation [3]:

$$G = H - T\Delta S \quad (\text{III.8})$$

From the above equation, it is evident that the Gibbs free energy is not constant, but changes with temperature and state (liquid or gas). The maximum energy, that a fuel cell produces, is equal to the change in Gibbs free energy. The released energy performs the useful work by the fuel cell. The change is the difference between the Gibbs free energy of the products and the Gibbs free energy of the reactants and is given by (for a per mole) [3]:

$$\Delta(g_f) = (g_f)_{\text{products}} - (g_f)_{\text{reactants}} \quad (\text{III.9})$$

Using equation III.4, we obtain the change in the Gibbs free energy is given by:

$$\Delta(g_f) = (g_f)_{\text{H}_2\text{O}} - (g_f)_{\text{H}_2} - 1/2(g_f)_{\text{O}_2} \quad (\text{III.10})$$

Equation 3.5 assumes that the chemical reaction in the fuel cell is reversible, then all of the Gibbs free energy is converted into electrical energy. We will use this to find the reversible open circuit voltage of a fuel cell.

For the hydrogen fuel cell, two electrons pass around the external circuit for using each hydrogen molecule and producing each water molecule. Therefore, for one mole of hydrogen using $2N$ electrons pass around the external circuit (N is Avogadro's number). If e is the charge on one electron, then the charge is,

$$-2Ne = -2F \quad (\text{III.11})$$

where:

N = number of molecules per mole (Avogadro's number)

e = charge of 1 electron

F = Faraday's constant, 96485 Coulombs/electron-mol

If E is the voltage of the fuel cell, then the electrical work done moving this charge around the circuit is:

$$\text{Electrical work done} = -2FE \quad (\text{III.12})$$

If the system is reversible then this electrical work done will be equal to the Gibbs free energy released, ΔG . Hence:

$$\text{Electrical work done} = -\Delta G \quad (\text{III.13})$$

and thus:

$$E = \frac{-\Delta G}{2F} \quad (\text{III.14})$$

Because ΔG and F are known, the theoretical fuel cell potential of hydrogen/oxygen can also be calculated:

$$E = \frac{-\Delta G}{2F} = \frac{237340 \text{ Jmol}^{-1}}{2 \times 96485 \text{ Asmol}^{-1}} = 1.23 \text{ Volts} \quad (\text{III.15})$$

At 25°C , the theoretical hydrogen/oxygen fuel cell potential is 1.23 Volts. This equation gives the reversible open circuit voltage of the hydrogen fuel cell.

For a fixed volume, isothermal and reversible process, the differential of the Gibbs free energy is given by:

$$dG = v_m dP \quad (\text{III.16})$$

where

v_m = molar volume, $\text{m}^3\text{mol}^{-1}$

P = pressure, Pa

Since for an ideal gas:

$$Pv_m = RT \quad (\text{III.17})$$

where,

R = universal gas constant, 8.314 kJ/kmol-K

Therefore:

$$dG = RT \frac{dP}{P} \quad (\text{III.18})$$

After integration:

$$G=G_0+RT\ln\left(\frac{P}{P_0}\right) \quad (\text{III.19})$$

Where G_0 is Gibbs free energy at standard temperature and pressure (25°C and 1 atm), and P_0 is the reference or standard pressure (1 atm).

For any chemical reaction:



The change in Gibbs free energy is the change between products and reactants:

$$\Delta G=mG_C+nG_D-jG_A-kG_B \quad (\text{III.21})$$

After substituting into equation (III.19):

$$\Delta G=\Delta G_0+RT\ln\left(\frac{\left(\frac{P_C}{P_0}\right)^m\left(\frac{P_D}{P_0}\right)^n}{\left(\frac{P_A}{P_0}\right)^j\left(\frac{P_B}{P_0}\right)^k}\right) \quad (\text{III.22})$$

This is known as the Nernst equation, where P is the partial pressure of the reactant or product species and P_0 is the reference pressure.

For the hydrogen/oxygen fuel cell reaction, the Nernst equation becomes:

$$\Delta G=\Delta G_0+RT\ln\left(\frac{P_{H_2O}}{P_{H_2}P_{O_2}^{0.5}}\right) \quad (\text{III.23})$$

Putting equation (III.23) into equation (III.8).

$$E=E_0+\frac{RT}{2F}\ln\left(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}}\right) \quad (\text{III.24})$$

Note that the previous equations are only valid for gaseous products and reactants. When liquid water is produced in a fuel cell, $P_{\text{H}_2\text{O}}=1$.

We can rewrite the Nernst equation as:

$$E = -\left(\frac{\Delta H}{2F} - \frac{T\Delta S}{2F}\right) + \frac{RT}{2F} \ln\left(\frac{P_{\text{H}_2} P_{\text{O}_2}^{0.5}}{P_{\text{H}_2\text{O}}}\right) \quad (\text{III.25})$$

For liquid water, $P_{\text{H}_2\text{O}}=1$.

III.3. FUEL CELL OUTPUT VOLTAGE AND ASSOCIATED LOSSES

If a fuel cell is supplied with reactant gases, but the electrical circuit is not closed (Figure III.4a), it will not generate any current, and one would expect the cell potential to be at, or at least close to, the theoretical cell potential for given conditions (temperature, pressure, and concentration of reactants). However, in practice this potential, called the open circuit potential, is significantly lower than the theoretical potential, usually less than 1 V. This suggests that there are some losses in the fuel cell even when no external current is generated. When the electrical circuit is closed with a load (such resistor) in it, as shown in the Figure III.4b, the potential is expected to drop even further as a function of current being generated, due to unavoidable losses. There are different kinds of voltage losses in a fuel cell caused by the following factors:

- kinetics of the electrochemical reactions
- internal electrical and ionic resistance
- difficulties in getting the reactants to reaction sites
- internal (stray) currents
- crossover of reactants

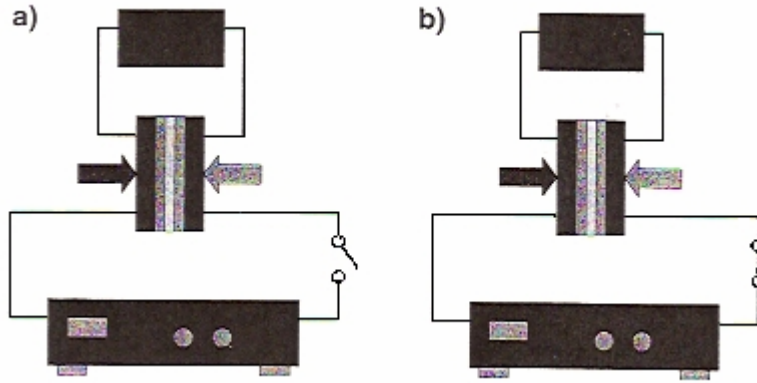


Figure III.4. Fuel cell with a load a) in open circuit; b) load connected.

PEM fuel cell characteristics are generally described with polarization curves. The thermodynamic equilibrium potential of the hydrogen/oxygen reaction is reduced by various overvoltage terms that depend on mass transport, kinetic, and ohmic phenomena within cell. In other words, the output voltage of a single cell is attributable to different current, temperature, and pressure dependant factors [1].

III.3.1. Activation Losses

III.3.1.1. The Tafel Equation

The electrochemical reaction which occurs at the interface of electrolyte and electrode causes a transfer of electrons through the load and protons through the electrolyte. In moving this charge, a barrier has to be overcome and the strength of this barrier determines the rate of the reaction. The electrochemical reactions that occur at the interface are standard reduction and oxidation processes [2].

In equilibrium, the standard reduction and oxidation processes occur at equal rates and the exchange currents produced by the two reactions balance each other. The current density, i A/cm², is given by Butler-Volmer equation [3]:

$$i = i_0 \left[\exp\left(-\frac{2\alpha F V_{Act}}{RT}\right) - \exp\left(\frac{2(1-\alpha) F V_{Act}}{RT}\right) \right] \quad (III.26)$$

where,

$$i_0 = \text{exchange current density, A/cm}^2$$

α = charge transfer coefficient

V_{act} = activation losses, V

The exchange current density i_0 is dependent on temperature and the concentrations of the oxidizing and reducing factors. The exchange current density can be considered as the current density at which the voltage losses begin to move from zero. It is vital to make its value as high as possible. α is called the charge transfer coefficient. Its value depends on the reaction and the material of the electrode. Both oxidation and reduction reactions occur on an electrode even if one direction is dominant. At equilibrium, when both rates are equal, electrons are produced and consumed at the same rate [2].

A simplified way to show the activation losses is to use the so-called Tafel equation:

$$V_{act} = a + b \log(i) \quad (III.27)$$

where

$$a = -2.3 \frac{RT}{\alpha F} \log(i_0) \quad (III.28)$$

$$b = 2.3 \frac{RT}{\alpha F} \quad (III.29)$$

Term b is called the Tafel slope. The constant b is higher for an electrochemical reaction which is slow. The constant i_0 is higher if the reaction is faster and the smaller i_0 the greater voltage loss in activation loss. Raising the temperature increases the overvoltage. In low and medium temperature, activation loss is the most important irreversibility and cause to voltage drop. At higher temperatures and pressures the activation loss becomes less important [10].

III.3.2. Internal Currents and Crossover Losses

Although the electrolyte, a polymer membrane, is not electrically conductive and is practically impermeable to reactant gases, some small amount of hydrogen will diffuse from anode to cathode, and some electrons may also find a "shortcut" through

the membranes. Because each hydrogen molecule contains two electrons, this fuel crossover and the so-called internal currents are essentially equivalent. Each hydrogen molecule that diffuses through the polymer electrolyte membrane and reacts with oxygen on the cathode side of the fuel cell results in two fewer electrons in the generated current of electrons that travels through an external circuit. These losses may appear insignificant in fuel cell operation, because the rate of hydrogen permeation or electron crossover is several orders of magnitude lower than hydrogen consumption rate or total electrical current generated. However, when the fuel cell is at open circuit potential or when it operates at very low current densities, these losses may have a dramatic effect on cell potential [1].

The total electrical current is the sum of external (useful) current and current losses due to fuel crossover and internal currents:

$$I = I_{\text{ext}} + I_{\text{loss}} \quad (\text{III.30})$$

Current divided by the electrode active area, A , is current density, A/cm^2 :

$$i = \frac{I}{A} \quad (\text{III.31})$$

Therefore:

$$i = i_{\text{ext}} + i_{\text{loss}} \quad (\text{III.32})$$

If this total current density is used in the equation that approximates the cell potential, the following equation results:

$$E_{\text{cell}} = E_{\text{Nernst}} - \frac{RT}{\alpha F} \ln \left(\frac{i_{\text{ext}} + i_{\text{loss}}}{i_0} \right) \quad (\text{III.33})$$

Therefore, even if the external current is equal to zero, such as at open circuit, the cell voltage may be significantly lower than the reversible cell potential for given

conditions. Indeed, open circuit potential of hydrogen/air fuel cells is typically below 1 V, most likely about 0.94 to 0.97 V (depending on operating pressure) [1].

$$E_{\text{cell,OCV}} = E_{\text{Nernst}} - \frac{RT}{\alpha F} \ln \left(\frac{i_{\text{loss}}}{i_0} \right) \quad (\text{III.34})$$

Although hydrogen crossover and internal currents are equivalent, they physically have different effects in a fuel cell. The loss of electrons occurs after the electrochemical reaction has taken place and therefore the effect on both anode and cathode activation polarization would have the effect as depicted by Equation (III.33). Hydrogen that permeates through the membrane does not participate in the electrochemical reaction on the anode side, and in that case the total current resulting from the electrochemical reaction would be the same as the external current. However, hydrogen that permeates through the membrane to the cathode side may react with oxygen on the surface of the catalyst in reaction $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$, and as a result would "depolarize" the cathode, that is, reduce the cathode (and cell) potential. Equations (III.33) and (III.34) are therefore only an approximation. As the fuel cell starts generating current, hydrogen concentration in the catalyst layer decreases, which reduces the driving force for hydrogen permeation through the membrane. That is one of the reasons these losses are mainly negligible at operating currents [1].

III.3.3. Ohmic Losses

Ohmic losses occur because of resistance to the flow of ions in the electrolyte and resistance to the flow of electrons through the electrically conductive fuel cell components. These losses can be expressed by Ohm's law:

$$V_{\text{ohm}} = iR_i \quad (\text{III.35})$$

where:

i = current density, Acm^{-2} , and

R_i = total internal resistance (Ωcm^2)

Typical values for R_i are between 0.1 and 0.2 Ωcm^2 .

In most fuel cells the resistance is mainly caused by the electrolyte and the cell interconnections or bipolar plates can be also important. The resistance decreases with the decrease in thickness of the electrolyte [10].

There are three ways to reduce the internal resistance of the fuel cell:

1. The use of electrodes with the highest possible conductivity.
2. Good design and use appropriate materials for bipolar plates or cell interconnections.
3. Making the electrolyte as thin as possible.

III.3.4. Concentration Losses

Concentration losses, is also defined by mass transport losses, occur when a reactant is rapidly consumed at the electrode by the electrochemical reaction so that concentration gradients are established [1]. This concentration change causes a small reduction in the partial pressures and it affects the open circuit voltage drop of the fuel cell. Resulting of these losses, hydrogen is supplied from a reformer [10].

The reactant concentration at the catalyst surface thus depends on current density – the higher the current density, the lower the surface concentration. The surface concentration reaches zero when the rate of consumption exceeds the diffusion rate – the rate is consumed faster than it can reach the surface. Current density at which this happens is called the limiting current density (i_L). A fuel cell cannot produce more than the limiting current because there are no reactants at the catalyst surface [1].

Concentration losses are described by the following equation:

$$V_{\text{conc}} = \frac{RT}{2F} \ln \left(\frac{i_L}{i_L - i} \right) \quad (\text{III.36})$$

III.3.5. Fuel Cell Output Voltage

The output voltage of the fuel cell is obtained by adding all the losses, which are activation, ohmic and mass transport, to the Nernst Equation, which is reversible open circuit voltage.

The Figure III.5 shows the proportions between the three types of losses in the fuel cell. Activation losses are by far the largest losses at any current density.

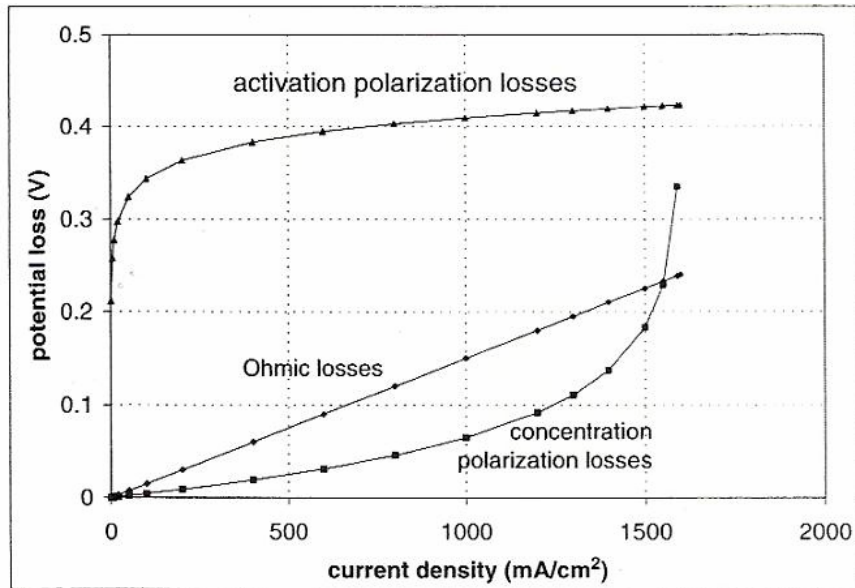


Figure III.5. Voltage losses in the fuel cell

A sufficiently accurate approximation of the fuel cell polarization curve may be obtained by the following equation:

$$E_{\text{cell}} = E_r - \frac{RT}{\alpha F} \ln \left(\frac{i}{i_0} \right) - iR_i - \frac{RT}{2F} \ln \left(\frac{i_L}{i_L - i} \right) \quad (\text{III.37})$$

III.4. POLARIZATION CURVE AND ITS SENSITIVITY TO OPERATION PARAMETERS

III.4.1. Polarization Curve

A polarization curve is the most important characteristic of a fuel cell and its performance.

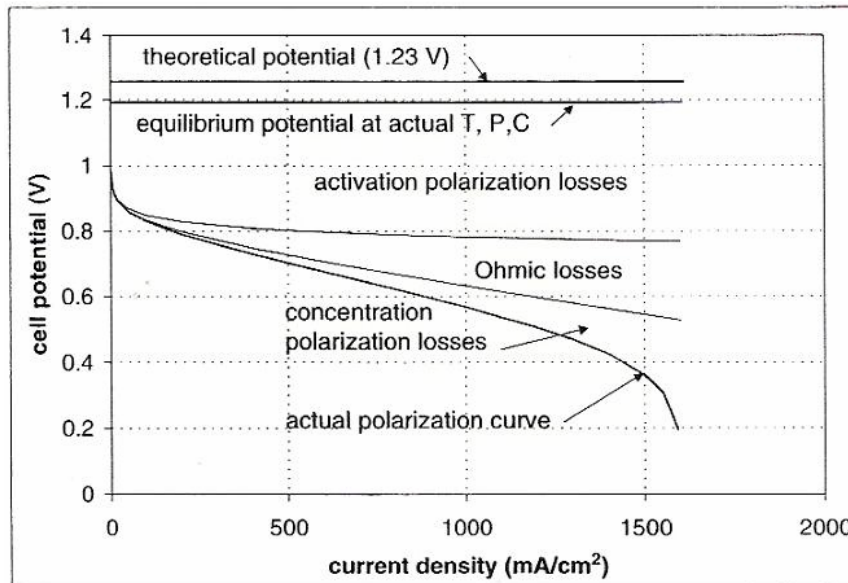


Figure III.6. Voltage losses in fuel cell and resulting polarization curve

It would be useful to see what effect each of the parameters has on the polarization curve shape.

III.4.1.1. Effect of Transfer Coefficient / Tafel Slope

The transfer coefficient, α , has strong effect on fuel cell performance. Although its typical value is about 1.

Transfer coefficient is the determining factor for the Tafel slope. The Tafel slope is a parameter in the equation (III.29) defined as:

$$b = 2.3 \frac{RT}{\alpha F}$$

With the previous numerical values the Tafel slope is 0.066 V /decade, which is a typical value for hydrogen/oxygen fuel cells. For $\alpha=0.5$ and $\alpha=1.5$ the Tafel slope is 0.132 and 0.44 V/decade. Higher Tafel slopes result in lower performance [1].

III.4.1.2. Effect of Exchange Current Density

For each order of magnitude higher exchange current density, the entire curve is shifted up approximately by the value of b , that is, Tafel slope [1].

III.4.1.3. Effect of Internal Resistance

Resistive or Ohmic losses are directly proportional to current density. The departure from the baseline becomes noticeable as the current density increases [1].

III.4.1.4. Effect of Limiting Current Density

Limiting current density only has an effect at very high current densities approaching the limiting current density. At low current densities there is almost no effect, that is, the three polarization curves for three different limiting currents fall on top of each other [1].

III.4.1.5. Effect of Operating Pressure

An increase in cell operating pressure results in higher cell potential due to:

- a) The Nernst equation, equation (III.24).
- b) An increase in exchange current density due to increased concentration of reactant gases in the electrode(s). Exchange current density is proportional to surface concentration which in turn is directly proportional to pressure [1].

III.4.1.6. Effect of Operating Temperature

Fuel cell performance usually improves with elevated temperature, although this cannot be predicted simply by the equations describing the polarization curve derived previously. Increased temperature results in potential loss due to $T\Delta S/nF$. It also results in higher Tafel slope, which in turn results in potential loss. However, increased temperature results in exponentially higher exchange current density and significantly improves mass transport properties. The Figure III.7 shows the results of an experiment in which the cell temperature gradually increased from -10°C to 60°C , and the resulting polarization curves clearly indicate voltage gain with increased temperature [13].

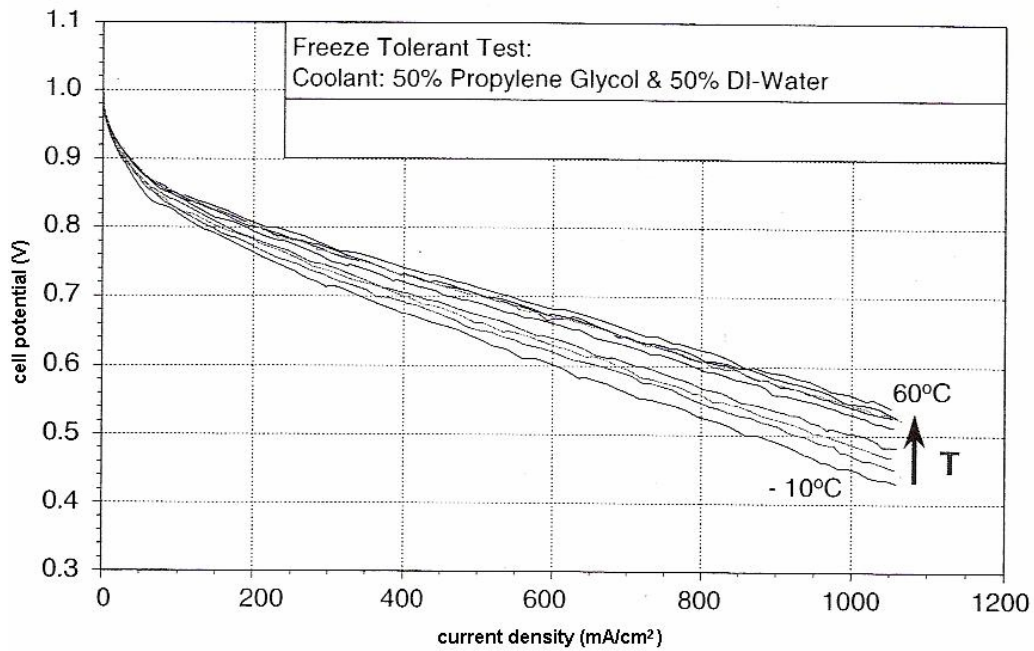


Figure III.7. Effect of operating temperature on fuel cell polarization curve [13].

III.4.1.7. Air vs. Oxygen

A similar effect may be expected if pure oxygen is used instead of air. Because oxygen concentration in air is only 21 %, operation with pure oxygen results in a gain similar to elevating the air pressure by a factor of $\frac{1}{0.21}$ [1].

III.5. FUEL CELL EFFICIENCY

The fuel cell efficiency is defined as a ratio between the electricity produced and hydrogen consumed. Of course, both must be in same units, such as Watts or kilowatts.

$$\eta = \frac{W}{W_{H_2}} \quad (III.38)$$

Electricity produced is simply a product between voltage and current.

$$W = IV \quad (III.39)$$

where I is the current in Amperes and V is the cell potential in Volts. Hydrogen consumed is (according to Faraday's Law) directly proportional to current:

$$N_{H_2} = \frac{I}{2F} \quad (\text{III.40})$$

where N_{H_2} is in mol s^{-1} , and

$$W_{H_2} = \Delta H \frac{I}{2F} \quad (\text{III.41})$$

where:

W_{H_2} = energy value of hydrogen consumed in Joules per second (Watts),
 ΔH = hydrogen's higher heating value (286 kJ mol^{-1}).

It should be noted that $\Delta H/2F$ has dimension of Volts, and for $\Delta H = 286 \text{ kJ/mol}$ it has a value of 1.482 V , which is the so-called thermo neutral potential.

By combining Equations (III.38) through (III.41), the fuel cell efficiency is simply directly proportional to cell potential:

$$\eta = \frac{V}{1.482} \quad (\text{III.42})$$

Sometimes, instead of hydrogen's higher heating value (HHV), $\Delta H = 286 \text{ kJ/mol}$, the lower heating value (LHV) is used ($\Delta H_{LHV} = 241 \text{ kJ/mol}$). The difference between the higher and lower heating value is the heat of product water condensation. Because the product water may leave the fuel cell in either form, that is, as liquid or as vapor, both values are correct; however, the type of heating value used to calculate the efficiency must be specified.

The lower heating value efficiency is:

$$\eta_{LHV} = \frac{V}{1.254} \quad (\text{III.43})$$

If hydrogen is supplied to the cell in excess of that required for the reaction stoichiometry, this excess will leave the fuel cell unused. In case of pure hydrogen, this excess may be recirculated back into the stack so it does not change the fuel cell efficiency (not accounting for the power needed for hydrogen recirculation pump) but if hydrogen is not pure (such as in reformat gas feed) unused hydrogen leaves the fuel cell and does not participate in the electrochemical reaction. The fuel cell efficiency is then:

$$\eta = \frac{V}{1.482} UF \quad (\text{III.44})$$

where UF is utilization factor, which is equal to $1/S_{H_2}$, where S_{H_2} is the hydrogen stoichiometric ratio, that is, the ratio between the amount of hydrogen actually supplied to the fuel cell and that consumed in the electrochemical reaction:

$$S_{H_2} = \frac{N_{H_2, \text{actual}}}{N_{H_2, \text{theoretical}}} = \frac{2F}{I} N_{H_2, \text{actual}} \quad (\text{III.45})$$

Well-designed fuel cells may operate with 83 % to 85 % utilization factor when operated with reformat, and above 90% when operated with pure hydrogen [1].

III.5.1. Effect of Fuel Cell Operating Conditions

III.5.1.1. Operating Pressure

A fuel cell may be operated at ambient pressure or it may be pressurized. As we have already learned, a fuel cell gains some potential when the pressure is increased, but the net gain, when the compression power is taken into account, is at least questionable. The issue of pressurization is also related to the issue of water management, and therefore must be addressed from a system perspective.

When a fuel cell is fed the reactant gases from a pressurized tank, its pressure is controlled by a backpressure regulator placed at the outlet (Figure III.8a). This pressure regulator keeps the desired, preset pressure at fuel cell outlet. Very often, in laboratory settings, the inlet pressure is not even recorded. The inlet pressure is

always higher because of inevitable pressure drop in tiny channels inside the fuel cell. However, when the reactant gas (for example, air) is fed to a fuel cell by a mechanical device, a blower or a compressor, which is the case in any practical system, it is the inlet pressure that matters (Figure III.8b). The compressor or the blower must be capable of delivering the required flow rate at desired pressure. The backpressure regulator is used; the gas leaves the cell at atmospheric pressure [1].

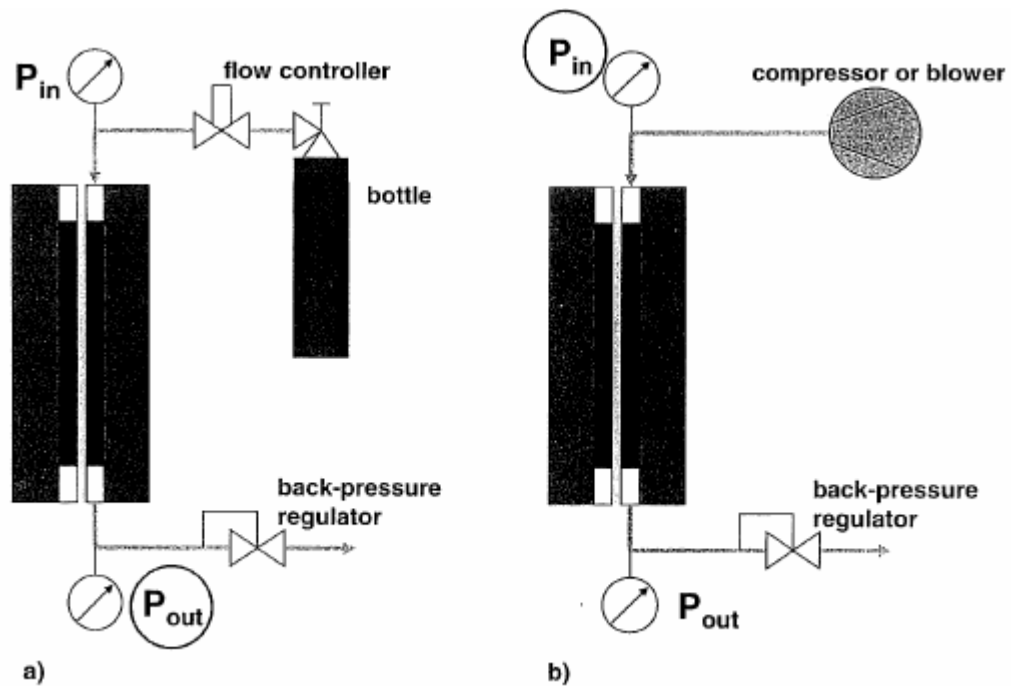


Figure III.8. Fuel cell operating pressure as a function of reactant gas supply; a) supply from a high pressure tank, b) supply by a mechanical device, a compressor or blower

III.5.1.2. Operating Temperature

The cell temperature is another operating parameter that may be selected and preset. In general, a higher operating temperature results in higher cell potential; however, for each fuel cell design there is an optimal temperature. A PEM fuel cell does not have to be heated up to the operating temperature in order to become operational.

The operating temperature of practical fuel cells, similarly to operating pressure, taken into account not only the cell performance but also the system requirements. A fuel cell generates heat as a by-product of the electrochemical reaction. To maintain the desired temperature, heat must be away from a fuel cell. Same heat dissipates from the outer surface of the fuel cell and same must be taken away with a cooling system. Medium that taken away the heat may be air, water, or a special coolant. The

inner design of the fuel cell must allow the heat transfer to occur. Sometimes, small fuel cells need a heater to reach the operating temperature. In these fuel cells so much heat is being taken away from the outer surface that an additional heater is required. This of course is not very practical, but it is sometimes necessary for testing of fuel cells at a desired temperature [1].

The following is the fuel cell heat balance:

$$Q_{\text{gen}} + Q_{\text{react,in}} = Q_{\text{dis}} + Q_{\text{react,out}} + Q_{\text{cool}} \quad (\text{III.46})$$

In other words, the heat generated in the fuel cell, plus the heat brought into the cell with reactant gases, is taken away from the cell by heat dissipation from the cell surface to the surrounding, by the reactant gases leaving the cell, and by the coolant. The temperature inside a fuel cell may not be uniform; it varies from inlet to outlet, from inside out, or from cathode to anode. The cell temperature may be approximated by the following temperatures, which are much easier to measure than the cell temperature:

- surface temperature
- temperature of air leaving the cell
- temperature of coolant leaving the cell

Because of finite temperature differences needed for heat transfer inside a fuel cell, none of the above is exactly the cell operating temperature. The surface temperature is clearly lower than the temperature inside a fuel cell in a case when the fuel cell is heating itself, and it is actually higher than the inside temperature if the fuel cell is heated with the heating pads on its surface. Because most of the losses in the fuel cell may be associated with the cathode reaction, the temperature of air exiting the fuel cell is a good approximation of the cell operating temperature, although again the temperature inside a fuel cell must be at least slightly higher than the air temperature. In a case when the cell temperature is maintained by the coolant through the cell, the coolant outlet temperature may be used as the operating temperature. The accuracy of these approximations depends on thermal conductivity of the cell materials and air and coolant flow rates [1].

III.5.1.3. Reactants Flow Rates

The reactants flow rate at the inlet of a fuel cell must be equal to or high than the rate at which those reactants are being consumed in the cell. The rates (in mol s^{-1}) at which hydrogen and oxygen are consumed and water is generated are determined by Faraday's Law:

$$\dot{N}_{\text{H}_2} = \frac{I}{2F} \quad (\text{III.47})$$

$$\dot{N}_{\text{O}_2} = \frac{I}{4F} \quad (\text{III.48})$$

$$\dot{N}_{\text{H}_2\text{O}} = \frac{I}{2F} \quad (\text{III.49})$$

where:

\dot{N} = consumption rate (mol s^{-1})

I = current (A)

F = Faraday's constant (Cmol^{-1})

The mass flow rates of reactants consumption (in g s^{-1}) are then:

$$\dot{m}_{\text{H}_2} = \frac{I}{2F} M_{\text{H}_2} \quad (\text{III.50})$$

$$\dot{m}_{\text{O}_2} = \frac{I}{4F} M_{\text{O}_2} \quad (\text{III.51})$$

The mass flow rate of water generation (in g s^{-1}) is:

$$\dot{m}_{\text{H}_2\text{O}} = \frac{I}{2F} M_{\text{H}_2\text{O}} \quad (\text{III.52})$$

The reactants may, and in some cases must, be supplied in excess of consumption. For example, this is always necessary on the cathode side where water is produced and must be carried out from the cell with excess flow. The ratio between the actual flow rate of a reactant at the cell inlet and the consumption rate of that reactant is called the stoichiometric ratio, S .

$$S = \frac{\dot{N}_{\text{actual}}}{\dot{N}_{\text{cons}}} = \frac{\dot{m}_{\text{actual}}}{\dot{m}_{\text{cons}}} \quad (\text{III.53})$$

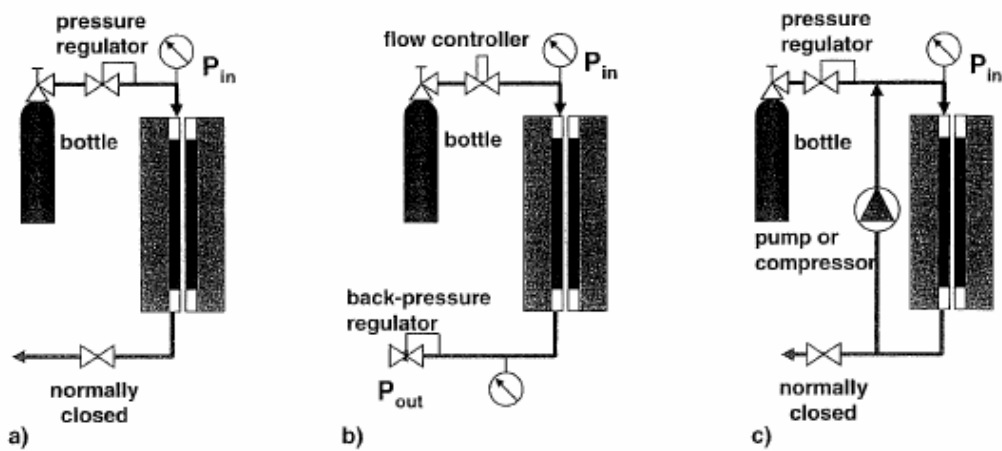


Figure III.9. Modes of reactant supply: a) dead-end mode, b) flow-through mode, c) recirculation mode.

Hydrogen may be supplied at the exact rate at which it is being consumed, in so-called dead-end mode (Figure III.9a). If hydrogen is available at elevated pressure, such as in a high-pressure storage tank, the dead-end mode does not require any controls, that is, hydrogen is being supplied as it is being consumed. In a dead-end mode $S = 1$. If hydrogen loss due to crossover permeation or internal currents is taken into account then the hydrogen flow rate at the fuel cell inlet is slightly higher than the consumption rate corresponding to the electrical current being generated:

$$S = \frac{\dot{N}_{\text{cons}} + \dot{N}_{\text{loss}}}{\dot{N}_{\text{cons}}} > 1 \quad (\text{III.54})$$

Utilization factor is reverse of stoichiometric ratio:

$$UF = \frac{1}{S} \quad (III.55)$$

Hydrogen may be supplied in excess ($S > 1$) in so called flow-through mode (Figure III.9b). In that case utilization factor is given by equation (III.55). Air is almost always supplied in a flow-through mode, with stoichiometry about $S = 2$ or higher. In case of pure reactants (hydrogen and/or oxygen), a recirculation mode may be utilized (Figure III.9c). In this case the unused gas is returned to the inlet by a pump or a compressor. Note that in case of recirculation, a cell may operate at stoichiometric ratio much higher than 1, but because unused reactant (hydrogen or oxygen) is not wasted but returned for consumption back to the cell inlet, fuel or oxidant utilization on a system level is high (close to 1).

Utilization factor in various modes of operation is summarized below.

In dead-end and recirculation mode:

$$UF = \frac{\dot{N}_{\text{cons}}}{\dot{N}_{\text{cons}} + \dot{N}_{\text{loss}}} \quad (III.56)$$

Flow-through mode:

$$UF = \frac{\dot{N}_{\text{cons}}}{\dot{N}_{\text{actual}}} \quad (III.57)$$

In general higher flow rates result in better fuel cell performance. Although pure hydrogen may be supplied in a dead-end mode ($S \sim 1$) or with a stoichiometry slightly higher than 1 (1.1 to 1.2), hydrogen in a mixture of gases (such as that coming out of a fuel processor) must be supplied with higher stoichiometries (1.1 to 1.5). The exact flow rate is actually a design variable. If the flow rate is too high the efficiency will be low (because hydrogen would be wasted), and if the flow rate is too low the fuel cell performance may suffer.

Similarly for pure oxygen flow rate, the required stoichiometry is between 1.2 and 1.5, but when air is used, typical stoichiometry is 2 or higher.

Air is supplied to the cell by means of a blower or a compressor (depending on operating pressure) whose power consumption is directly proportional to the flow rate. Therefore, at higher air flow rates the fuel cell may perform better, but power consumption of a blower or particularly of a compressor may significantly affect the system efficiency. There are at least two reasons why fuel cell performance improves with excess air flow rate, namely:

- 1) Higher flow rate helps remove product water from the cell.
- 2) Higher flow rates keep oxygen concentration high.

III.5.2. Second Law Efficiency

Determination of an effective utilization of a proton exchange membrane fuel cell and measuring its true performance based on thermodynamic laws are considered to be extremely essential. Theoretically, the efficiency of a PEM fuel cell based on the first law of thermodynamics makes no reference to the best possible performance of the fuel cell, and thus, it could be misleading. On the other hand, the second law efficiency or exergetic efficiency of a PEM fuel cell, which is the ratio of the electrical output over the maximum possible work output, could give a true measure of the PEM fuel cell's performance. Energy analysis performed on a system based on the second law of thermodynamics is known as exergy analysis (availability analysis). Unlike energy, this deal merely with the quantity of energy, exergy deals with both the quantity as well as the quality of energy [8]. The total exergy consists of physical exergy, which is associated with the temperature and pressure of the matter, and chemical exergy, which is associated with the departure of the chemical composition of a system from that of the environment [10].

III.5.2.1. Mathematical Model

Exergetic efficiency, which is defined as the second law efficiency, gives the true value of the performance of an energy system from the thermodynamic viewpoint [9]. The exergetic efficiency of a fuel cell system, is the ratio of the power output, over the differences between the exergy of the inlets (oxygen + hydrogen) and the exergy of the outlets (oxygen + water), which can be determined by the following formula:

$$\eta = \frac{\text{Power Output}}{(\text{Exergy})_{\text{in}} - (\text{Exergy})_{\text{out}}} \quad (\text{III.58a})$$

$$\eta = \frac{\text{Power Output}}{(\dot{E}_{\text{H}_2,\text{in}} + \dot{E}_{\text{O}_2,\text{in}}) - (\dot{E}_{\text{H}_2,\text{out}} + \dot{E}_{\text{O}_2,\text{out}})} \quad (\text{III.58b})$$

where $\dot{E}_{\text{H}_2,\text{in}}$, $\dot{E}_{\text{O}_2,\text{in}}$, $\dot{E}_{\text{H}_2,\text{out}}$ and $\dot{E}_{\text{O}_2,\text{out}}$ are the total exergies of the reactants and the products.. Assuming negligible potential and kinetic energy effects on the fuel cell electrochemical process, the total exergy transfer per unit mass of each reactant and product consists of the combination of both physical and chemical exergies [9]:

$$e = e_{\text{ch}} + e_{\text{ph}} \quad (\text{III.59})$$

1.a. Physical Exergy

Physical exergy is associated with the temperature and pressure of the reactants and the products in the fuel cell system. The physical exergy is expressed in terms of the differences of enthalpy from those and entropy from those at standard conditions of temperature and pressure of $T_0 = 298 \text{ K}$ and $P_0 = 1 \text{ atm}$, respectively. The general expression of the physical exergy can be described as:

$$e_{\text{ph}} = (h - h_0) - T_0 (s - s_0) \quad (\text{III.60})$$

where h_0 and s_0 denote the specific enthalpy and entropy evaluated at standard conditions, respectively. The physical exergy of an ideal gas with constant specific heat C_p and specific heat ratio k can be written as:

$$e_{\text{ph}} = C_p T_0 \left[\frac{T}{T_0} - 1 - \ln \left(\frac{T}{T_0} \right) \right] + R T_0 \ln \left(\frac{P}{P_0} \right) \quad (\text{III.61a})$$

I.b. Chemical Exergy

The chemical exergy is associated with the departure of the chemical composition of a system from that of the environment. For the sake of simplicity, the chemical exergy considered in the analysis is rather a standard chemical exergy that is based on the standard values of the environmental temperature of $T_0 = 298 \text{ K}$ and pressure of $P_0 = 1 \text{ atm}$. Generally, these values are in good agreement with the calculated chemical exergy relative to alternative specifications of the environment [9]. Values of the chemical exergies for both the reactants and products are taken from published literature or calculated by equation below:

$$e_{\text{ch}} = \sum x_n e_{\text{ch},n} + RT_0 \sum x_n \ln x_n \quad (\text{III.62})$$

where

x = mole fraction

IV. RESIDENTIAL COGENERATION WITH PEM FUEL CELLS

Cogeneration (also known as combined heat and power, CHP) is the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy stream such as oil, coal, natural or liquefied gas, biomass or solar [11].

Cogeneration applications in buildings have to satisfy either both the electrical and thermal demands, or satisfy the thermal demand and part of the electrical demand, or satisfy the electrical demand and part of the thermal demand. Depending on the magnitude of the electrical and thermal loads, whether they match or not, and the operating strategy, the cogeneration system may have to be run at part-load conditions, the surplus energy (electricity or heat) may have to be stored or sold, and deficiencies may have to be made up by purchasing electricity (or heat) from other sources such as the electrical grid (or a boiler plant). The surplus heat produced can be stored in a thermal storage device such as a water tank or in phase change materials, while surplus electricity can be stored in electrical storage devices such as batteries or capacitors [11].

The power to most residential buildings is supplied from power generation plants supply power to most residential buildings over the nationwide electricity grid. The thermal efficiency of the off-site power generation is typically less than 40 percent. Furthermore, the waste heat generated at the utility plant cannot be used effectively. Therefore, resources are wasted and excessive amounts of greenhouse gases are emitted. To increase the efficiency and decrease the emission rates in the residential sector have led companies to develop on-site energy generation systems. Researches are being made to develop on-site energy systems for single-family housing [12].

An on-site energy system can supply the electricity needs of the residence while yielding “waste heat” that can be used for space and domestic water heating

purposes. Energy systems based on renewable energy sources, such as geothermal, wind, and solar energy and systems based on fossil fuels, such as diesel generators and fuel cells are only a few of the possibilities for small scale residential applications. A fuel cell represents a particularly promising system for a residence due to its high efficiency, excellent part load performance, small-scale applicability, and quiet operation [12].

IV.1. BRIEF HISTORY OF COGENERATION

Cogeneration is not a new concept. Industrial plants led to the concept of cogeneration back in the 1880s when steam was the primary source of energy in industry, and electricity was just surfacing as a product for both power and lighting. The use of cogeneration became common practice as engineers replaced steam driven belt and pulley mechanisms with electric power and motors, moving from mechanical powered systems to electrically powered systems. During the early parts of the 20th century, most electricity generation was from coal fired boilers and steam turbine generators, with the exhaust steam used for industrial heating applications. In the early 1900s, as much as 58 % of the total power produced in the USA by on-site industrial power plants was estimated to be cogenerated [11].

The construction of central electric power plants and reliable utility grids led to the reduction in the cost of electricity, and many industrial plants began buying electricity from utility companies and stopped generating their own. Thus, on-site industrial cogeneration declined in the US accounting for only 15 % of total electrical generation capacity by 1950 and dropped to about 5 % by 1974. In addition, other factors that led to the decline of cogeneration were the increasing regulatory policies regarding electricity generation, low fuel costs, advances in technology resulting in products like packaged boilers, and tightening environmental controls. However, the downward trend started reverting after the first fuel crisis in 1973. Because of energy price increases and uncertainty of fuel supplies, systems that are efficient and can utilize alternative fuels started drawing attention. In addition, cogeneration gained attention because of the lower fuel consumption and emissions associated with the application of cogeneration. Today, because of these reasons, various governments especially in Europe, US, Canada and Japan are taking leading roles in establishing and/or promoting the increased use of cogeneration

applications not only in the industrial sector but also in other sectors including the residential sector [11].

IV.2. Micro-Cogeneration

There is a growing potential for the use of micro-cogeneration systems in the residential sector because they have the ability to produce both useful thermal energy and electricity from a single source of fuel such as hydrogen for PEM fuel cell. In cogeneration systems, the efficiency of energy conversion increases to over 80 % as compared to an average of 30–35 % for conventional fossil fuel fired electricity generation systems. This increase in energy efficiency can result in lower costs and reduction in greenhouse gas emissions when compared to the conventional methods of generating heat and electricity separately. Cogeneration systems and equipment suitable for residential and small-scale commercial applications like hospitals, hotels or institutional buildings are available, and many new systems are under development. These products are used or aimed for meeting the electrical and thermal demands of a building for space and domestic hot water heating, and potentially, absorption cooling [11].

The Figure IV.1 illustrates how the internal energy from the fuel is converted into useful thermal energy and electrical energy for a conventional fossil fuel fired electricity generation and a cogeneration system. Cogeneration versus conventional generation, where α_E , part of the energy transformed into electricity in a cogeneration unit, α_Q , part of the energy transformed into usable in a cogeneration unit, η_E , electrical yield of an electrical power plant (production of electricity only), η_Q , yield of a boiler (production of heat only) E, electricity demand, Q, heat demand [11].

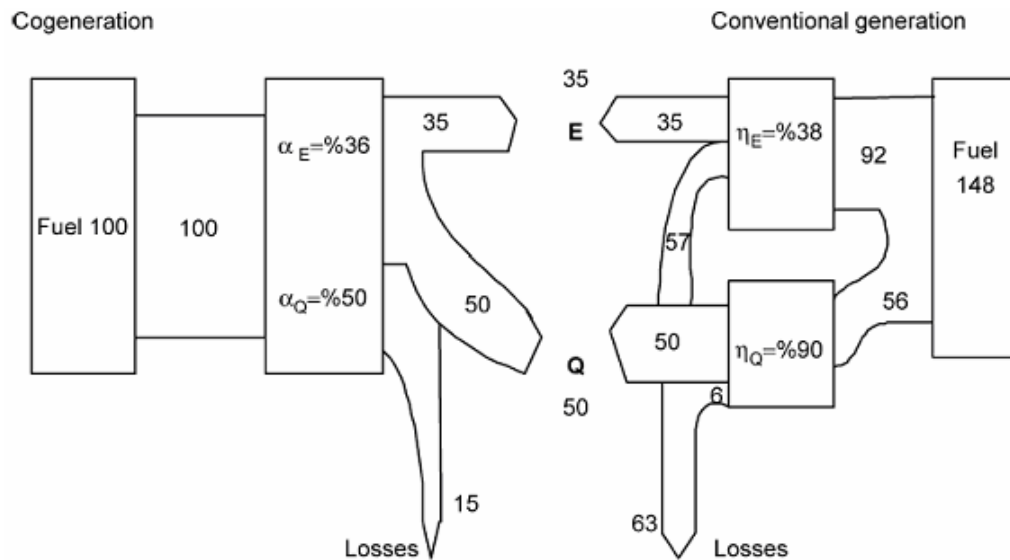


Figure IV.1. Cogeneration versus conventional generation

Micro-cogeneration in residential applications is one of the efficient ways of improving the energy conversion efficiency in buildings. Cogeneration systems will cover electrical and thermal. PEM fuel cell seems to be one of the major emerging technologies in this field. The advantages of fuel cell cogeneration systems include low noise level, potential for low maintenance, excellent part load management, low emissions, and a potential to achieve an overall efficiency of 85–90 % even with small units [11].

V. METHODOLOGY

V.1. PEM FUEL CELL MODELING

The purpose of this part is to present the model of a PEM fuel cell in a simplified form, based on chemical and electrical equations. The model is used to design a theoretical fuel cell delivering an output power for electricity and heat. Efficiencies according to first and second law of thermodynamics, and reactants consumptions and water production are calculated with the model. The model calculates these performance related parameters with choosing oxidant type is oxygen. The modeling is performed by studying several models describing the electrochemical behavior of a PEM fuel cell. The model is performed by the software program of Matlab.

V.1.1. Model Assumptions and Operation Principles

The model is based on an engineering approach and requires knowledge of modeling constants such as resistance of membrane, transfer coefficient, etc. The main assumptions of the model are as follows:

1. The model is one dimensional.
2. The temperature is uniform in the cell.
3. Hydrogen and oxygen pressures are assumed uniform in the fuel cell
4. The membrane is highly humidified and is capable of good proton conduction.
5. The electrode layers are considered to have constant and uniform porosity.
6. Internal current losses are negligible.

7. Number of cells in stack is 11 and the active area of each cell is chosen as 516 cm^2 according to Nafion® perfluorinated membrane Nafion 117, thickness 0.007 in (0.1778 mm) [14].

The model represents operation of a PEM fuel cell. The program represents the performance behavior for different operation temperatures and different pressures of reactant gases for a range of current densities of the PEM fuel cell. Operation principles of the model in Matlab program as follows:

1. Determine the operation temperature and pressure
2. Determine the model constants, such as charge transfer coefficient, limiting current density, etc.
3. Specify the general constants, such as faraday's constant, universal gas constant, etc.
4. Make a loop for current density.
5. Calculate the Nernst voltage.
6. Calculate the voltage losses.
7. Calculate the output voltage of the fuel cell.
8. Calculate electrical power output of the fuel cell.
9. Calculate mass flow rates of inlets and outlets.
10. Calculate exergies of inlets and outlets.
11. Calculate heat dissipation to the surrounding and required heat for inlets to the operation temperature.
12. Calculate heat generation and useful heat generation of the fuel cell.
13. Calculate mass flow rate of cooling water.
14. Calculate efficiency values of the fuel cell.
15. Plot all the results.

The flow chart of the PEM fuel cell model is shown in the Figure V.1.

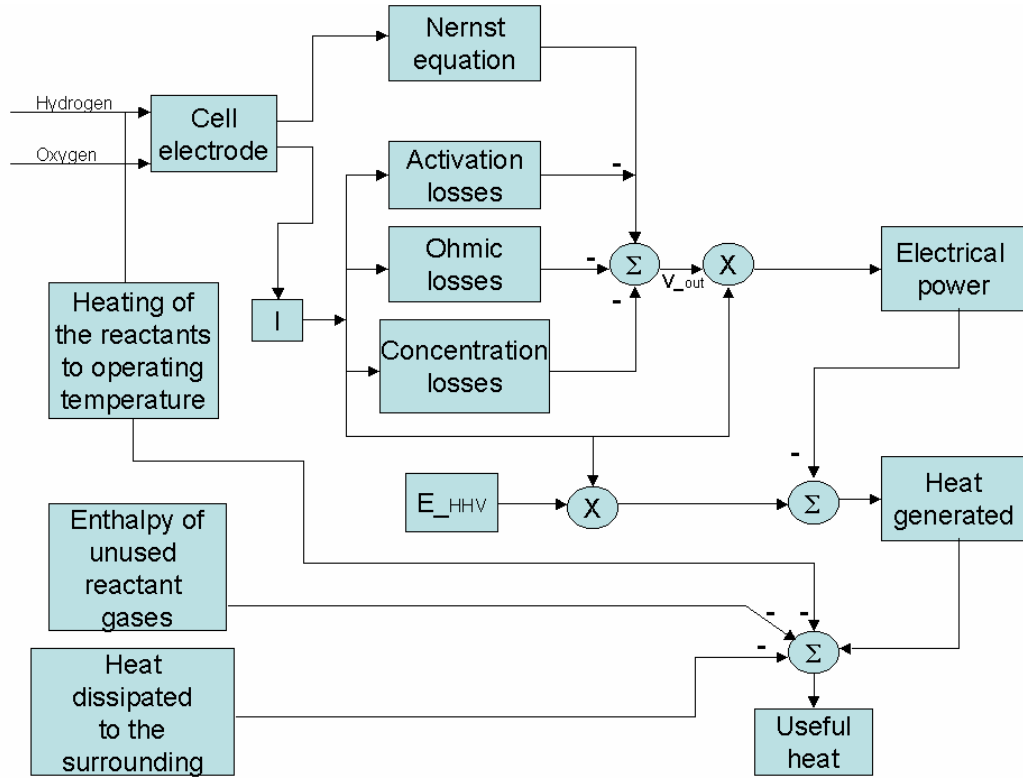


Figure V.1. Flow chart of the PEM fuel cell model

V.1.2. Calculations of PEM Fuel Cell Modeling

V.1.2.1. Calculation of Output Voltage

The output voltage of the fuel cell is obtained by adding all the losses, which are activation, ohmic and concentration, to the Nernst Equation, which is reversible open circuit voltage.

$$V_{\text{out}} = E_{\text{Nernst}} - V_{\text{act}} - V_{\text{ohmic}} - V_{\text{con}} \quad (\text{V.1})$$

where,

$$E_{\text{Nernst}} = -\left(\frac{\Delta H}{2F} - \frac{T\Delta S}{2F}\right) + \frac{RT}{2F} \ln(P_{\text{H}_2} P_{\text{O}_2}^{0.5}) \quad (\text{V.2})$$

$$V_{\text{act}} = \frac{RT}{\alpha F} \ln \frac{i}{i_0} \quad (\text{V.3})$$

where, $\alpha = 1$ in the model

$$i_0 = i_0^{\text{ref}} a_c L_c \left(\frac{P_r}{P_r^{\text{ref}}} \right)^\gamma \exp \left[-\frac{E_c}{RT} \left(1 - \frac{T}{T_{\text{ref}}} \right) \right] \quad (\text{V.4})$$

where,

i_0^{ref} = reference exchange current density (at reference temperature and pressure) per unit catalyst surface area, Acm^{-2}

a_c = catalyst specific area, $\text{cm}^2\text{mg}^{-1}$

L_c = catalyst loading (state of the art electrodes have $0.3\text{-}0.5 \text{ mgPtcm}^{-2}$; lower loadings are possible but would result in lower cell voltages)

P_r = reactant partial pressure, kPa

P_r^{ref} = reference pressure, 101.325 kPa

γ = pressure coefficient (0.5-1.0)

E_c = activation energy, Jmol^{-1}

R = gas constant, $8.314 \text{ Jmol}^{-1}\text{K}^{-1}$

T = operation temperature, K

T_{ref} = reference temperature, 298.15 K

The constant values used in the model of the equation (V.4) are

$$i_0^{\text{ref}} = 3 \times 10^{-9} \text{ Acm}^{-2}$$

$$a_c = 2400 \text{ cm}^2\text{mg}^{-1}$$

$$L_c = 0.4 \text{ mgPtcm}^{-2}$$

$$\gamma = 0.75$$

$$E_c = 66000 \text{ Jmol}^{-1} \text{ for oxygen reduction on Pt}$$

It is important that to remember that the equation (V.3) is only true when $i > i_0$.

$$V_{\text{ohmic}} = iR_i \quad \text{same as equation (III.35)}$$

where,

$$R_i = 0.15 \text{ } \Omega\text{cm}^2 \text{ in the model}$$

$$V_{\text{con}} = \frac{RT}{2F} \ln \frac{i_L}{i_L - i}$$

same as equation (III.36)

where,

$$i_L = 1.4 \text{ Acm}^{-2} \text{ in the model}$$

The equation (III.36) is only valid when $i_L > (i_L - i)$.

V.1.2.2. Calculation of Electrical Power

The output power is given by the following equation:

$$W_{\text{out}} = V_{\text{out}} n_{\text{cells}} iA \quad (\text{V.5})$$

where,

$$n_{\text{cells}} = \text{number of cells in the fuel cell}$$

$$A = \text{area of a cell, cm}^2$$

In our model, there are 11 cells in the model.

V.1.2.3. Calculation of Heat Generation

The total heat generation is the difference between the total power generation in the fuel cell at reversible condition (no losses) and electrical power generated at operation conditions with losses and this is defined by the following equation:

$$\dot{Q}_{\text{gen}} = (E_{\text{HHV}} - V_{\text{out}}) n_{\text{cells}} iA \quad (\text{V.6})$$

If we consider enthalpies of all inlets, heat generation of inlets is,

$$\dot{Q}_{in} = \left(-dH \frac{\dot{m}_{H_2_{in}}}{M_{H_2}} + h_g \dot{m}_{H_2O_{in_H_2_{in}}} \right) + \left(h_g \dot{m}_{H_2O_{in_O_2_{in}}} \right) \quad (V.7)$$

where,

- $\dot{m}_{H_2_{in}}$ = mass flow rate of hydrogen inlet, g/s
- M_{H_2} = molar mass of hydrogen, 2.016 g/mol
- h_g = enthalpy of water vapor, J/g
- $\dot{m}_{H_2O_{in_H_2_{in}}}$ = mass flow rate of water vapor in hydrogen inlet, g/s
- $\dot{m}_{H_2O_{in_O_2_{in}}}$ = mass flow rate of water vapor in oxygen inlet, g/s

Heat generation of outlets is,

$$\dot{Q}_{out} = \left(-dH \frac{\dot{m}_{H_2_{out}}}{M_{H_2}} + h_f \dot{m}_{H_2O_{in_H_2_{out}}} \right) + \left(h_f \dot{m}_{H_2O_{in_O_2_{out}}} \right) \quad (V.8)$$

where,

- $\dot{m}_{H_2_{out}}$ = mass flow rate of unused hydrogen, g/s
- h_f = enthalpy of water, J/g
- $\dot{m}_{H_2O_{in_H_2_{out}}}$ = mass flow rate of water in unused hydrogen, g/s
- $\dot{m}_{H_2O_{in_O_2_{out}}}$ = mass flow rate of water in unused oxygen, g/s

In equation (V.8), all vapor content in hydrogen and oxygen turn to water in outlet.

As a result, total heat generation considering enthalpies of all inlets is

$$\dot{Q}_{gen} = \dot{Q}_{in} - W_{out} - \dot{Q}_{out} \quad (V.9)$$

V.1.2.4. Calculation of Useful Heat Generation

Useful heat generation is difference between heat taken away from the fuel cell by active cooling and heating of inlets to the operation temperature.

$$\dot{Q}_{\text{useful}} = \dot{Q}_{\text{cooling}} - \left[\left(\dot{Q}_{\text{H}_2\text{-Heat}} + \dot{Q}_{\text{H}_2\text{O_in_H}_2\text{-Heat}} \right) + \left(\dot{Q}_{\text{O}_2\text{-Heat}} + \dot{Q}_{\text{H}_2\text{O_in_O}_2\text{-Heat}} \right) \right] \quad (\text{V.10})$$

where,

\dot{Q}_{cooling} = heat taken by active cooling

$\dot{Q}_{\text{H}_2\text{-Heat}}$ = required heat for heating of hydrogen to the operation temperature

$\dot{Q}_{\text{H}_2\text{O_in_H}_2\text{-Heat}}$ = required heat for heating of water vapor in hydrogen to the operation temperature

$\dot{Q}_{\text{O}_2\text{-Heat}}$ = required heat for heating of oxygen to the operation temperature

$\dot{Q}_{\text{H}_2\text{O_in_O}_2\text{-Heat}}$ = required heat for heating of water vapor in oxygen to the operation temperature

$$\dot{Q}_{\text{H}_2\text{-Heat}} = \dot{m}_{\text{H}_2\text{-in}} C_{p\text{-H}_2} (T - T_0) \quad (\text{V.11})$$

$$\dot{Q}_{\text{O}_2\text{-Heat}} = \dot{m}_{\text{O}_2\text{-in}} C_{p\text{-O}_2} (T - T_0) \quad (\text{V.12})$$

$$\dot{Q}_{\text{H}_2\text{O_in_H}_2\text{-Heat}} = \dot{m}_{\text{H}_2\text{O_in_H}_2\text{-in}} C_{p\text{-H}_2\text{O}} (T - T_0) \quad (\text{V.13})$$

$$\dot{Q}_{\text{H}_2\text{O_in_O}_2\text{-Heat}} = \dot{m}_{\text{H}_2\text{O_in_O}_2\text{-in}} C_{p\text{-H}_2\text{O}} (T - T_0) \quad (\text{V.14})$$

where,

$C_{p\text{-H}_2}$ = specific heat of hydrogen, 14.307 J/g-K

$\dot{m}_{\text{O}_2\text{-in}}$ = mass flow rate of oxygen inlet, g/s

$C_{p\text{-O}_2}$ = specific heat of oxygen, 0.918 J/g-K

$C_{p\text{-H}_2\text{O}}$ = specific heat of water vapor, 1.8723 J/g-K

T_0 = reference temperature, 298.15 K

Heat taken by active cooling is heat generation minus heat dissipated to the surrounding. Heat generation, as discussed in Chapter V.1.2.4, is total power generation in the fuel cell minus electrical power generation. Therefore, we can write heat taken by active cooling as following equation:

$$\dot{Q}_{\text{cooling}} = \frac{(E_{\text{HHV}} n_{\text{cells}} i A)}{UF_{\text{H}_2}} - W_{\text{out}} - \dot{Q}_{\text{out}} - \dot{Q}_{\text{dis}} \quad (\text{V.15})$$

where,

UF_{H_2} = Utilization factor of hydrogen

\dot{Q}_{dis} = heat dissipated to the surrounding

Utilization factor of hydrogen is 0.8 in the model.

Heat lose to the surrounding, that the fuel cell may lose through natural convection and radiation, is:

$$\dot{Q}_{\text{dis}} = \frac{T - T_{\text{surr_wall}}}{R_{\text{th}}} \quad (\text{V.16})$$

where:

$T_{\text{surr_wall}}$ = surrounding walls' temperature

R_{th} = thermal resistance

Thermal resistance is defined as,

$$R_{\text{th}} = \frac{1}{\frac{1}{R_{\text{C}}} + \frac{1}{R_{\text{R}}}} \quad (\text{V.17})$$

where,

R_{C} = convective thermal resistance

R_{R} = radiative thermal resistance

Convective thermal resistance, R_C , is defined as,

$$R_C = \frac{1}{hA_s} \quad (\text{V.18})$$

where,

- h = heat transfer coefficient
- A_s = stack exposed surface area, m^2

Radiative thermal resistance is,

$$R_R = \frac{1}{\sigma f A_s (T + T_{\text{surr_wall}})(T^2 + T_{\text{surr_wall}}^2)} \quad (\text{V.19})$$

where,

- σ = Stefan-Boltzman constant, $5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$
- f = shape factor, it may be assumed as 1

The heat transfer coefficient, h , is a function of the Nusselt number, Nu :

$$h = \frac{k}{L} Nu_L \quad (\text{V.20})$$

where,

- k = thermal conductivity
- L = characteristic length or length of travel of the liquid in the boundary layer, that is, the height of the stack, m

For vertical plates and natural convection, the Nusselt number is some empirical function of Prandtl and Rayleigh numbers, $Nu_L = f(\text{Pr}, Ra_L)$, such as [1]:

$$Nu_L = \left[0.825 + \frac{0.387 Ra_L^{1/6}}{\left[1 + \left(\frac{0.5}{\text{Pr}} \right)^{1/6} \right]^{4/7}} \right]^2 \quad (\text{V.21})$$

where,

$$Ra_L = \frac{g\beta(T - T_{surr_wall})L^3}{\nu\alpha_{td}} \quad (V.22)$$

where,

- g = gravity acceleration, 9.81 m/s^2
- β = thermal expansion coefficient, for gases $\beta = 1/T$
- ν = kinematic viscosity, m^2s^{-1}
- α_{td} = thermal diffusivity, m^2s^{-1}

If we consider enthalpies of all inlets for calculation of useful heat generation, then Heat taken by active cooling is calculated as follows,

$$\dot{Q}_{cooling} = \dot{Q}_{in} - W_{out} - \dot{Q}_{out} - \dot{Q}_{dis} \quad (V.23)$$

In this equation \dot{Q}_{in} and \dot{Q}_{out} are calculated according to equation (V.7) and (V.8), respectively.

V.1.2.5. Calculation of Mass Flow Rates

5.a. Mass Flow Rate of Inlets

Inlets of the fuel cell are hydrogen, oxygen and their water vapor contents.

The mass flow rate of hydrogen at inlet is calculated by the following equation.

$$\dot{m}_{H_2_in} = \frac{M_{H_2} \left(\frac{W_{out}}{V_{out}} \right)}{UF_{H_2}} \quad (V.24)$$

Mass flow rate of oxygen at inlet is,

$$\dot{m}_{O_2_in} = \frac{M_{O_2} \left(\frac{W_{out}}{V_{out}} \right)}{UF_{O_2}} \quad (V.25)$$

where,

M_{O_2} = molar mass of oxygen, 32 g/mol

UF_{O_2} = utilization factor of oxygen. The value is 0.8 in the model.

Water vapor in hydrogen inlet is calculated as:

$$\dot{m}_{H_2O_in_H_2_in} = \frac{\frac{M_{H_2O}}{2F} \left(\frac{W_{out}}{V_{out}} \right)}{UF_{H_2}} \frac{\phi P_{vs}}{P_{H_2} - \phi P_{vs}} \quad (V.26)$$

where,

M_{H_2O} = molar mass of water, 18.016 g/mol

ϕ = relative humidity, 0.4 in the model

P_{vs} = saturation pressure, kPa

P_{H_2} = hydrogen pressure, kPa

Water vapor content in oxygen inlet is calculated by the following equation.

$$\dot{m}_{H_2O_in_O_2_in} = \frac{\frac{M_{H_2O}}{4F} \left(\frac{W_{out}}{V_{out}} \right)}{UF_{O_2}} \frac{\phi P_{vs}}{P_{O_2} - \phi P_{vs}} \quad (V.27)$$

where,

P_{O_2} = oxygen pressure, kPa

5.b. Mass Flow Rate of Outlets

Mass flow rate of outlets from the fuel cell are unused hydrogen and oxygen, their water contents which enter as a vapor at inlet and water production.

The mass flow rate of unused hydrogen is,

$$\dot{m}_{H_2_out} = \frac{M_{H_2}}{2F} \left(\frac{W_{out}}{V_{out}} \right) \left(\frac{1}{UF_{H_2}} - 1 \right) \quad (V.28)$$

Mass flow rate of unused oxygen is,

$$\dot{m}_{O_2_out} = \frac{M_{O_2}}{4F} \left(\frac{W_{out}}{V_{out}} \right) \left(\frac{1}{UF_{O_2}} - 1 \right) \quad (V.29)$$

All water vapor content of hydrogen and oxygen at inlet extract from the fuel cell and they condense to liquid water.

$$\dot{m}_{H_2O_in_H_2_out} = \dot{m}_{H_2O_in_H_2_in} \quad (V.30)$$

$$\dot{m}_{H_2O_in_O_2_out} = \dot{m}_{H_2O_in_O_2_in} \quad (V.31)$$

Mass flow rate of water production of the fuel cell is calculated as follows:

$$\dot{m}_{H_2O_out} = \frac{M_{H_2O}}{2F} \left(\frac{W_{out}}{V_{out}} \right) \quad (V.32)$$

5.c. Mass Flow Rate of Cooling Water

Mass flow rate of cooling water equals to:

$$\dot{m}_{cooling} = \frac{\dot{Q}_{cooling}}{C_{p_water} (T_{cooling_out} - T_{cooling_in})} \quad (V.33)$$

where,

C_{p_water} = specific heat of water, 4.18 J/g-K

$T_{cooling_out}$ = temperature of cooling water at outlet

$T_{cooling_in}$ = temperature of cooling water at inlet

Cooling water mass rate is calculated according to heat taken by cooling water calculations of both equations (V.15) and (V.23).

V.1.2.6. Calculation of Exergy Values

Inlet and outlet exergies are calculated in the following equations, respectively.

$$\dot{E}_{in} = \sum(\dot{m}_{in} e_{in}) \quad (V.34)$$

$$\dot{E}_{out} = \sum(\dot{m}_{out} e_{out}) \quad (V.35)$$

Exergy is composed of two parts, which are physical exergy and chemical exergy, as discussed in Chapter III.5.2.1. Physical equations are calculated by the equation (III.62) for liquids and equation (III.63a) for gases. Chemical exergies are obtained from the table A.1.

Physical and chemical exergies of hydrogen are,

$$e_{ph_H_2} = C_{p_H_2} T_0 \left(\frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right) + \left(RT_0 \ln \frac{P_{H_2}}{P_0} \right) / M_{H_2} \quad (V.36)$$

$$e_{ch_H_2} = \frac{236100}{M_{H_2}} \quad (V.37)$$

Total exergy of hydrogen is sum of the physical and chemical exergies.

$$e_{H_2} = e_{ph_H_2} + e_{ch_H_2} \quad (V.38)$$

Physical, chemical and total exergies of oxygen are,

$$e_{ph_O_2} = C_{p_O_2} T_0 \left(\frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right) + \left(RT_0 \ln \frac{P_{O_2}}{P_0} \right) / M_{O_2} \quad (V.39)$$

$$e_{ch_O_2} = \frac{3970}{M_{O_2}} \quad (V.40)$$

$$e_{O_2} = e_{ph_{O_2}} + e_{ch_{O_2}} \quad (V.41)$$

Physical, chemical and total exergies of water vapor in hydrogen inlet are, respectively,

$$e_{ph_{H_2O_in_H_2_in}} = C_{p_{H_2O}} T_0 \left(\frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right) + \left(RT_0 \ln \frac{P_{H_2}}{P_0} \right) / M_{H_2O} \quad (V.42)$$

$$e_{ch_{H_2O_in_H_2_in}} = \frac{9500}{M_{H_2O}} \quad (V.43)$$

$$e_{H_2O_in_H_2_in} = e_{ph_{H_2O_in_H_2_in}} + e_{ch_{H_2O_in_H_2_in}} \quad (V.44)$$

Exergies of water vapor in oxygen inlet are same as hydrogen inlet so,

$$e_{ph_{H_2O_in_H_2_in}} = e_{ph_{H_2O_in_O_2_in}} \quad (V.45)$$

$$e_{ch_{H_2O_in_H_2_in}} = e_{ch_{H_2O_in_O_2_in}} \quad (V.46)$$

$$e_{H_2O_in_H_2_in} = e_{H_2O_in_O_2_in} \quad (V.47)$$

At outlet, exergies of water in hydrogen and oxygen, and exergies of production of water are same to each other. Exergy calculations of these products are,

$$e_{ph_{H_2O_out}} = e_{ph_{H_2O_in_H_2_out}} = e_{ph_{H_2O_in_O_2_out}} = (h_f - h_0) - T(s_f - s_0) \quad (V.48)$$

$$e_{ch_{H_2O_out}} = e_{ch_{H_2O_in_H_2_out}} = e_{ch_{H_2O_in_O_2_out}} = \frac{900}{M_{H_2O}} \quad (V.49)$$

$$e_{H_2O_out} = e_{H_2O_in_H_2_out} = e_{H_2O_in_O_2_out} = e_{ph_{H_2O_out}} + e_{ch_{H_2O_out}} \quad (V.50)$$

V.1.2.6. Calculation of Efficiencies

6.a. Electrical Efficiency

Electrical efficiency of the fuel cell changes according to first or second law of thermodynamics and considering change of enthalpy of fuel cell reaction or enthalpies of all inlets. For second law efficiency, exergy of electrical power is same as electrical power.

Electrical efficiency according to thermodynamics first law considering change of enthalpy of fuel cell reaction is calculated as,

$$\eta_{\text{electrical_TD1_H}_2} = \frac{W_{\text{out}}}{-\dot{dH} \frac{\dot{m}_{\text{H}_2\text{-in}}}{M_{\text{H}_2}}} \times 100 \quad (\text{V.51})$$

Electrical efficiency according to thermodynamics second law considering exergy of hydrogen is,

$$\eta_{\text{electrical_TD2_H}_2} = \frac{W_{\text{out}}}{E_{\text{H}_2\text{-in}}} \times 100 \quad (\text{V.52})$$

Calculation of electrical efficiency according to first law of thermodynamics considering enthalpies of all inputs is shown in the following equation.

$$\eta_{\text{electrical_TD1_All}} = \frac{W_{\text{out}}}{\dot{Q}_{\text{in}}} \times 100 \quad (\text{V.53})$$

Electrical efficiency according to thermodynamics second law considering all inputs' exergies is calculated as follows,

$$\eta_{\text{electrical_TD2_All}} = \frac{W_{\text{out}}}{\dot{E}_{\text{in}}} \times 100 \quad (\text{V.54})$$

6.b. Total Efficiency

Total efficiency includes electrical and thermal efficiency. Total efficiency also has different type of calculations. For second law efficiency, thermal power is multiplied by $(1 - T_0/T)$.

Total efficiency according to thermodynamics first law considering change of enthalpy of fuel cell reaction is calculated in the following equation.

$$\eta_{All_TD1_H_2} = \frac{(W_{out} + \dot{Q}_{useful})}{-dH \frac{\dot{m}_{H_2_in}}{M_{H_2}}} \times 100 \quad (V.55)$$

Total efficiency according to second law of thermodynamics as only input is exergy of hydrogen is,

$$\eta_{All_TD2_H_2} = \frac{\left(W_{out} + \dot{Q}_{useful} \left(1 - \frac{T_0}{T} \right) \right)}{E_{H_2_in}} \times 100 \quad (V.56)$$

Total efficiency according to thermodynamics first law considering enthalpies of all inlets is calculated as follows,

$$\eta_{All_TD1_All} = \frac{(W_{out} + \dot{Q}_{useful})}{\dot{Q}_{in}} \times 100 \quad (V.57)$$

Calculation of total efficiency according to thermodynamics second law considering exergies of all inlets is,

$$\eta_{All_TD2_All} = \frac{\left(W_{out} + \dot{Q}_{useful} \left(1 - \frac{T_0}{T} \right) \right)}{\dot{E}_{in}} \times 100 \quad (V.58)$$

For the last two efficiencies, \dot{Q}_{useful} value is used as according to $\dot{Q}_{cooling}$ value in equation (V.23).

V.2. COGENERATION

Cogeneration, or combined heat and power (CHP) technology, is the combined production of electrical power and useful heat. In electricity generation from PEM fuel cell, the waste heat can be recovered from the cooling water and combustion gases to be used in heating purposes.

Energy is used in a residence for:

- Space heating in winter
- Space cooling in summer
- Domestic water heating
- Lights and electrical appliances.

Thermal energy of the fuel cell can be used for domestic water heating and space heating. Unused hydrogen can also be combusted to increase thermal energy. However, thermal energy of the fuel cell may not be sufficient at all times. An electric resistance heater can supply domestic water heating and space heating can be supplied by a heat pump or electrical heater. During the cooling season electricity is used to operate the heat pump in the air conditioning mode. The lights and appliances must be powered by electricity at all times.

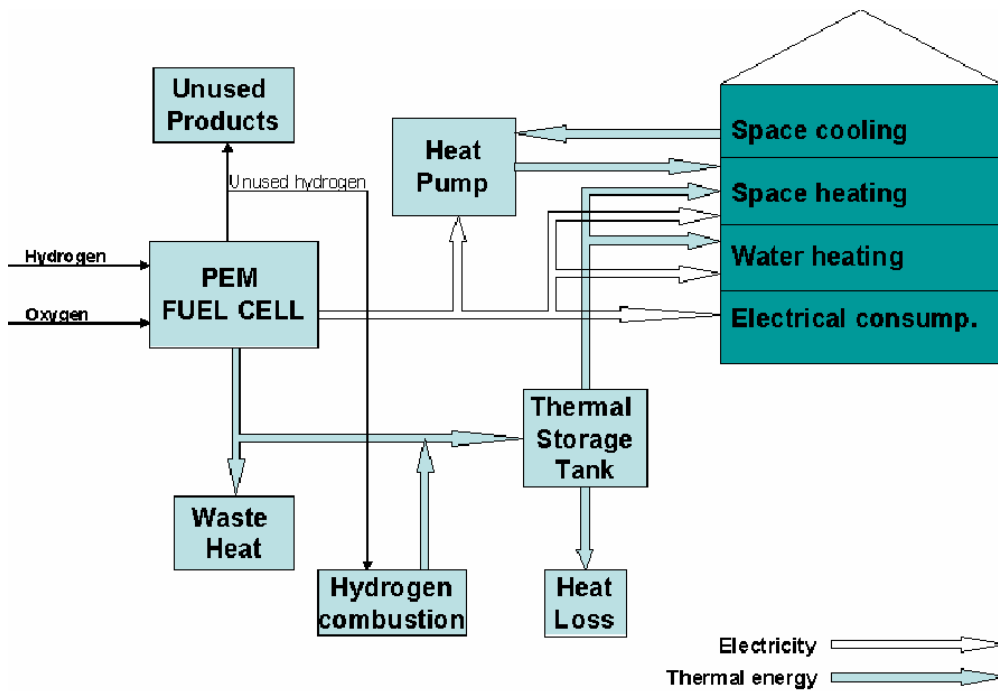


Figure V.2. The PEM fuel cell with cogeneration options

V.2.1. Heating and Cooling Loads

Heating and cooling load calculations are computed by the software program of HVAC-Calc Residential 4.0. The program is used as trial version so design conditions are not changed. Obtaining heating and cooling loads are required to only show using options of electrical and thermal power of PEM fuel cell.

In order to show cogeneration options, heating and cooling loads of a residential house must be calculated and to calculate these loads a residential house must be designed. Residential is selected as 90 m² areas at second floor building. There are living room, kitchen, 2 bedroom, bathroom and hall, and four people are living in residence. Schematic representation of the residence is shown in the Figure V.3.

Table B.1 shows design conditions of the residence. Location of residence is in Iowa in Newville. Outside temperatures are 40 °C in summer and -31 °C in winter. For summer, grains of moisture are 100. Inside temperatures are 24 °C in summer and 21 °C in winter. Relative humidity is 55 %.

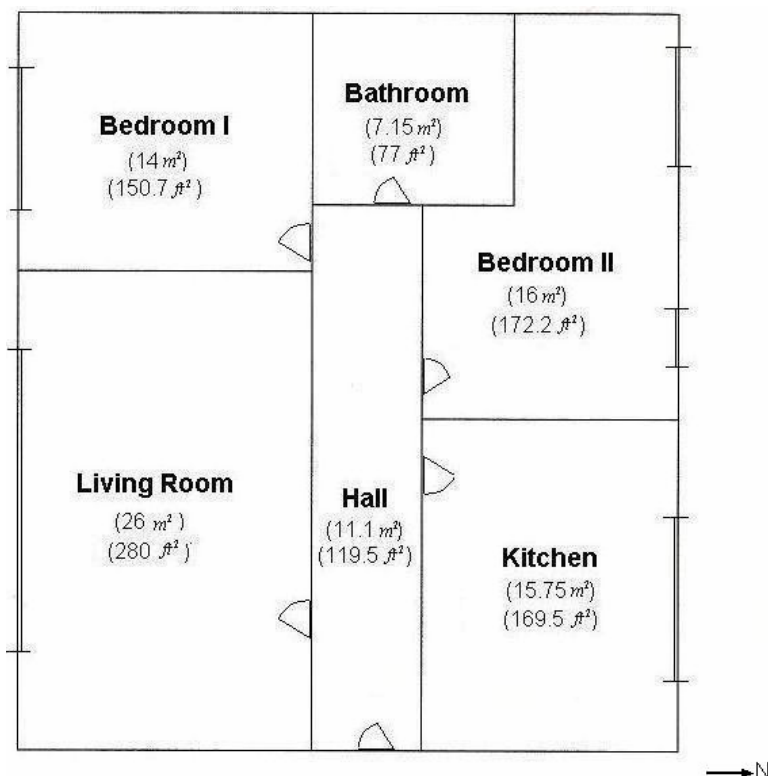


Figure V.3. Schematic representation of the residence

In heating season, temperature of supply air is below 49°C (heat pump). The duct is enclosed in unheated space e.g. vented or unvented crawl space or basement. The duct insulation is selected as R-2 (Table B.3). Based on the floor area of 90 m², the recommendation of the software for infiltration is selected. Infiltration air changes per hour are 0.5 for summer and 1.08 for winter (Table B.2).

The wall construction of the residence is 8 or 12 in. (20.32 or 30.48 cm) block, extends to 5' below grade. Insulation of the walls is selected as R-5 (1 in.-2.54 cm). Selection of construction tightness is average that is loose construction and poor vapor barrier. Windows are double pane with clear glass and have no external shading. Frames of windows are vinyl. Inside shading is provided by draperies or blinds. Floors are over conditioned space.

Living room has 26 m² floor areas. In living room, 4 people are selected for during the time of peak cooling load. There is a fireplace in living room and it affects air leakage. It is selected as average-glass door, damper.

Kitchen has 15.75 m² floor areas. There are has 4 people in the kitchen during the time of the peak cooling load. There is 1200 Btu/h (351.69 W) miscellaneous cooling load. Fireplace is selected as same quality as in the living room.

Hall is 11.1 m² and maximum 2 people are in hall during the time of the peak cooling load. Outdoor of the residence is in hall and door is solid wood with a metal storm.

Bedroom-I and bedroom-II has 14 m² and 16 m² floor areas, respectively. During the time of the peak cooling day, there are 2 people in the bedrooms.

Bathroom is 7.15 m². Floor of the bathroom is over unheated basement that is different from other rooms. There is carpet over the floor. In bathroom, there is a ventipane. It is single pane with 85 % outside shading and it has 0.6 emittance of glass. Frame of the window is vinyl. Window is also reflective coating.

After entering all data to the software program, total heat gain and heat loss are obtained. Total heat gain or cooling load of the house is 14812 Btu/h (4.34 kW) and total heat loss or heating load of the house is 18567 Btu/h (5.44 kW). The results are rounded off 15000 Btu/h (4.4 kW) for cooling load and 19000 Btu/h (5.6 kW) for heating load.

V.2.2. Electrical Consumption

Electrical consumption of the residence includes lights and electrical appliances that household use. Electrical consumption is separated according to summer and winter with day and night options. In summer, daylight is selected as 14 hours and night is selected as 10 hours. In winter, daylight is selected as 10 hours and night is selected as 14 hours. Electrical consumption of the residence is calculated according to electric consumption of each room per day.

In living room, electrical appliances are chosen as 6 times 60W bulb, a 25 inch (63.5 cm) Television, a CD/DVD player, a portable stereo, surrounding sound system and a mobile phone. Total electrical energy requirement of the appliances is 1135 Watts. Usage hours of the appliances and energy consumptions according to season and time options are shown in the tables C.1 and C.2.

In kitchen, there are more electrical appliances than in living room. Electrical appliances are chosen as 2 times 20W energy efficient light, a cooker, a fridge freezer, a microwave, a fan, a kettle, a toaster, a coffee maker, a washing machine, a dish dryer and a dishwasher. Total energy requirement of the appliances is 16110 W. Usage hours and energy consumptions of the appliances in the kitchen are shown in the tables C.3 and C.4, respectively.

In bedroom-I, there are 2 times 20W energy efficient light, a computer with 17" monitor, an ink-jet printer, a fax machine and a portable stereo. Total electrical energy requirement of the appliances is 975 Watts (Table C.5). Daily consumptions according to season and time options are shown in the table C.6.

In bedroom-II, electrical appliances are 2 times 20W energy efficient light, a TV, a video recorder, a CD/DVD player and an iron. Total energy requirement of the appliances is 1480 Watts (Table C.7). Daily consumptions according to season and time options are shown in the table C.8.

In bathroom, there are 2 times 40W bulb, a hairdryer, an electrical shaver and an extractor fan. Total electrical energy requirement is 2100 Watts. Usage hours and electrical consumptions of the appliances of the bathroom are shown in the tables C.9 and C.10, respectively.

Other electrical appliances of the house are 2 times 20W energy efficient light in the hall, a fan heater, an alarm/security system and a vacuum cleaner. Total energy

requirement of these appliances is 1745 Watts (Table C.11). Energy consumptions of the appliances at different times are shown in the table C.12.

Total household daily electrical energy consumptions are 5.741 kWh in summer day, 8.316 kWh in summer night, 4.905 kWh in winter day and 11.404 kWh in winter night (Table C.13). Electrical appliances are used more at nights than days because high energy required appliances are used at nights. In winter nights, there are more electrical energy consumption than in summer nights because of longer winter nights than summer nights, and vice versa for daylight option.

Total electrical energy consumption of appliances in summer is 14.057 kWh per day and total electrical energy consumption of appliances in winter is 16.309 kWh per day. Average daily electrical consumption of the house is 15.183 kWh (Table C.13).

V.2.3. Domestic Water Heating

Requirement of domestic water heating is presented both in winter and in summer. Daily hot water consumption of the house depends on some parameters such as age, race, income, seasonal variation and number of people in the household. The energy required for domestic water heating depends on the volume, the design hot water temperature, and the temperature of the incoming city water. The typical 4 people single family household (two adults and two children) represents the best estimate of the mean consumption [12].

The main factors in determining the energy use for water heating are the consumption profile, the heater efficiency, the design hot water temperature, and the incoming city water temperature. The temperature of city water depends on the air, water reservoir, and ground temperatures. However, for sufficiently long water pipes the city water temperature would be practically the same as the ground temperature at the depth of the pipes [12].

Domestic hot water temperatures are assumed to be 50°C in winter and 35°C in summer conditions. The incoming water temperature changes at seasonal variations. The incoming water temperatures are selected as 5°C in winter and 20°C in summer.

Domestic hot water is approximately used 50-100 liters per person per day. Usage of domestic hot water is assumed to be 300 liters per day in winter and 250 liters per day in summer for 4 people household.

Required energy of the domestic water heating can be calculated with the help of the above data that is assumed. Calculation of the required energy of the domestic water heating is made by the following equation.

$$Q_{DWH} = m_{\text{water}} C_{p_water} (\Delta T_{\text{water}}) \quad (V.58)$$

where,

m_{water} = mass of the domestic water per day

ΔT_{water} = temperature difference between hot water and incoming water.

In winter, 300 liters/day water must be heated from 5°C to 50°C, required energy is,

$$Q_{DWH} = 300 \times 4.18 \times (50 - 5) = 56430 \text{ kJ} = 15.675 \text{ kWh}$$

In summer, 250 liters/day water must be heated from 20°C to 35°C, required energy is,

$$Q_{DWH} = 250 \times 4.18 \times (35 - 20) = 15675 \text{ kJ} = 4.355 \text{ kWh}$$

V.2.4. Calculation of Cogeneration Cases

From the previous sections, all energy requirements of the residential house are calculated. Cooling and heating loads of the residence are 15000 Btu/h (4.4 kW) and 19000 Btu/h (5.6 kW), respectively. Required energy of the domestic hot water is 15.7 kWh in winter and 4.4 kWh in summer. Electrical energy required for appliances is about 16.3 kWh in winter and 14 kWh in summer. All required energies are daily calculations.

Required energies are supplied by electrical and thermal energies of the PEM fuel cell model. Operation temperature and pressure of the PEM fuel cell model is selected to be 80°C and 3 atm, respectively. At that temperature and pressure, electrical power is 5437 W and thermal power (useful heat generation according to change of enthalpy of the fuel cell reaction) is 5703 W of the PEM fuel cell. Electrical energy can be used for electrical appliances, domestic water heating and space heating (heat pump or electrical heater). Thermal energy can be used for domestic water heating and space heating. Obtaining thermal energy of the fuel cell is conserved in the insulated thermal storage tank. There are some heat losses in the

storage tank. In the storage tank, there are 10 % heat loss of the produced thermal energy in winter and 4 % heat loss of the produced thermal energy in summer.

There are 12 cases to compensate energy requirement of the house at different conditions. These are:

Cases 1-4

For the first four cases, space heating is supplied by heat pump at different types for each cases and water heating is supplied by thermal energy. Heat pump model is chosen according to winter condition. In summer, energy consumption of partial load of the heat pump is neglected. The brand of the heat pump is selected as Whirlpool. From case-1 to case-4, models of the heat pump are WGH100, WGH200, WH100 and WH200, respectively. For case-1, model of the heat pump is WGH100, WGH142, WEC, WUC46B with 20180 Btu/h (5.91 kW) heating capacity, COP=1.91, and 3.10 kW electric consumption. For case-2, model of the heat pump is WGH200, WGH248, WEC, WUC58C, D with 19030 Btu/h (5.58 kW) heating capacity, COP=1.69, and 3.30 kW electric consumption. For case-3, model of the heat pump is WH100, WH148, WEC, WUC58C, D with 19100 Btu/h (5.6 kW) heating capacity, COP= 1.70, and 3.45 kW electric consumption. For case-4, model of the heat pump is WH200, WH248, WEC, WUC60D with 19200 Btu/h (5.63 kW) heating capacity, COP=1.90, and 3.18 kW electric consumption.

For space heating, running time of the heat pump is calculated as,

$$t_{HP} = \frac{19000 \times 24}{HP \text{ capacity (Btu/h)}} \quad (V.59)$$

Required energy for space heating is,

$$Q_{SH} = \text{energy consumption of HP} \times t_{HP} \quad (V.60)$$

For cases 1-4,

Electrical energy need \Rightarrow space heating (HP) + electric consumption

Thermal energy need \Rightarrow water heating

Calculation of the operation time of the fuel cell is found according to electrical energy need. This means all electrical energy of the fuel cell is consumed.

$$t_{\text{fuel cell}} = \frac{\text{EE need}}{5.437} \quad (\text{V.61})$$

Obtaining thermal energy in the storage tank is,

$$\text{TE} = 5.703 \times t_{\text{fuel cell}} - 10\% \text{ loss} \quad (\text{V.62})$$

Remaining thermal energy is calculated as,

$$\text{remaining TE} = \text{TE} - \text{TE need} \quad (\text{V.63})$$

In summer, same heat pump models are used. For case-1, cooling capacity is 36775 Btu/h (10.78 kW) with 5.28 kW electrical consumption. For case-2, cooling capacity is 43400 Btu/h (12.72 kW) with 4.85 kW electrical consumption. For case-3, cooling capacity is 43000 Btu/h (12.6 kW) with 5.07 kW electrical consumption. For case-4, cooling capacity is 44000 Btu/h (12.9 kW) with 4.87 kW electrical consumption.

For space cooling, operation time of the heat pump is calculated as,

$$t_{\text{HP}} = \frac{15000 \times 24}{\text{HP capacity}} \quad (\text{V.64})$$

Using heat pump, required energy for space cooling is,

$$Q_{\text{SC}} = \text{energy consumption of HP} \times t_{\text{HP}} \quad (\text{V.65})$$

For cases from 1 to 4,

Electrical energy need \Rightarrow space heating (HP) + electric consumption

Thermal energy need \Rightarrow water heating

Calculation of the run time of the fuel cell is same as equation (V.61) and production of the thermal energy in the storage tank is,

$$\text{TE} = 5.703 \times t_{\text{fuel cell}} - 4\% \text{ loss} \quad (\text{V.66})$$

Remaining thermal energy is calculated as in equation (V.63)

Cases 5-8

For cases from 5 to 8, space heating is supplied by heat pump at different types for each cases and water heating is supplied by thermal energy as cases 1-4. However, heat pump model is chosen according to summer condition. When heat pump capacity is chosen for summer condition it is inadequate for winter. Therefore, thermal energy is used to supplement space heating requirement of the residential in winter. Needed thermal energy is compensated by thermal energy of fuel cell and combustion of unused hydrogen of fuel cell.

The brand of the heat pump is Whirlpool. From case-5 to case-8, models of the heat pump are WGH100, WGH200, WH100 and WH200, respectively. For case-5, model of the heat pump is WGH100, WGH118, WEC, WUC24A, B, C with 16150 Btu/h (4.73 kW) cooling capacity and 2.05 kW electric consumption. For case-6, model of the heat pump is WGH200, WGH218, WEC, WUC30A, B, C with 15545 Btu/h (4.56 kW) cooling capacity and 1.80 kW electric consumption. For case-7, model of the heat pump is WH100, WH118, WEC, WUC24A, B, C with 15500 Btu/h (4.54 kW) cooling capacity and 1.92 kW electric consumption. For case-8, model of the heat pump is WH200, WH218, WEC, WUC30A, B, C with 15500 Btu/h (4.54 kW) power capacity and 1.72 kW electric consumption.

Calculations are same as in summer condition of cases 1-4.

In winter, same heat pump models are used as in summer. For case-5, heating capacity is 7160 Btu/h (2.1 kW), COP=1.59, with 1.32 kW electrical consumption. For case-6, heating capacity is 4640 Btu/h (1.36 kW), COP=1.30, with 1.05 kW electrical consumption. For case-7, heating capacity is 5300 Btu/h (1.55 kW), COP=1.40, with 1.29 kW electrical consumption. For case-8, heating capacity is 7300 Btu/h (2.14 kW), COP= 1.60, with 1.37 kW electrical consumption.

Heat pumps work all day in winter.

$$Q_{HP} = \text{energy consumption of HP} \times 24 \quad (\text{V.67})$$

Required thermal energy for space heating equals to required energy for space heating minus heating capacity of heat pump.

Electrical and thermal energy needs are:

Electrical energy need \Rightarrow space heating (HP) + electric consumption

Thermal energy need \Rightarrow space heating (TE) + water heating

There are 4 scenarios of each cases of from 5 to 8 in winter.

Scenario I:

In this scenario, operation time of the fuel cell is calculated according to thermal energy need so all thermal energy is consumed.

$$t_{\text{fuel cell}} = \frac{\text{TE need}}{5.703 - 10\% \text{ loss}} \quad (\text{V.68})$$

Production of the electrical energy of the fuel cell is,

$$EE = 5.437 \times t_{\text{fuel cell}} \quad (\text{V.69})$$

Remaining electrical energy is,

$$\text{remaining EE} = EE - EE \text{ need} \quad (\text{V.70})$$

Scenario II:

Operation time of the fuel cell is calculated according to both electrical and thermal energy need. In this scenario, some electrical energy remains and this energy is changed to thermal energy in the storage tank to compensate thermal energy need of the house. Therefore, all electrical and thermal energy is consumed.

$$t_{\text{fuel cell}} = \frac{\text{Electrical energy need} + \text{thermal energy need}}{5.437 + (5.703 - 10\% \text{ loss})} \quad (\text{V.71})$$

Obtaining electrical and thermal energies are calculated by the equations (V.69) and (V.62).

Scenario III:

In scenario III, unused hydrogen of the fuel cell is combusted at 350°C with 95 % efficiency to obtain more thermal energy.



At 350°C ,

$$\begin{aligned} TE(H_2) &= \dot{m}_{H_2-in} \times \left(\frac{241000}{M_{H_2O}} + C_{p-H_2O} \times (350 - 25) \right) \\ &= 0.02016 \times \left(\frac{241000}{2.016} + 1.8723 \times (350 - 25) \right) = 2422 \text{ W} = 2.422 \text{ kW} \end{aligned} \quad (V.73)$$

Operation time of the fuel cell is calculated according to thermal energy need.

$$t_{\text{fuel cell}} = \frac{\text{thermal energy need}}{(5.703 + 2.422 \times 0.95) - 10\% \text{ loss}} \quad (V.74)$$

Production of electrical energy and remaining electrical energy are calculated by equations (V.69) and (V.70), respectively.

Scenario IV:

Operation time of the fuel cell is calculated by the equation (V.61). Combustion of unused hydrogen is added to thermal energy of the storage tank.

Obtaining thermal energy is,

$$\text{thermal energy} = (5.703 + 2.422 \times 0.95) - 10\% \text{ loss} \quad (V.75)$$

Obtaining thermal energy does not compensate required thermal energy so needed thermal energy is,

$$\text{required TE} = \text{TE need} - \text{TE} \quad (V.76)$$

Case-9

Energy requirement at case-9 is same as at case-1 except water heating is supplied by electrical energy.

In winter,

Electrical energy need \Rightarrow space heating (HP) + water heating + electric consumption

Thermal energy need $\Rightarrow 0$

Calculations are same as in the equations (V.59), (V.60), (V.61), (V.62) and (V.63).

In summer,

Electrical energy need \Rightarrow space cooling (HP) + water heating + electric consumption

Thermal energy need $\Rightarrow 0$

Calculations are same as at case-1 in summer condition.

Case-10

In this case, space heating is supplied by thermal energy, space cooling is supplied by same heat pump model as at case-8 and domestic water heating is supplied by electrical energy.

In winter,

Electrical energy need \Rightarrow water heating + electric consumption

Thermal energy need \Rightarrow space heating (TE)

There are four scenarios of case-10 in winter.

Scenario I:

The fuel cell works 24 hours in a day. Obtaining electrical and thermal energies are calculated by the equations (V.69) and (V.62), respectively. Obtaining thermal energy does not compensate thermal energy requirement of the residence. Therefore, some electrical energy is changed to thermal energy in the storage tank.

Required thermal energy is calculated by the equation (V.76). Remaining electrical energy is,

$$\text{remaining EE} = \text{EE} - \text{EE need} - \text{required TE} \quad (\text{V.77})$$

Scenario II:

Calculations are made according to scenario II of cases 5-8.

Scenario III:

Calculations are made according to scenario III of cases 5-8.

Scenario IV:

Calculations are made according to scenario IV of cases 5-8.

In summer,

Electrical energy need \Rightarrow space cooling (HP) + water heating + electric consumption

Thermal energy need $\Rightarrow 0$

Calculations are same as at case-8.

Case-11

Space heating is supplied by thermal energy and space cooling is supplied by heat pump. Model of the heat pump is same as at case-8 and case-10. Domestic water heating is supplied by thermal energy.

In winter,

Electrical energy need \Rightarrow electric consumption

Thermal energy need \Rightarrow space heating (TE) + water heating

There are four scenarios of case-11 and scenarios are same as at case-10.

Calculations are same as at case-10 in winter.

In summer,

Electrical energy need \Rightarrow space cooling (HP) + electric consumption

Thermal energy need \Rightarrow water heating

Calculations are same as at case-8 in summer.

Case-12

In this case, all energy requirements of the residence is supplied by electrical energy. In summer, case-12 is same as case-10. In winter, space heating is supplied by heat pump and electrical heater.

In summer,

Electrical energy need \Rightarrow space cooling (HP) + water heating + electric consumption

Thermal energy need \Rightarrow 0

In winter,

Electrical energy need \Rightarrow space heating (HP + EE) + water heating + electric cons.

Thermal energy need \Rightarrow 0

The fuel cell works 24 hours per day. Obtaining electrical energy is calculated by the equation (V.69) and required electric energy except the fuel cell is calculated as,

$$\text{required EE} = \text{EE need} - \text{EE} \quad (\text{V.78})$$

Unused thermal energy is calculated by the equation (V.62).

For all cases, usage of electrical and thermal energies of the fuel cell is calculated by the following equations.

$$\text{usage of produced EE (\%)} = \frac{\text{EE need}}{\text{EE}} \times 100 \quad (\text{V.79})$$

$$\text{usage of produced TE (\%)} = \frac{\text{TE need}}{\text{TE}} \times 100 \quad (\text{V.80})$$

Calculation results of the equations (V.79) and (V.80) exceed 100 % means that obtaining energy of the fuel cell does not compensate energy need of the residence. If

results of the equations (V.79) and (V.80) exceed 100, it is assumed that results are 100 %.

Usable energy efficiencies for I. and II. law of thermodynamics are calculated as follows,

$$\text{usable energy efficiency (I.law) (\%)} = \frac{\text{total energy produced}}{-dH \frac{\dot{m}_{H_2-in}}{M_{H_2}} t_{\text{fuel cell}}} \times 100 \quad (\text{V.81})$$

$$\text{usable energy efficiency (II.law) (\%)} = \frac{\text{total exergy produced}}{E_{H_2-in} t_{\text{fuel cell}}} \times 100 \quad (\text{V.82})$$

Used energy efficiencies according to I. and II. law of thermodynamics are calculated as,

$$\text{used energy efficiency (I.law) (\%)} = \frac{\text{total energy used}}{-dH \frac{\dot{m}_{H_2-in}}{M_{H_2}} t_{\text{fuel cell}}} \times 100 \quad (\text{V.83})$$

$$\text{used energy efficiency (II.law) (\%)} = \frac{\text{total exergy used}}{E_{H_2-in} t_{\text{fuel cell}}} \times 100 \quad (\text{V.84})$$

VI. RESULTS AND DISCUSSION

VI.1. PEM FUEL CELL MODELING

The presented results are based on the fuel cell model built up within the frame of this thesis study using Matlab. Details of the applied methodology are presented in Chapter V.1. Results are presented for three operation temperature levels, 60, 80 and 100°C and three operation pressures, 1, 3 and 5 atm. are parametrically investigated to observe their effect on selected outputs and inputs of the fuel cell and its efficiencies calculated on different bases. All results are plotted against current density of the fuel cell at selected temperatures and pressures.

Figures VI.1 to VI.25 present the effect of temperature to polarization curve, electrical power, heat generation for fuel cell reaction and all inlets, useful heat generation for the fuel cell reaction and all inlets, hydrogen inlet mass flow rate, oxygen inlet mass flow rate, water vapor in hydrogen inlet, water vapor in oxygen inlet, unused hydrogen flow rate, unused oxygen flow rate, water in hydrogen outlet, water in oxygen outlet, water production, cooling water mass flow rate for the fuel cell reaction and all inlets, electrical efficiencies according to thermodynamics first and second law for the fuel cell reaction and all inlets, and total efficiencies according to first and second law of thermodynamics for the fuel cell reaction and all inlets.

Figures VI.26 to VI.50 show the effect of pressure on the above mentioned parameters.

VI.1.1. Temperature Effects

Polarization curve: The shape of the curve of the output voltage is affected by non-linear terms as activation loss occurs at low current densities (0-0.3 A/cm²) and mass transport loss occurs at high current densities (1.1-1.4 A/cm²). Ohmic polarization affects the fuel cell output voltage in the range of 0.3-1.1 A/cm² current densities. Ohmic loss produces a linear relationship between voltage and current density. As current density increases, output voltage decreases because voltage losses are directly proportional to current density. As fuel cell stack temperature increases, output voltage increases as shown in the Figure VI.1 because at low current densities, activation losses are dominant. Activation losses are greatly dependent to temperature changes. Ohmic losses are dominant at the straight line of the polarization curve. Temperature change does not affect ohmic losses because of equation of ohmic loss (Equation (III.35)). Concentration losses are dominant at high current densities of the polarization curve.

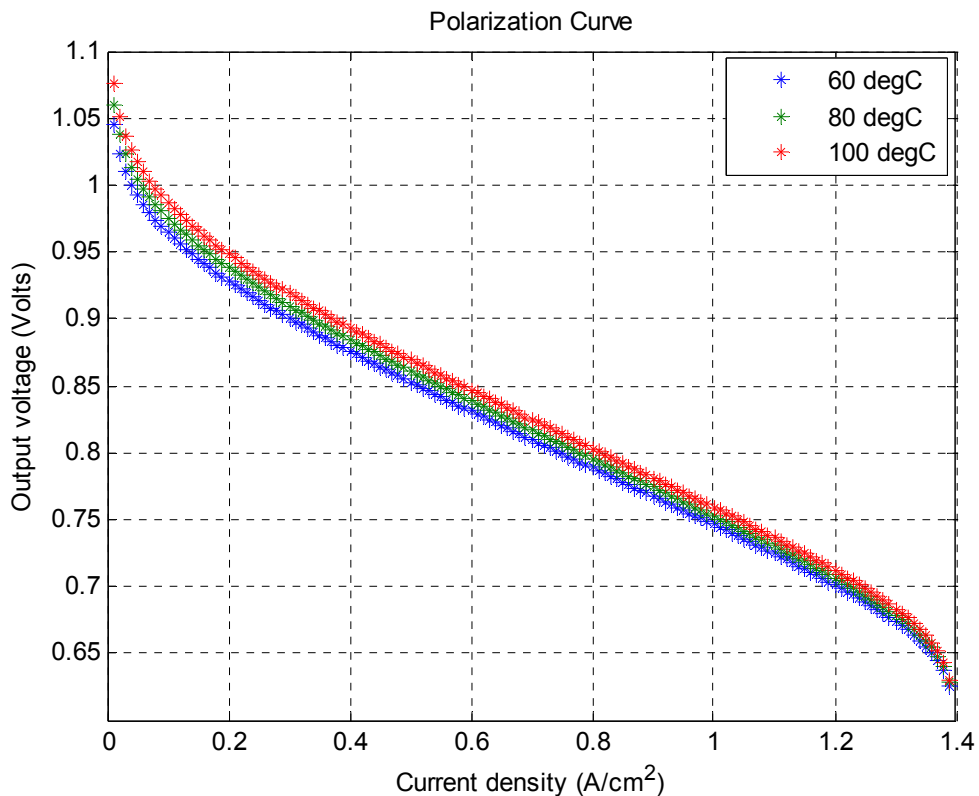


Figure VI.1. Polarization curve at different temperatures

Electrical power output: Electrical power output is linearly proportional to output voltage and current density. However, output voltage and current density are reversely proportional as shown in the Figure VI.1. Therefore, temperature change does not affect the electrical power much especially up to about current density of 1 A/cm^2 . Moreover, as temperature increases electrical power output increases as shown in the Figure VI.2. After about 1.35 A/cm^2 current density, electrical power output is reduced because of mass transport losses. If mass transport losses are neglected a totally linear relationship is observed.

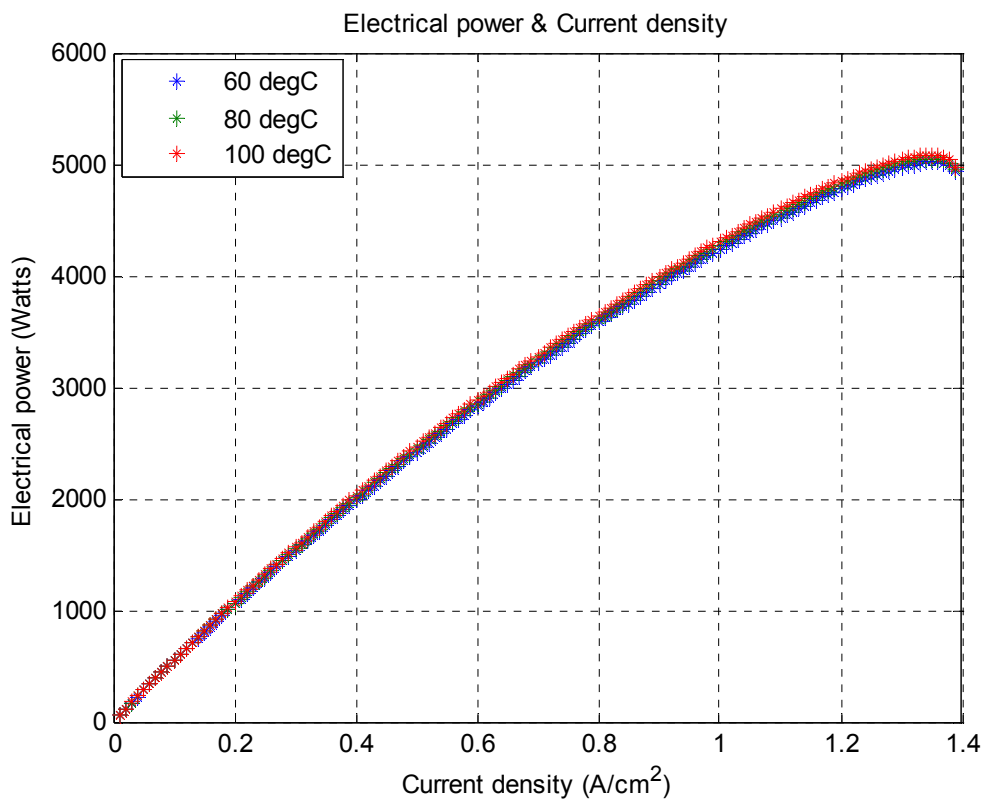


Figure VI.2.Electrical power at different temperatures

Heat generation (Hydrogen only): Heat generation of fuel cell is enthalpy of fuel cell reaction minus electrical power (Chapter V.1.2.3). When considering change of enthalpy of fuel cell reaction, heat generation in PEM fuel cell decreases as temperature increases (Figure VI.3). The reason is all energy enters in fuel cell divides two parts which are electrical and thermal power. Since increasing temperature results power increases, heat generation decreases as temperature increases. As presented in the Figure VI.2, temperature change does not affect heat generation considerably.

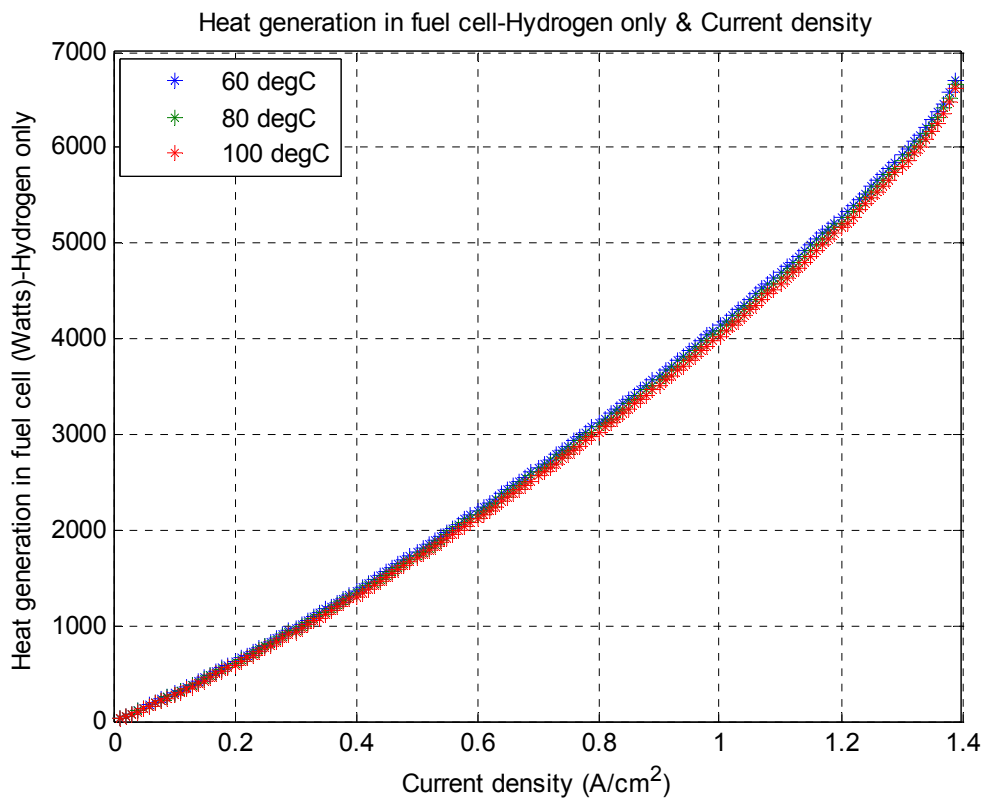


Figure VI.3.Heat generation in fuel cell (Hydrogen only) at different temperatures

Heat generation (All inlets): When considering enthalpies of all inputs, heat generation in PEM fuel cell increases as temperature increases (Figure VI.4). This figure is reverse of the Figure VI.3 according to temperature change. So ever input energy increases in the Figure VI.4 with respect to the Figure VI.3; electrical power output does not increase at constant operation temperature. Therefore, enthalpies of unreacted inputs, moisture contents of inlets, turn to heat generation and at elevated temperatures there are more heat generations. Therefore, as temperature increases enthalpy of inlets increases which results increasing heat generation.

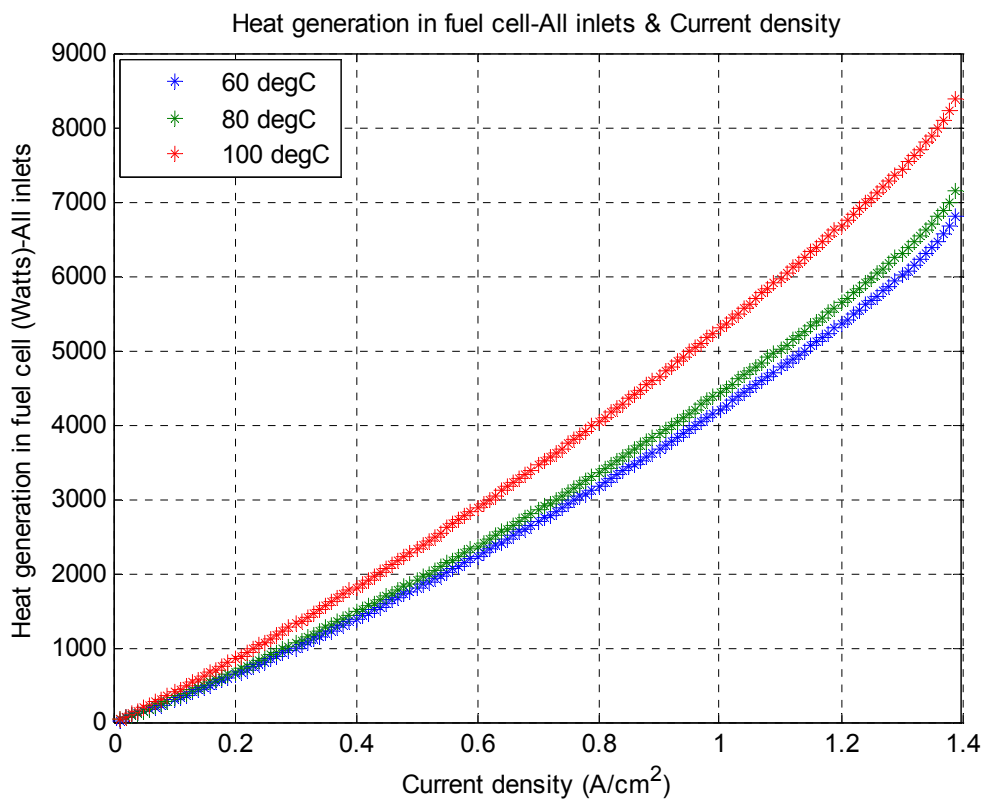


Figure VI.4.Heat generation in fuel cell (All inlets) at different temperatures

Useful heat generation (Hydrogen only): Useful heat generation considering change of enthalpy of fuel cell reaction is heat generation in the fuel cell stacks minus dissipation heat to the surrounding and heating of the hydrogen and oxygen from the ambient temperature to the operating temperature (Chapter V.1.2.4). Therefore, this graph is very similar to the Figure VI.3. As shown in the Figure VI.5, when temperature increases useful heat generation decreases.

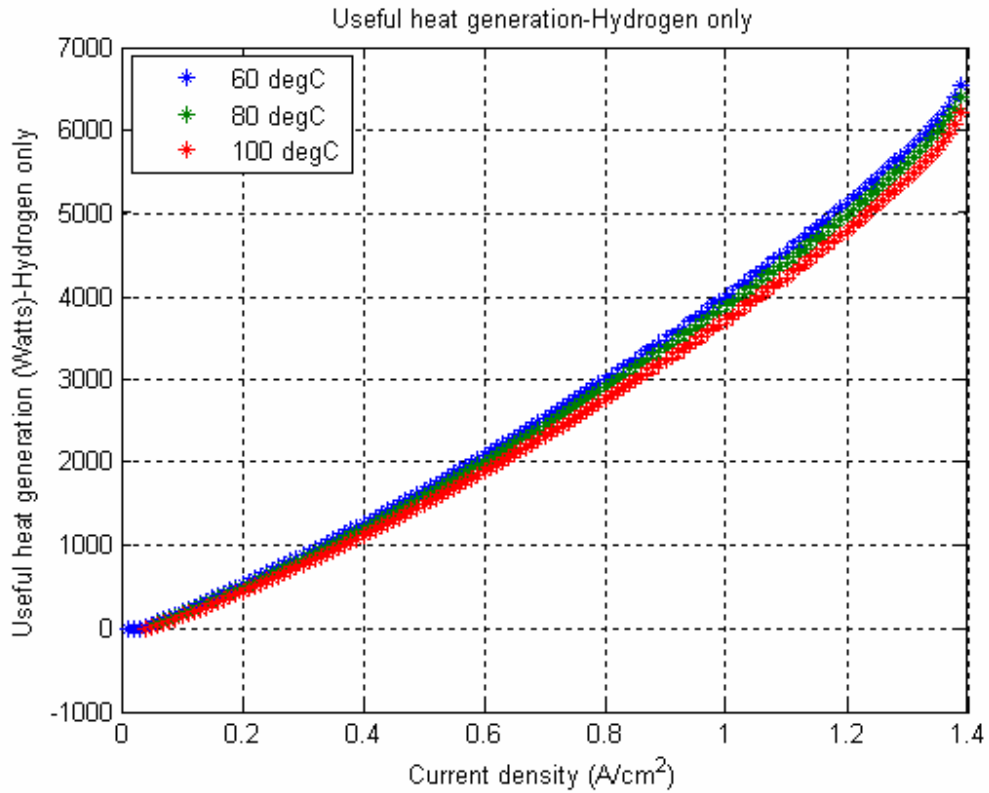


Figure VI.5. Useful heat generation (Hydrogen only) at different temperatures

Useful heat generation (All inlets): Useful heat generation considering enthalpies of all inputs is heat generation in the fuel cell stacks minus dissipation heat to the surrounding and heating of the hydrogen and oxygen from the ambient temperature to the operating temperature. The Figure VI.6 is similar to the Figure VI.4. For this reason, when temperature increases useful heat generation increases as in the Figure VI.4.

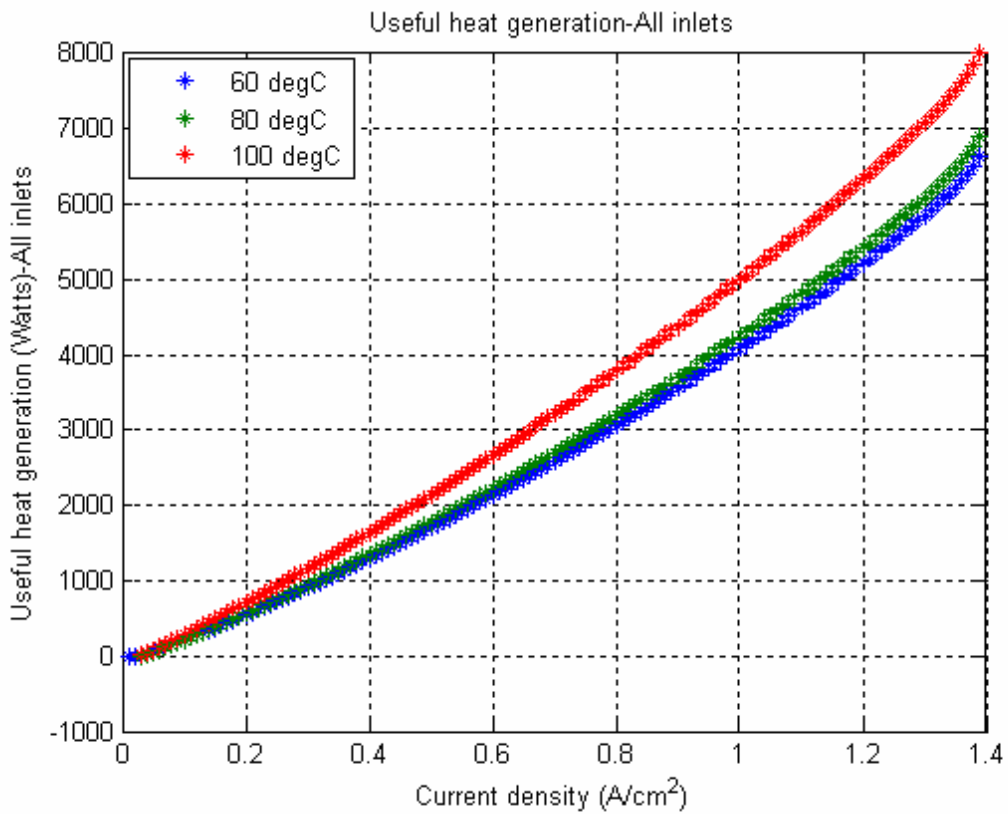


Figure VI.6. Useful heat generation (All inlets) at different temperatures

Hydrogen inlet mass flow rate: Hydrogen inlet mass flow rate is linearly proportional to current density. As temperature increases output electrical power and output voltage increases but ratio of electrical power to output voltage which gives current does not change and mass flow rate is not related to temperature changes. Therefore, hydrogen inlet mass flow rate is constant when temperature changes as illustrated in the Figure VI.7.

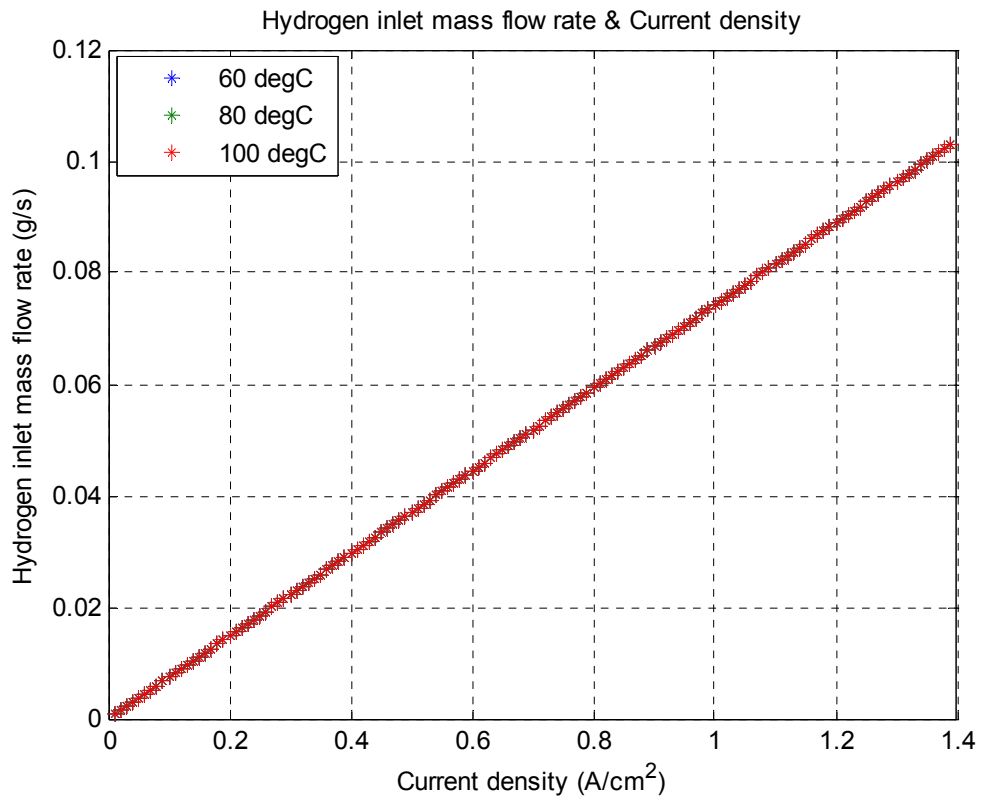


Figure VI.7.Hydrogen inlet mass flow rate at different temperatures

Oxygen inlet mass flow rate: Oxygen inlet mass flow rate is linearly proportional to current density. Temperature change does not affect oxygen inlet mass flow rate (Figure VI.8).

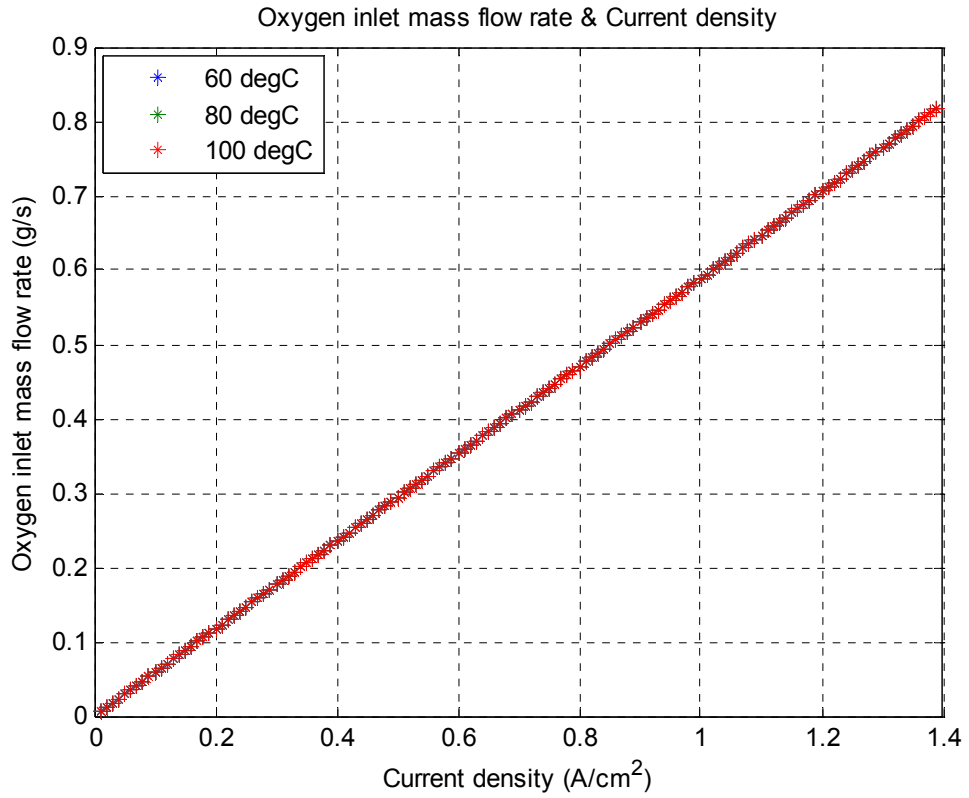


Figure VI.8. Oxygen inlet mass flow rate at different temperatures

Water vapor in hydrogen inlet: At elevated temperatures water vapor content of gases rises. Therefore, as temperature increases water vapor in hydrogen inlet increases (Figure VI.9).

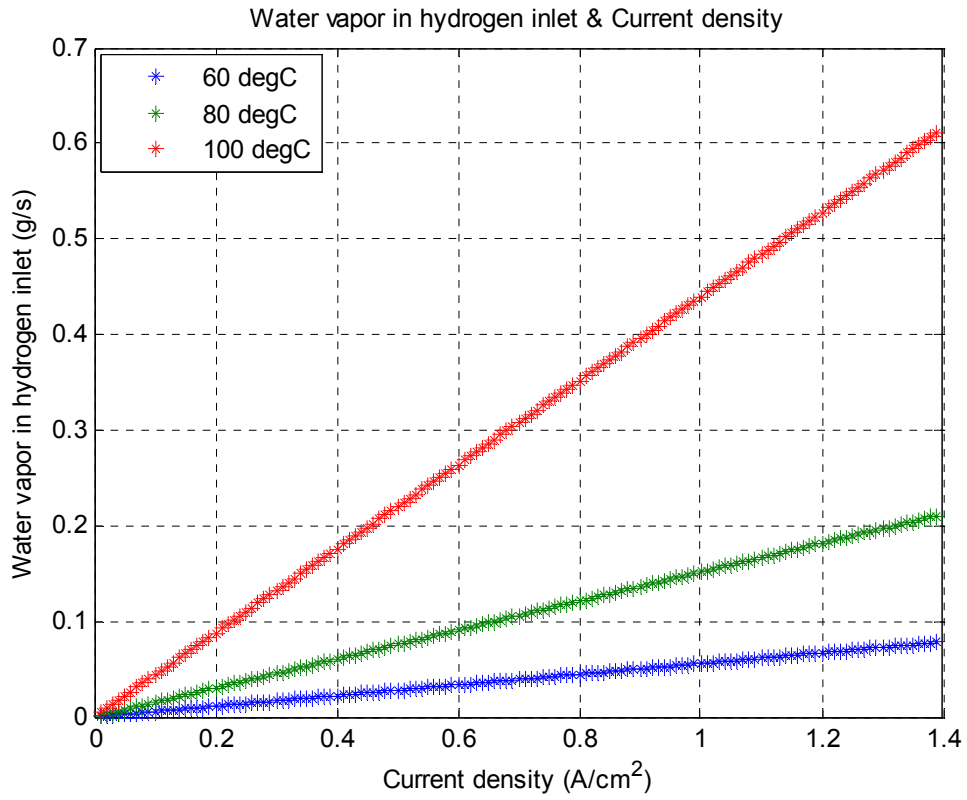


Figure VI.9. Water vapor in hydrogen inlet at different temperatures

Water vapor in oxygen inlet: Higher temperatures higher water vapor content of gases. Therefore, as temperature increases water vapor in oxygen inlet increases (Figure VI.10).

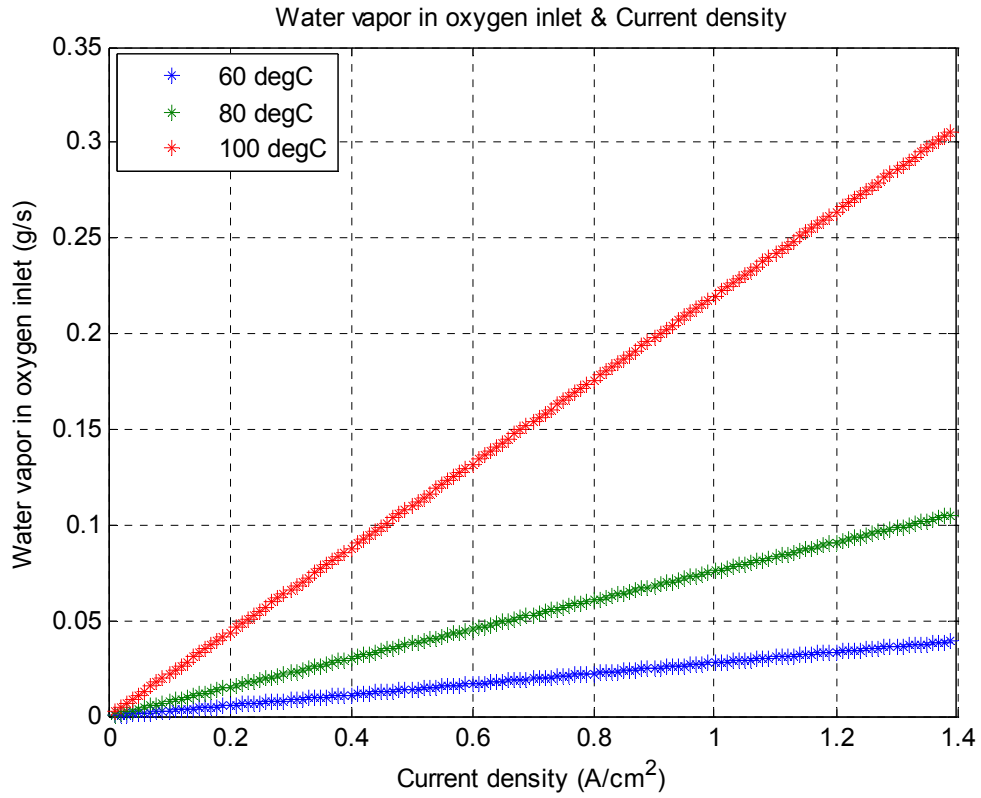


Figure VI.10. Water vapor in oxygen inlet at different temperatures

Unused hydrogen mass flow rate: Because hydrogen inlet mass flow rate is constant when temperature changes, unused hydrogen mass flow rate becomes constant as temperature changes (Figure VI.11).

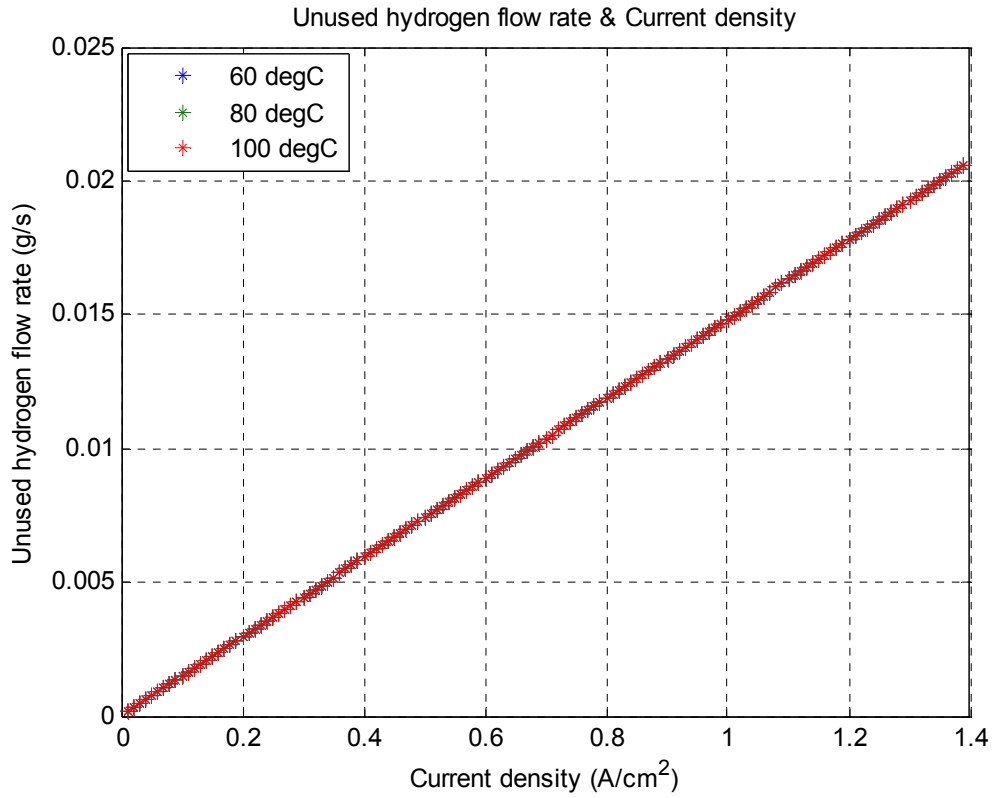


Figure VI.11. Unused hydrogen flow rate at different temperatures

Oxygen outlet mass flow rate: The figure of oxygen outlet mass flow rate is similar to the figure of oxygen inlet mass flow rate according to temperature changes. Therefore, Changing temperature does not affect oxygen outlet mass flow rate (Figure VI.12).

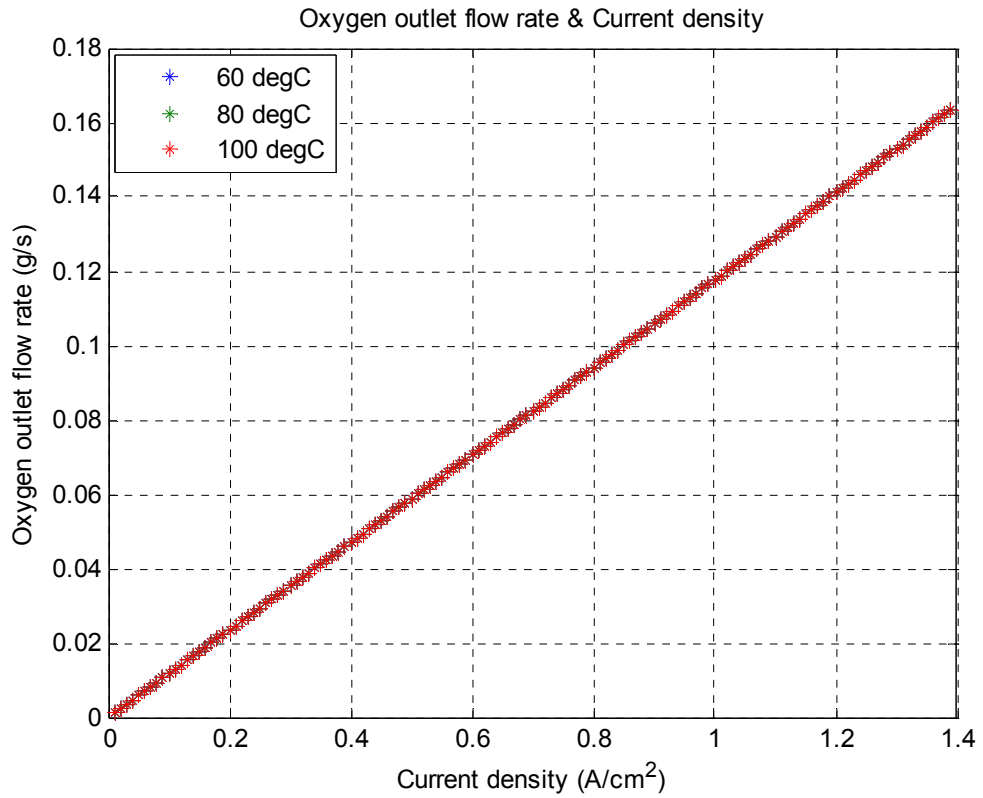


Figure VI.12. Oxygen outlet flow rate at different temperatures

Water in hydrogen and oxygen outlet: The fuel cell membrane requires humidification of reactant gases to maintain only protonic conductivity. Therefore, all water vapor in hydrogen and oxygen inlet exit from the fuel cell. Exit phase of the water vapor is liquid water. As a result, the Figures VI.13 and VI.14 are same as the Figures VI.9 and VI.10, respectively.

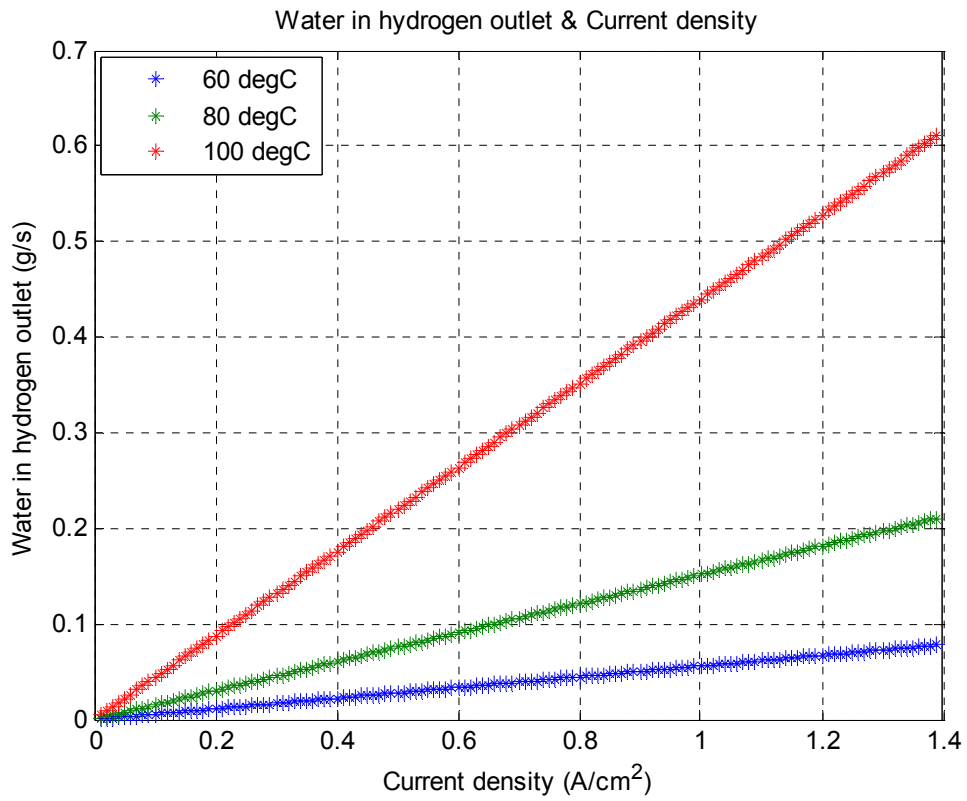


Figure VI.13. Water in hydrogen outlet at different temperatures

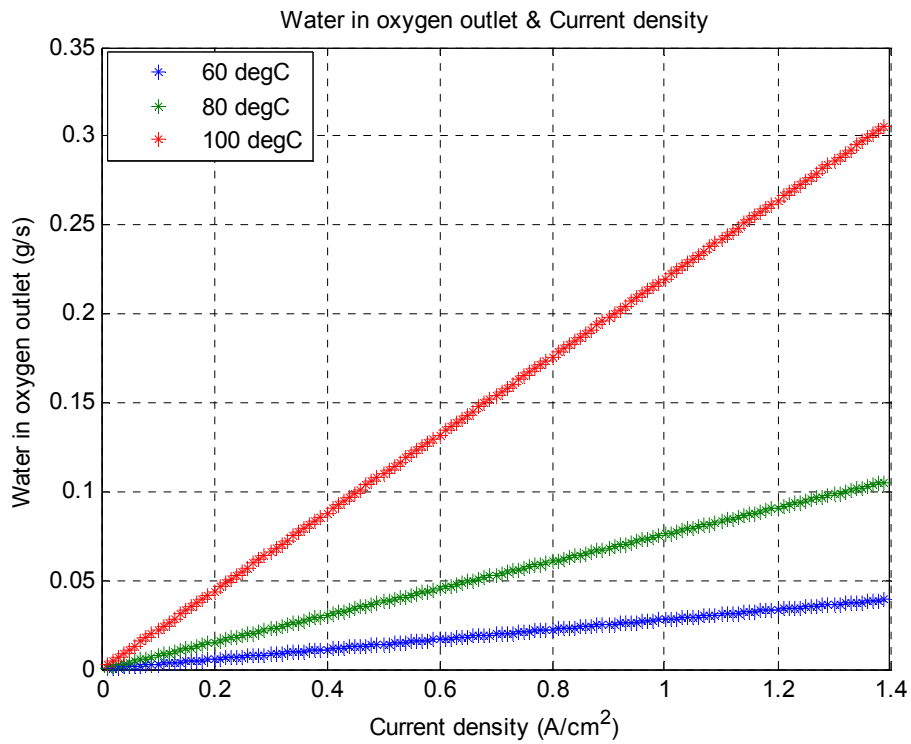


Figure VI.14.Water in oxygen outlet at different temperatures

Water production: Water consists of hydrogen and oxygen. Since when temperature changes hydrogen and oxygen consumptions become constant, water production also is not affected temperature changes (Figure VI.15).

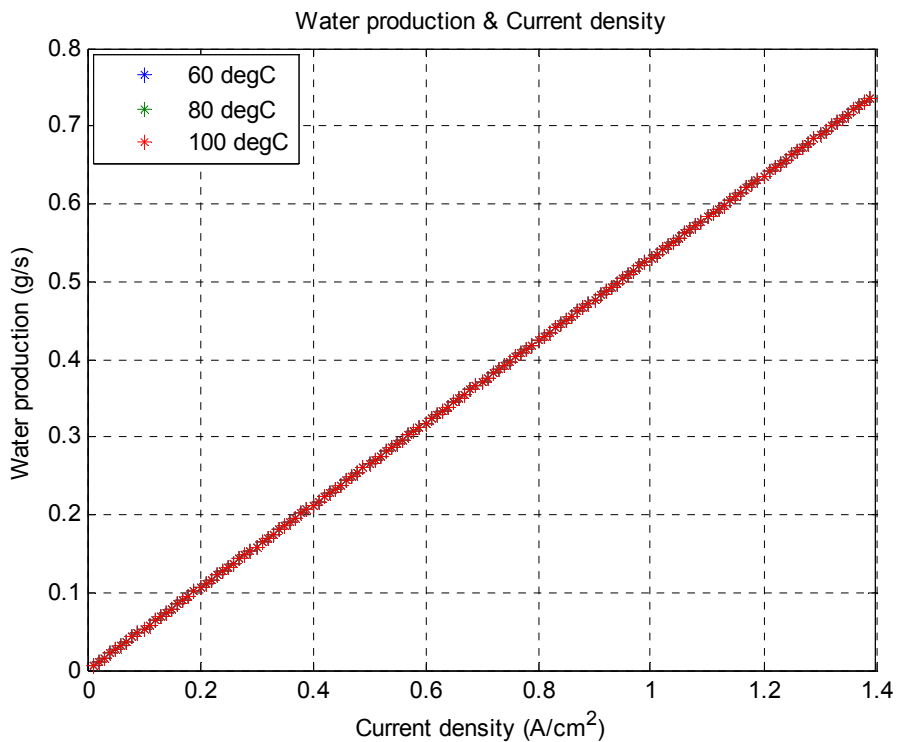


Figure VI.15.Water production at different temperatures

Cooling water mass flow rate (Hydrogen only): Cooling water takes the heat which is heat generation considering only change of enthalpy of fuel cell reaction minus heat dissipated from the stacks. Cooling water mass flow rate decreases when temperature increases as shown in the Figure VI.16. Because heat taken by cooling water decreases as temperature increases, and temperature difference increases between cooling water outlet and inlet at elevated temperatures. Furthermore, according to calculation of cooling water mass flow rate, higher temperatures lower nominator and higher denominator, and lower mass flow rate of cooling water.

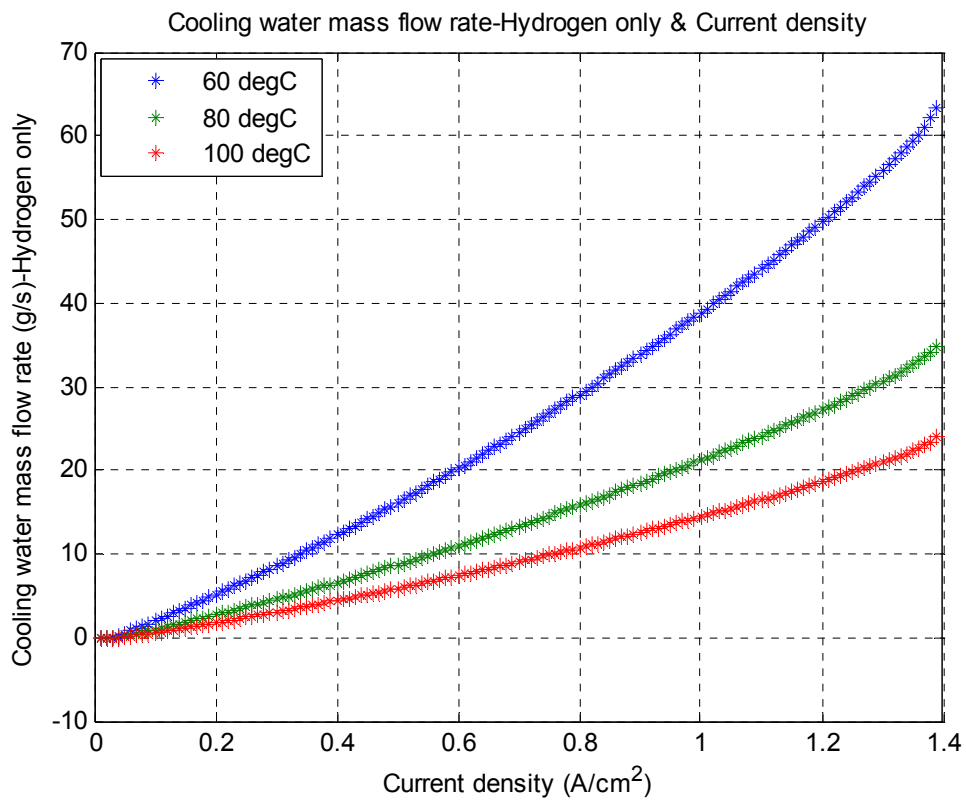


Figure VI.16. Cooling water mass flow rate (Hydrogen only) at different temperatures

Cooling water mass flow rate (All inlets): Cooling water takes the heat which is heat generation considering enthalpies of all inlets minus heat dissipated from the stacks. Figure VI.17 is very similar to previous figure. Calculation of cooling water is heat divided by differences of cooling water outlet and inlet. In contrast to heat taken by cooling water considering only enthalpy of hydrogen, heat taken by cooling water considering enthalpies of all inlets increases when temperature increases. Namely, higher temperatures higher nominators and denominators of calculation of cooling water mass flow rate. However, ratio of nominator to denominator decreases as temperature increases. Therefore, when temperature increases cooling water mass flow rate decreases.

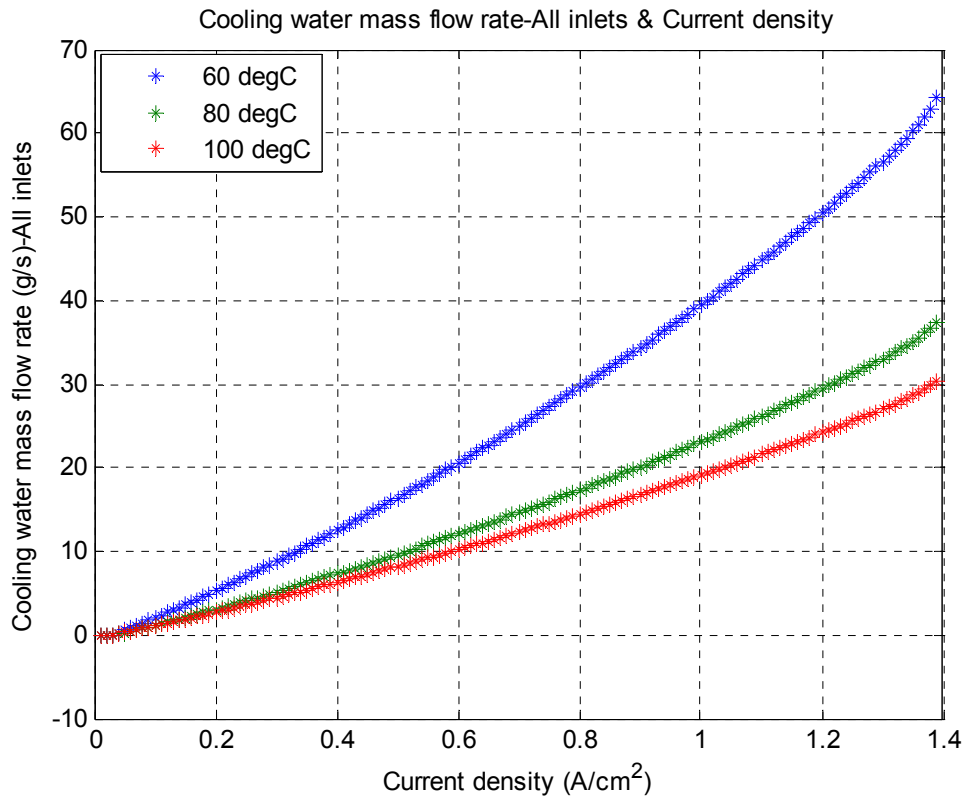


Figure VI.17. Cooling water mass flow rate (All inlets) at different temperatures

Efficiency of electricity - TD1 (Hydrogen only): Electrical efficiency according to thermodynamics first law considering only change of enthalpy of fuel cell reaction is similar to output voltage figure. Higher current densities higher voltage losses occur. As a result of this, increasing losses decrease efficiency. When temperature increases, electrical efficiency according to thermodynamics first law considering only hydrogen's HHV increases (Figure VI.18).

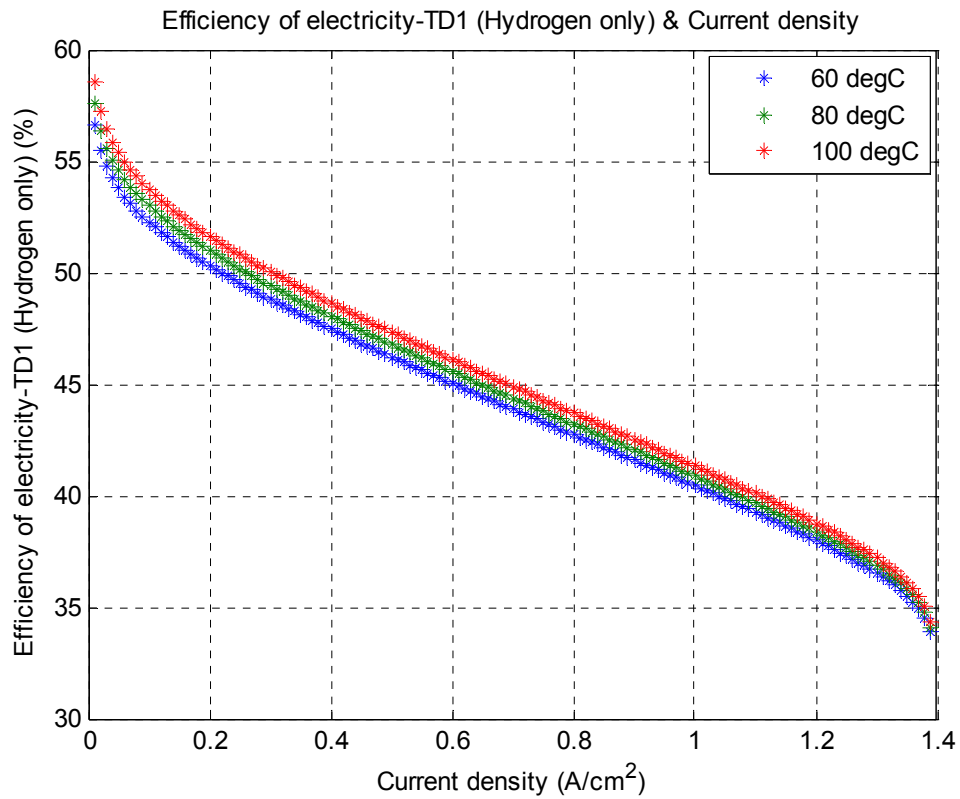


Figure VI.18.Electrical efficiency according to thermodynamics first law (Hydrogen only) at different temperatures

Efficiency of electricity - TD2 (Hydrogen only): Electrical efficiency according to thermodynamics second law considering exergy of hydrogen increases as temperature increases as shown in the Figure VI.19. In the Figure VI.19, electrical efficiency according to previous figure is higher because exergy of hydrogen is lower than hydrogen's HHV. In contrast to hydrogen's HHV, exergy of hydrogen increases when temperature increases but these increases are very small at these temperature changes.

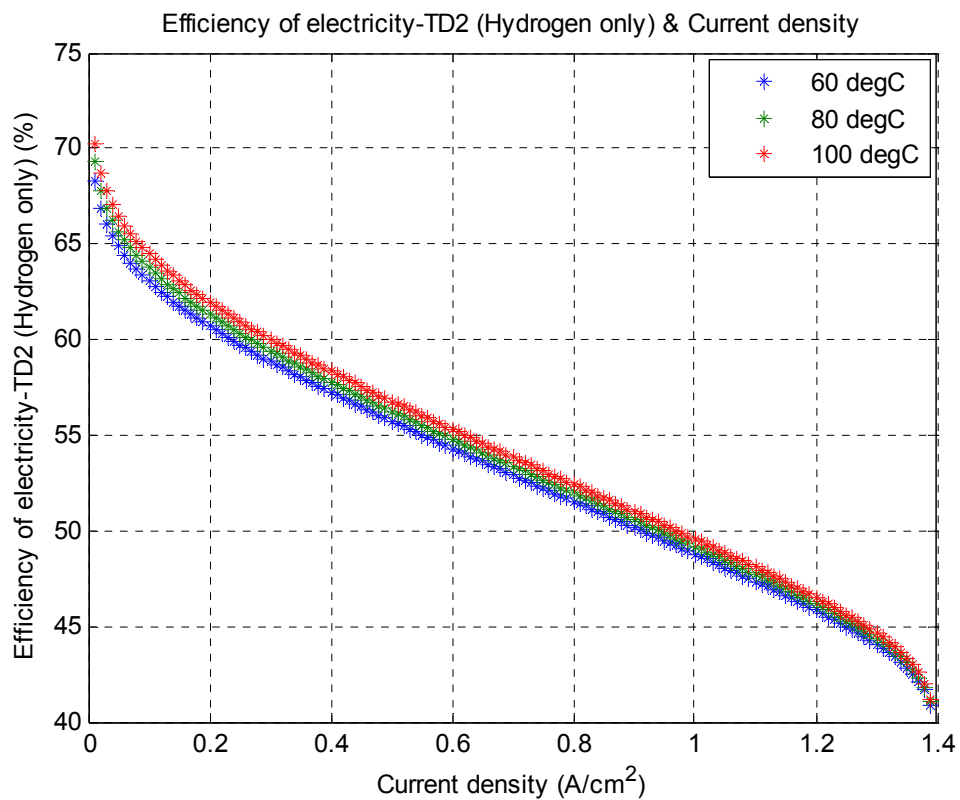


Figure VI.19.Electrical efficiency according to thermodynamics second law (Hydrogen only) at different temperatures

Efficiency of electricity - TD1 (All inlets): Electrical efficiency according to thermodynamics first law considering enthalpies of all inputs increases when temperature decreases (Figure VI.20). The reason is the enthalpies of all inputs increase much higher than electrical power at increasing temperatures and ratio of electrical power to enthalpies of all inputs is lower at elevated temperatures. Furthermore, efficiency differences are much higher between 80⁰C and 100⁰C than between 60⁰C and 80⁰C.

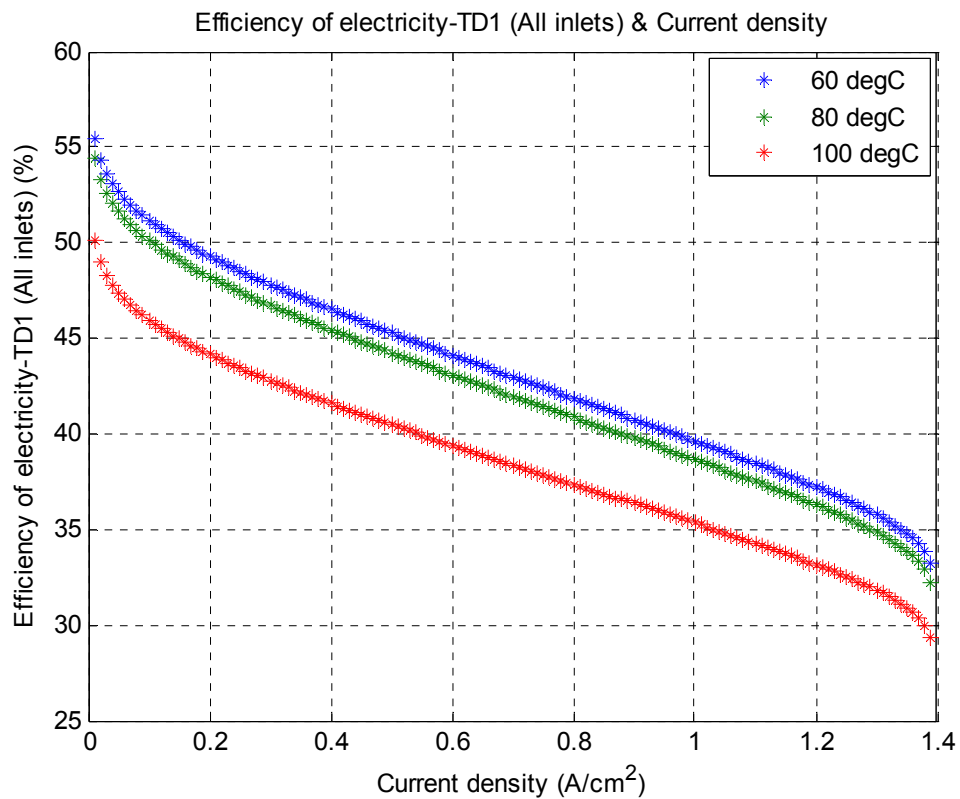


Figure VI.20.Electrical efficiency according to thermodynamics first law (All inlets) at different temperatures

Efficiency of electricity - TD2 (All inlets): Electrical efficiency according to thermodynamics second law considering all inputs' exergies increases when temperature decreases at low current densities (about 0-0.3 A/cm²) and high current densities (about 0.8-1.4 A/cm²), but in the range of the 0.3-0.8 A/cm² current densities, efficiency at 60⁰C is lower than 80⁰C (Figure VI.21). There are not many differences between the curves especially at 60⁰C and 80⁰C. The reason is that at increasing temperatures both electrical power and total inlet exergy increase very slightly and at some points efficiencies are almost same.

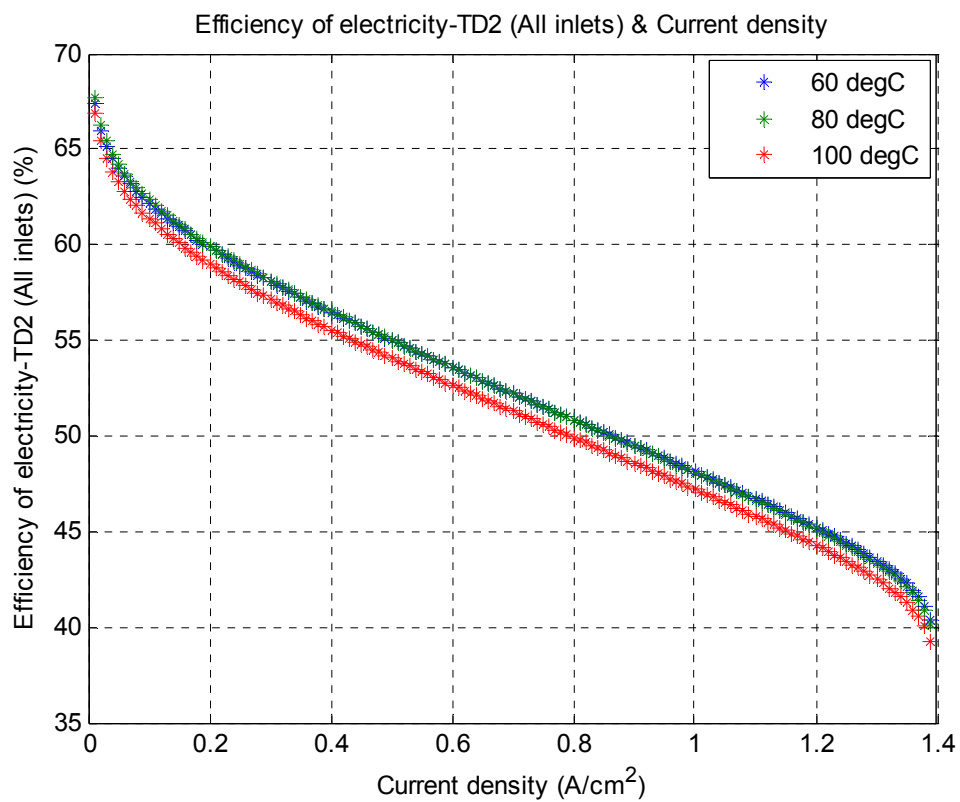


Figure VI.21.Electrical efficiency according to thermodynamics second law (All inlets) at different temperatures

Total efficiency - TD1 (Hydrogen only): Total efficiency, which includes electrical and thermal efficiency, according to thermodynamics first law considering change of enthalpy of fuel cell reaction increases when temperature decreases. Total power (electrical + thermal) according to change of enthalpy of hydrogen/oxygen fuel cell reaction decreases as temperature increases. Therefore, ratio of total energy to reaction enthalpy decreases as temperature increases (Figure VI.22).

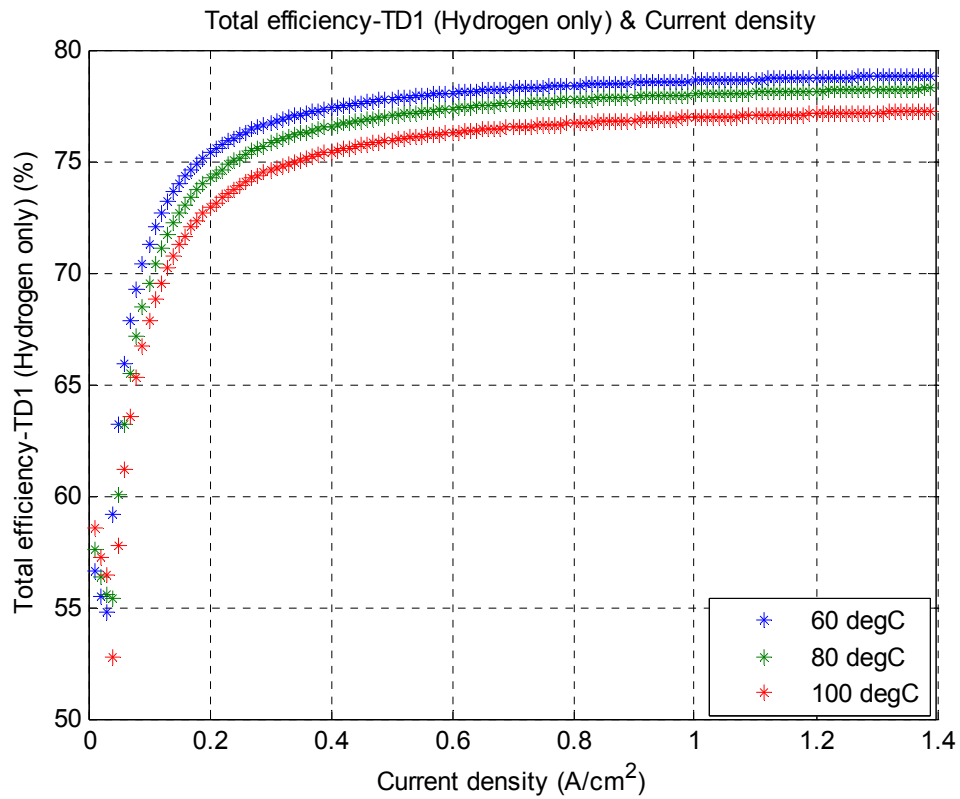


Figure VI.22. Total efficiency according to thermodynamics first law (Hydrogen only) at different temperatures

Total efficiency - TD2 (Hydrogen only): Total efficiency according to thermodynamics second law, as exergy of hydrogen is input only, increases as temperature increases as shown in the Figure VI.23. This curve is similar to electrical efficiency curves because exergy of useful heat is very small. Up to 0.05 A/cm² current density, there is some unsteadiness. The reason is that useful heat generation is zero up to 0.05 A/cm² current density. Furthermore, efficiency differences at changing temperatures are higher than electrical efficiencies. Also efficiency of this figure is lower than efficiency of first law of thermodynamics.

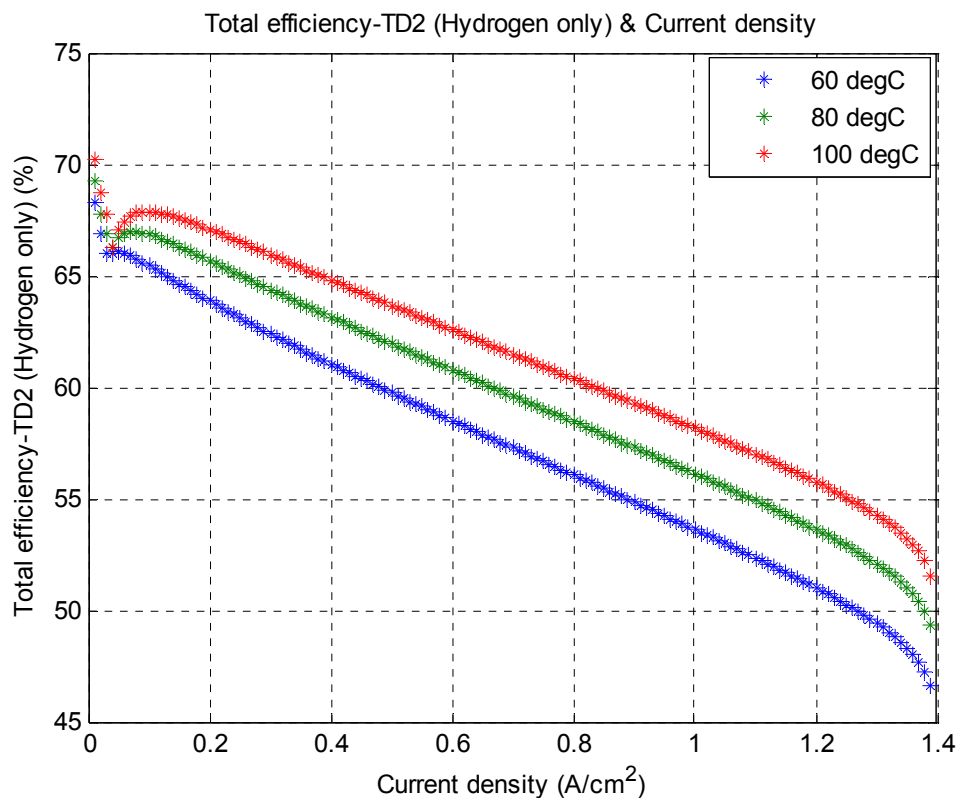


Figure VI.23. Total efficiency according to thermodynamics second law (Hydrogen only) at different temperatures

Total efficiency - TD1 (All inlets): Total efficiency according to thermodynamics first law considering enthalpies of all inlets is very similar to the Figure VI.22, as temperature increases total efficiency decreases (Figure VI.24).

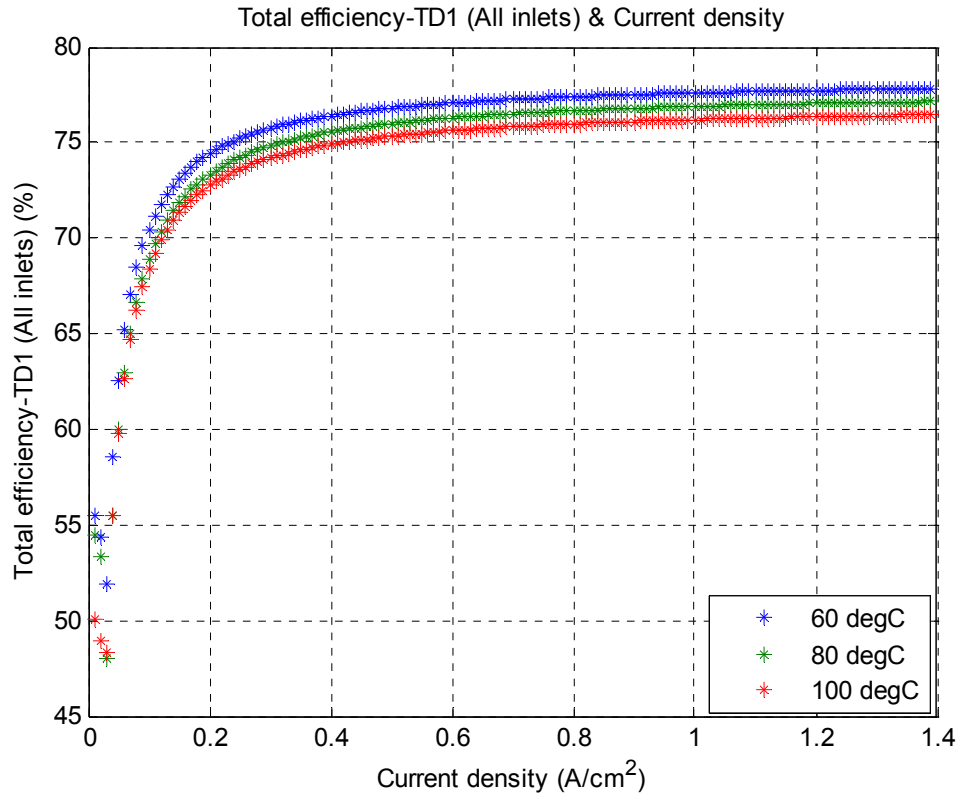


Figure VI.24. Total efficiency according to thermodynamics first law (All inlets) at different temperatures

Total efficiency - TD2 (All inlets): Total efficiency according to thermodynamics second law considering exergies of all inlets increases as temperature increases (Figure VI.25). The Figure VI.25 is similar to the Figure VI.23, but in the Figure VI.25 efficiencies are lower according to the Figure VI.23 because exergies of all inlets are higher than exergy of hydrogen.

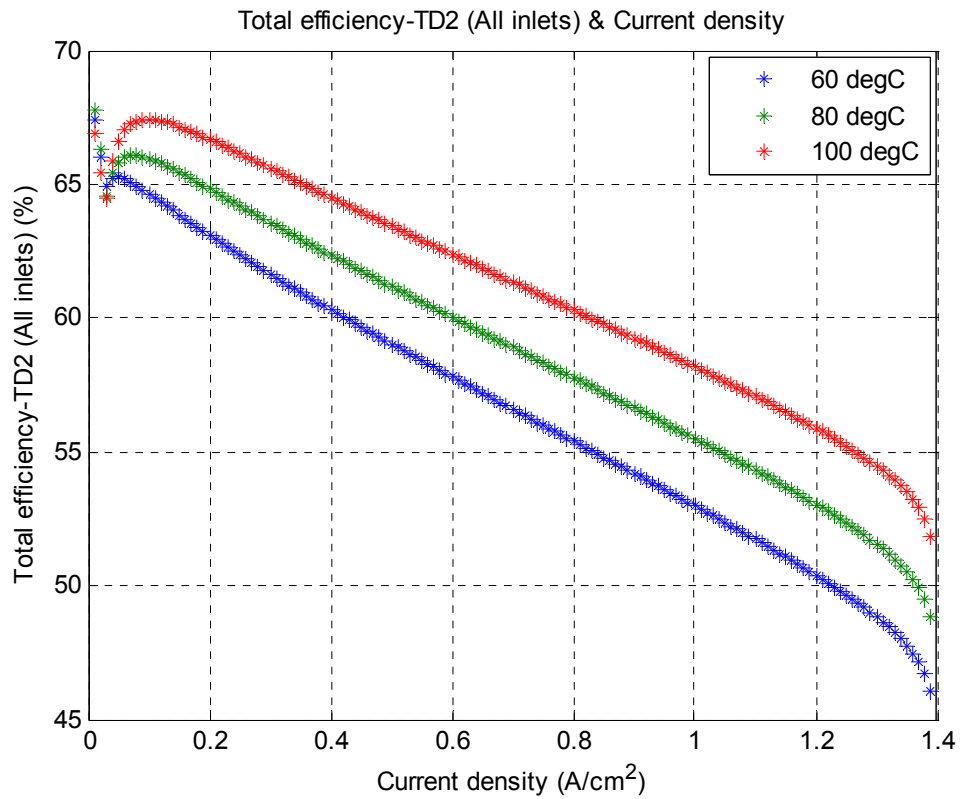


Figure VI.25. Total efficiency according to thermodynamics second law (All inlets) at different temperatures

VI.1.2. Pressure Effects

Polarization curve: The shape of the curve of the output voltage is affected by non-linear terms at low current densities (0-0.3 A/cm²) and at high current densities (1.1-1.4 A/cm²) where activation and mass transport losses are predominant respectively. Ohmic polarization affects the fuel cell output voltage in the range of 0.3-1.1 A/cm² current densities and produces a linear relationship between voltage and current density. When fuel cell operation pressure increases, output voltage increases as shown in the Figure VI.26 because Nernst equation increases at elevated pressures. Furthermore, output voltage differences are higher between 1 and 3 atm pressures than 3 and 5 atm pressures.

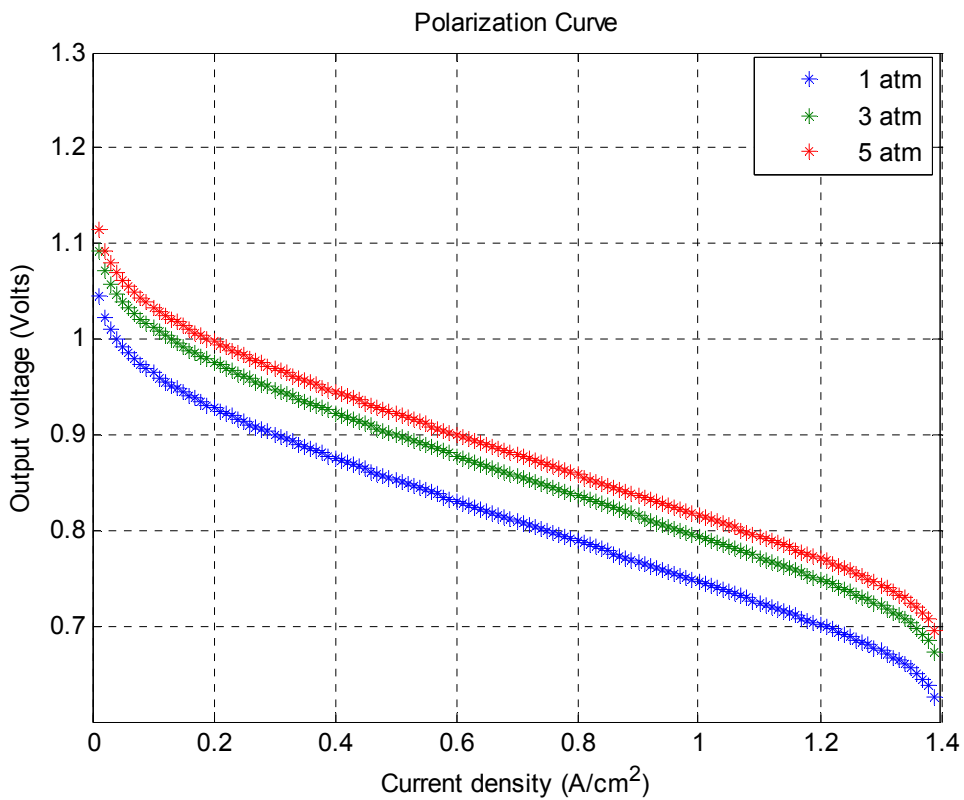


Figure VI.26. Polarization curve at different pressures

Electrical power output: Electrical power output is linearly proportional to output voltage and current density. However, output voltage and current density are reversely proportional. As a result, when pressure increases electrical power increases (Figure VI.27). After about 1.35 A/cm^2 current densities electrical power reduces because of mass transport losses. Pressure change is dominant at high current densities. At high current densities pressure change from 1 to 3 atm is more important than pressure change from 3 to 5 atm.

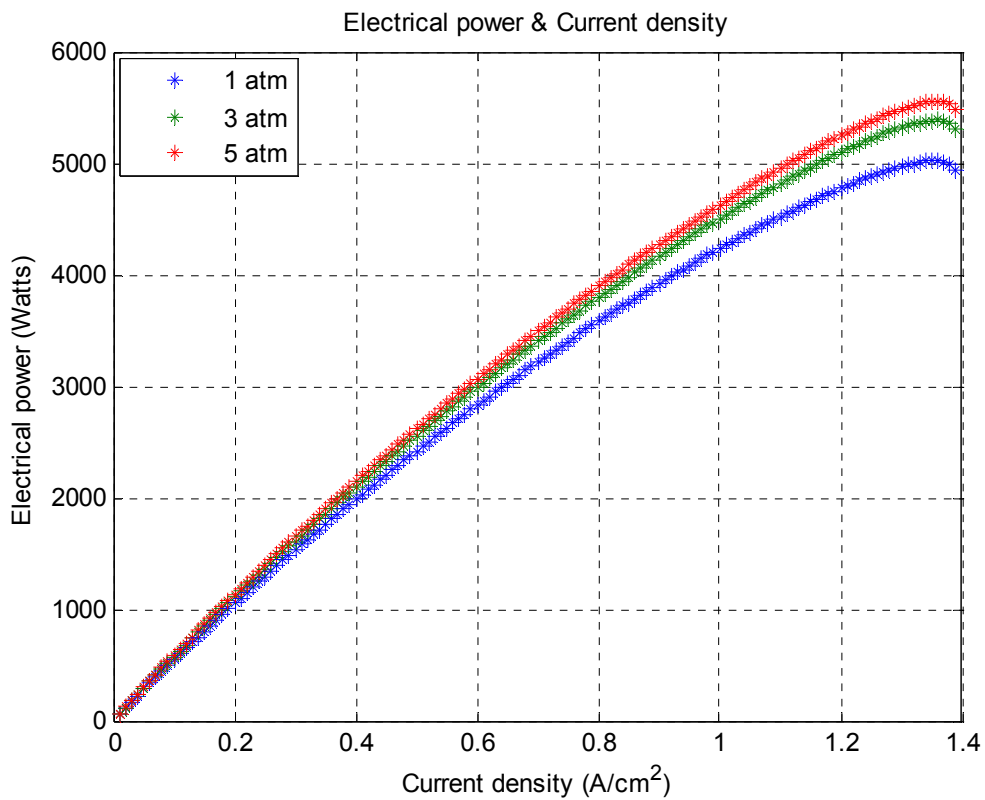


Figure VI.27. Electrical power at different pressures

Heat generation (Hydrogen only): Heat generation is considered as change of enthalpy of fuel cell reaction minus electrical power (Chapter V.1.2.3). As considering only hydrogen's HHV, heat generation in the fuel cell decreases as pressure increases (Figure VI.28). Because there is a reverse relationship between electrical power and heat generation when pressure changes.

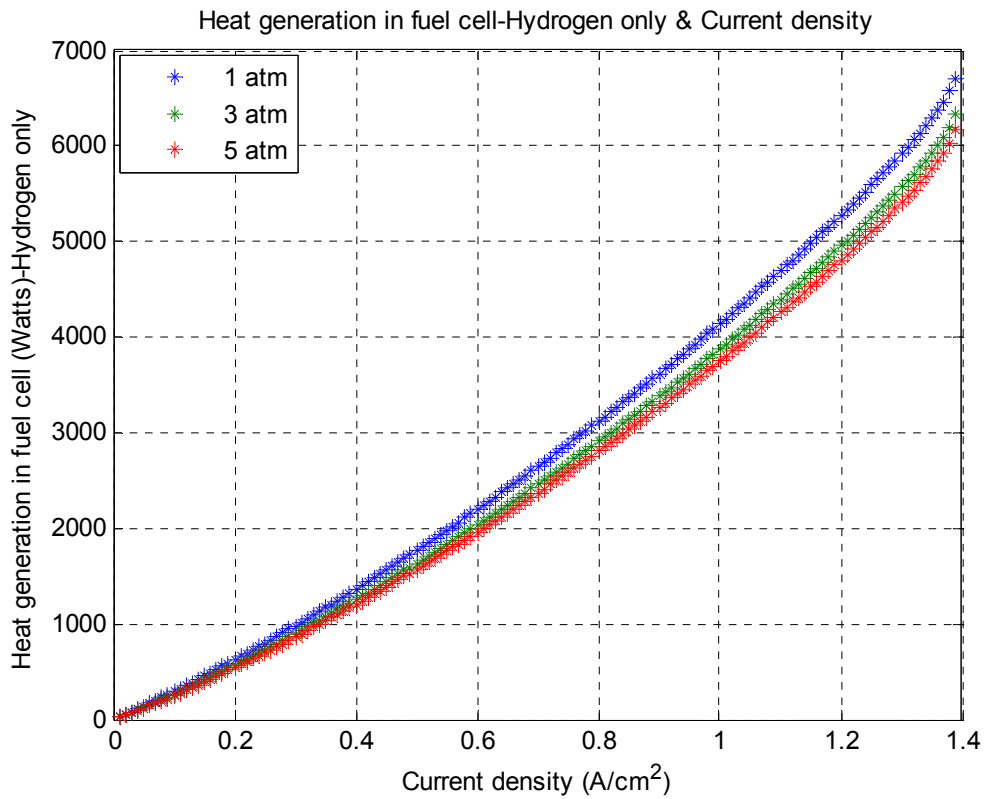


Figure VI.28.Heat generation in fuel cell (Hydrogen only) at different pressures

Heat generation (All inlets): The Figure VI.29 is very similar to the previous figure but heat generation results are higher. The reason is that in the Figure VI.29 we considered enthalpies of all inlets. Enthalpies of unreacted inlets in the fuel cell turn to heat generation.

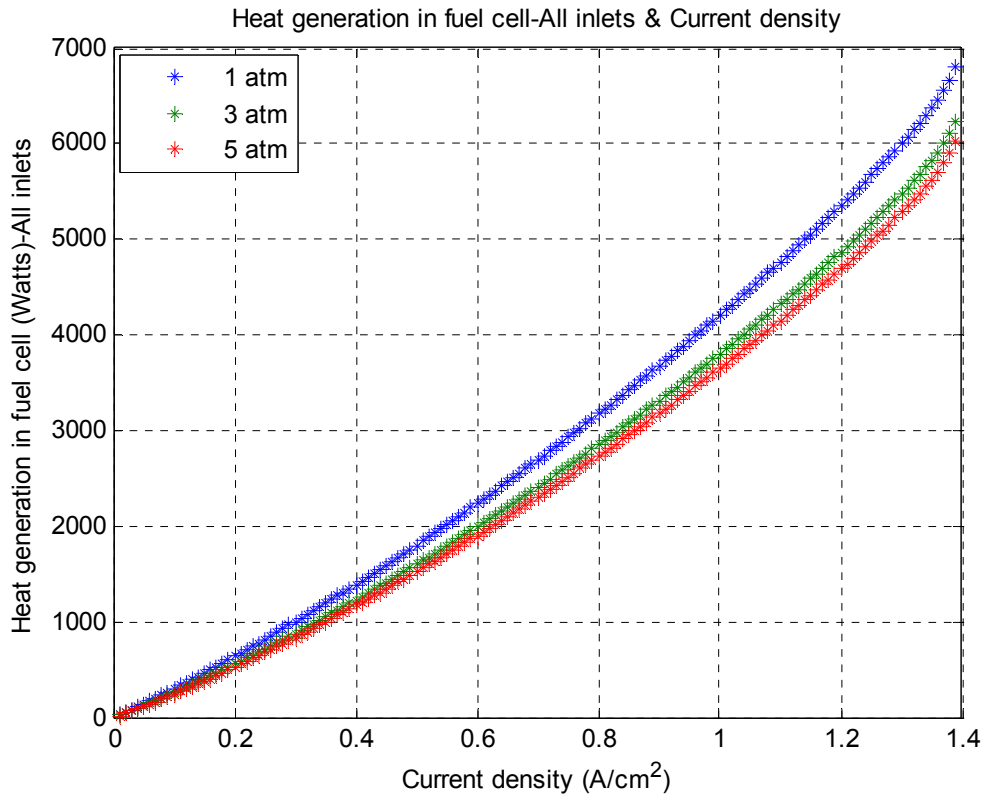


Figure VI.29.Heat generation in fuel cell (All inlets) at different pressures

Useful heat generation (Hydrogen only): Useful heat generation considering change of enthalpy of fuel cell reaction is heat generation in the fuel cell stacks minus dissipation heat to the surrounding and heating of the hydrogen and oxidant from the ambient temperature to the operating temperature (Chapter V.1.2.4). Therefore, the Figure VI.30 is almost same as the Figure VI.28 according to pressure change. As pressure increases useful heat generation decreases.

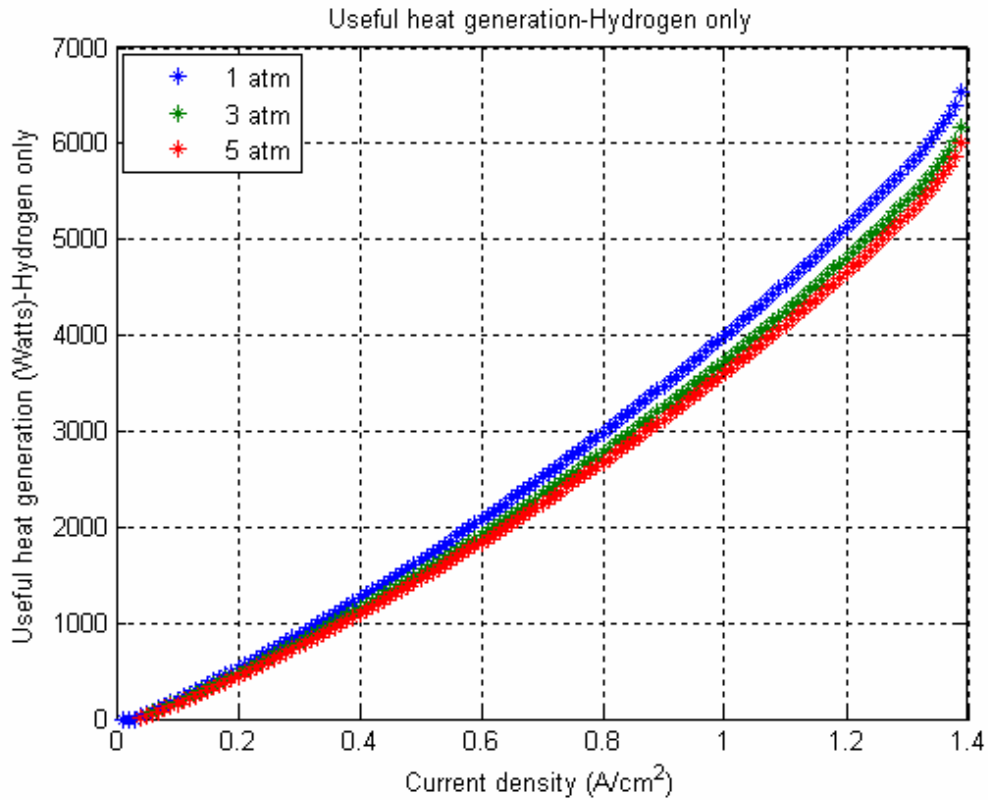


Figure VI.30. Useful heat generation (Hydrogen only) at different pressures

Useful heat generation (All inlets): Useful heat generation considering enthalpies of all inlets is heat generation in the fuel cell stacks minus dissipation heat to the surrounding and heating of the hydrogen and oxidant from the ambient temperature to the operating temperature (Chapter V.1.2.4). The Figure VI.31 is same as to the Figure VI.29 according to pressure changes. As pressure increases useful heat generation considering all inlets decreases as in the Figure VI.29.

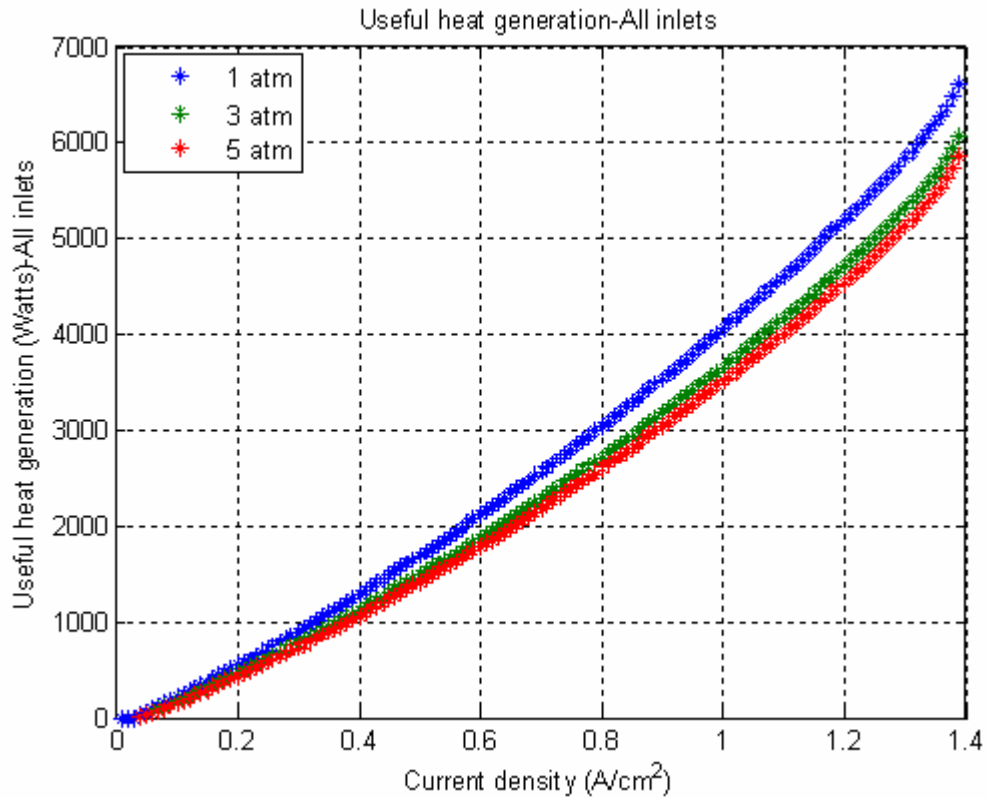


Figure VI.31. Useful heat generation (All inlets) at different pressures

Hydrogen inlet mass flow rate: Hydrogen inlet mass flow rate is linearly proportional to current density. As pressure increases output electrical power and output voltage increases but ratio of electrical power to output voltage which gives current does not change. Mass flow rate is not related to pressure changes. Therefore, hydrogen inlet mass flow rate is constant at changing pressure (Figure VI.32).

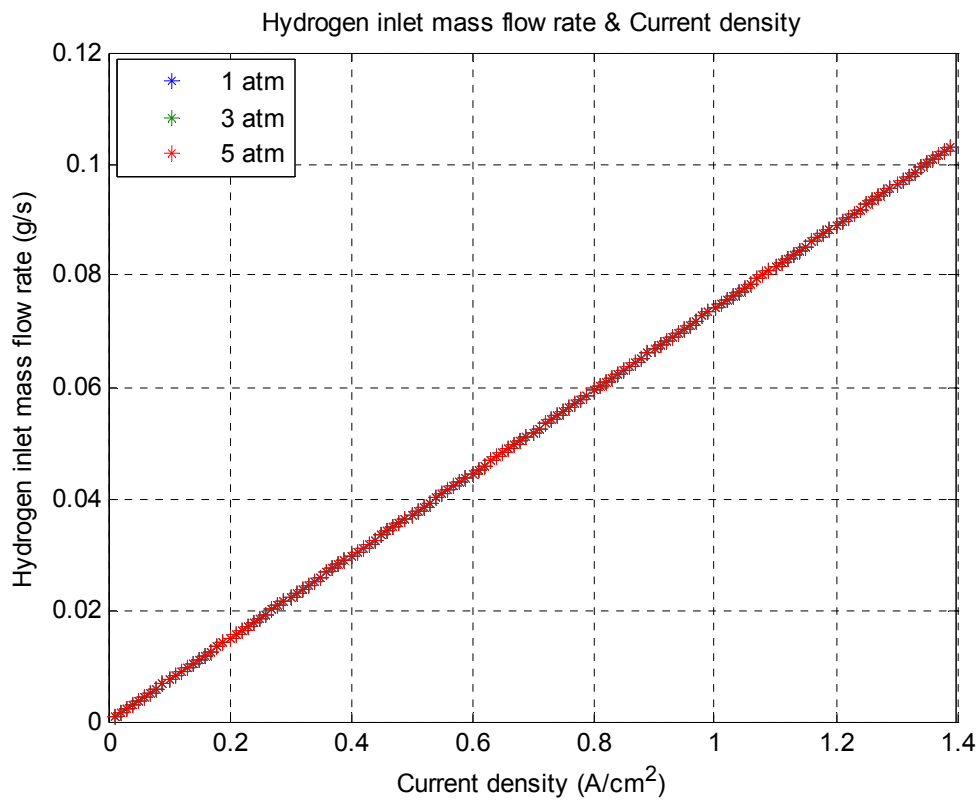


Figure VI.32.Hydrogen inlet mass flow rate at different pressures

Oxygen inlet mass flow rate: Pressure change does not affect oxygen inlet mass flow rate like hydrogen mass flow rate (Figure VI.33).

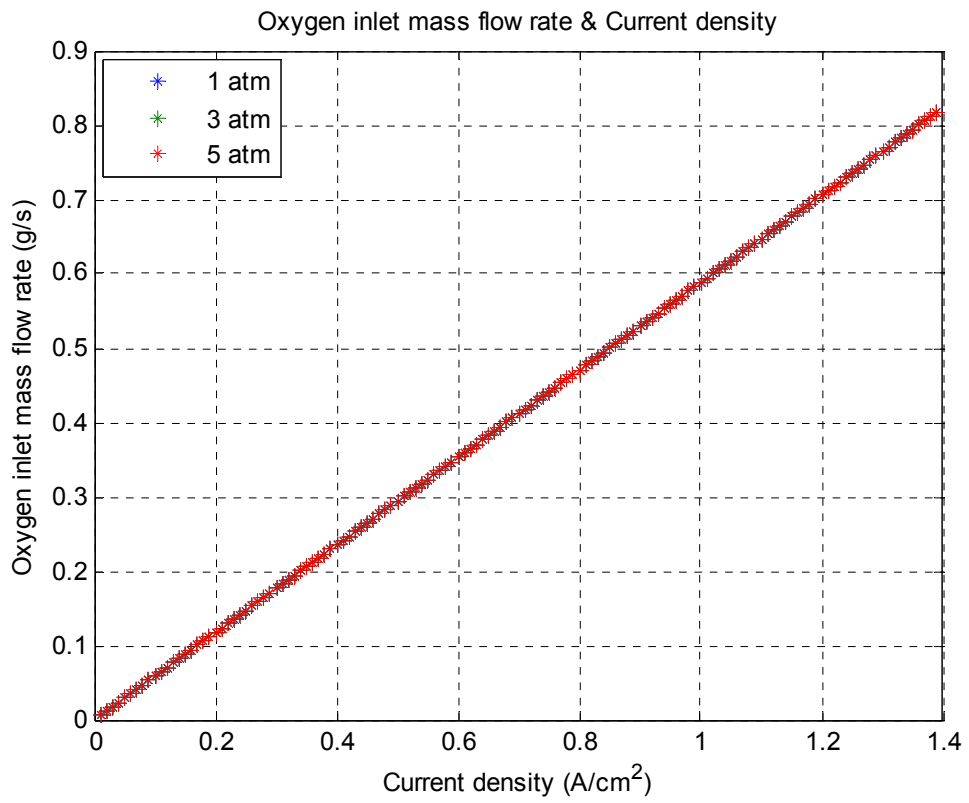


Figure VI.33. Oxygen inlet mass flow rate at different pressures

Water vapor in hydrogen inlet: Higher pressures lower water vapor content of gases so when pressure increases water vapor content of hydrogen decreases as shown in the Figure VI.34.

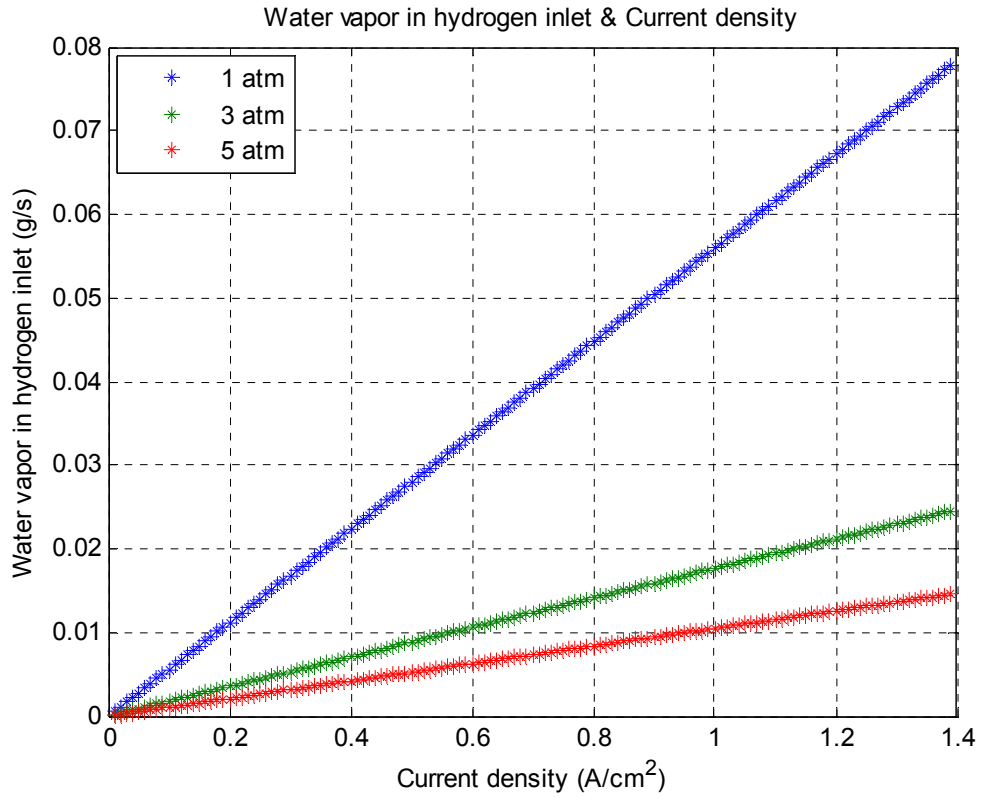


Figure VI.34. Water vapor in hydrogen inlet at different pressures

Water vapor in oxygen inlet: At elevated pressures water vapor content of gases decreases so as pressure decreases water vapor in oxygen increases (Figure VI.35).

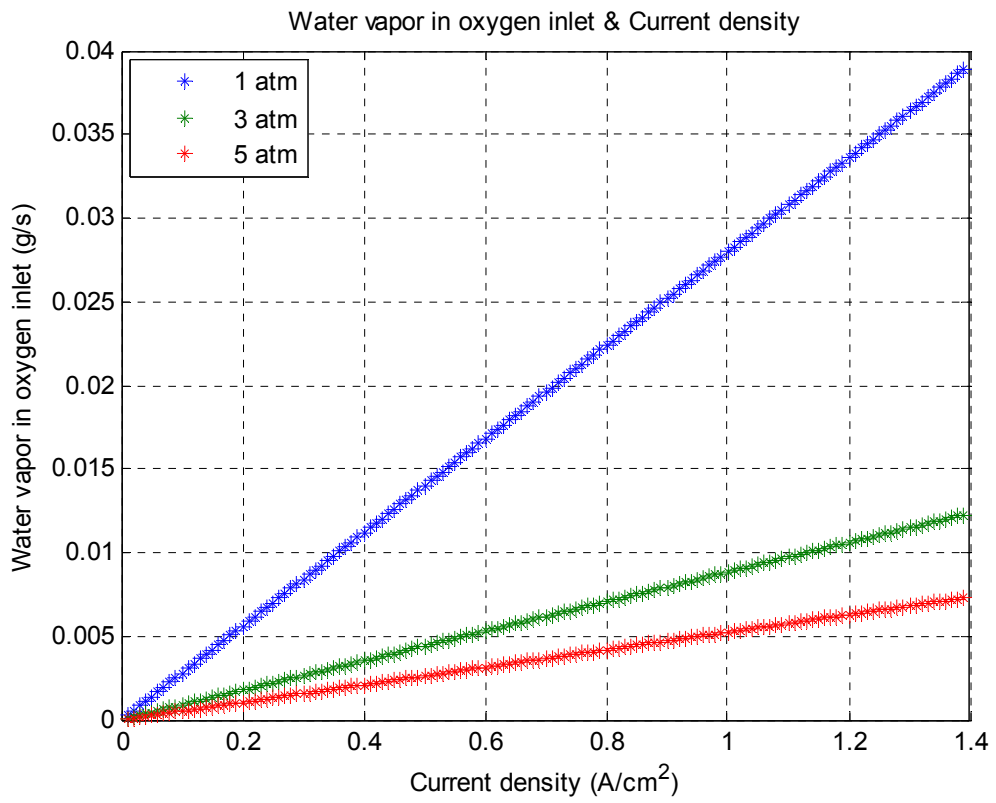


Figure VI.35. Water vapor in oxygen inlet at different pressures

Unused hydrogen mass flow rate: Unused hydrogen mass flow rate is dependent to hydrogen inlet flow rate. Therefore, when pressure changes unused hydrogen mass flow rate becomes constant (Figure VI.36) like hydrogen inlet mass flow rate.

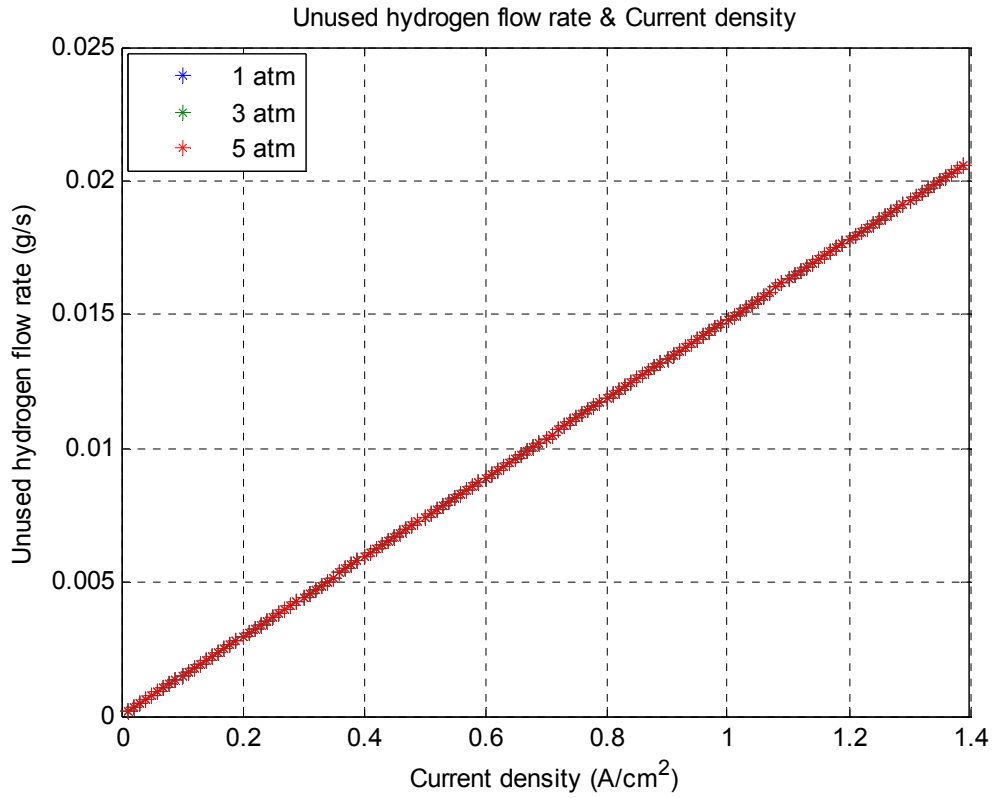


Figure VI.36. Unused hydrogen flow rate at different pressures

Oxygen outlet mass flow rate: Oxygen inlet mass flow rate is similar to oxygen outlet mass flow rate considering pressure changes. Therefore, when pressure changes oxygen outlet flow rate becomes constant (Figure VI.37).

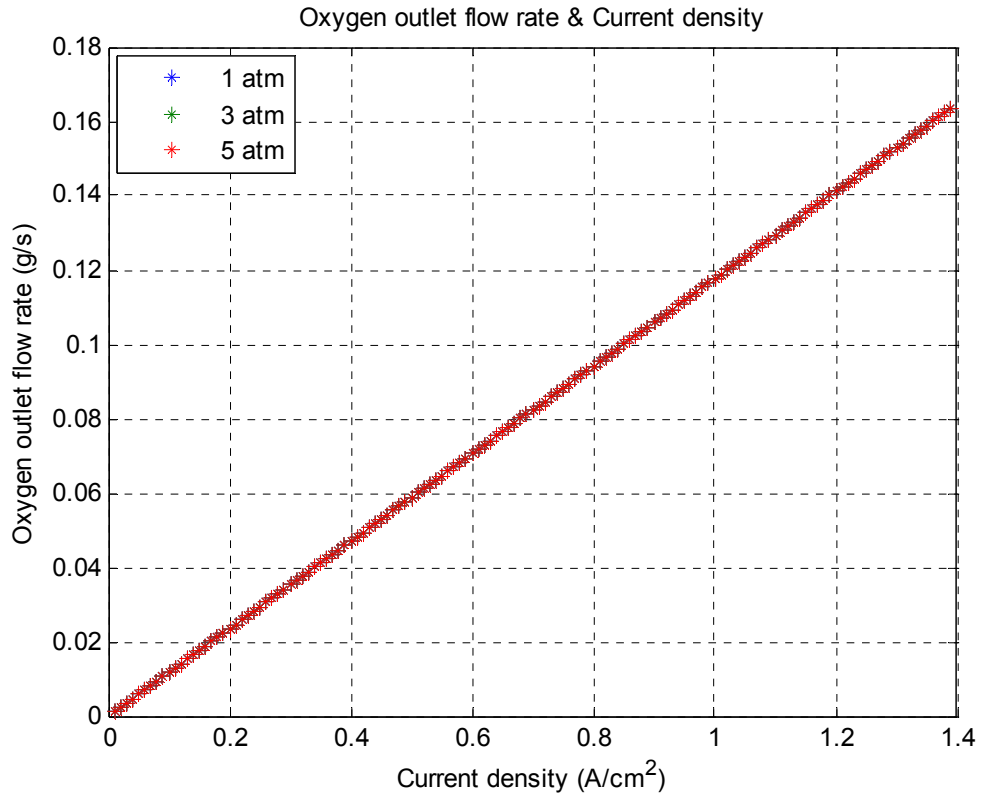


Figure VI.37.Oxygen outlet flow rate at different pressures

Water in hydrogen and oxygen outlet: All water vapor in hydrogen and oxygen inlet exit from the fuel cell as water. Membrane requires humidification of reactant gases to only maintain protonic conductivity. Therefore, the Figures VI.38 and VI.39 are same as the Figures VI.34 and VI.35, respectively.

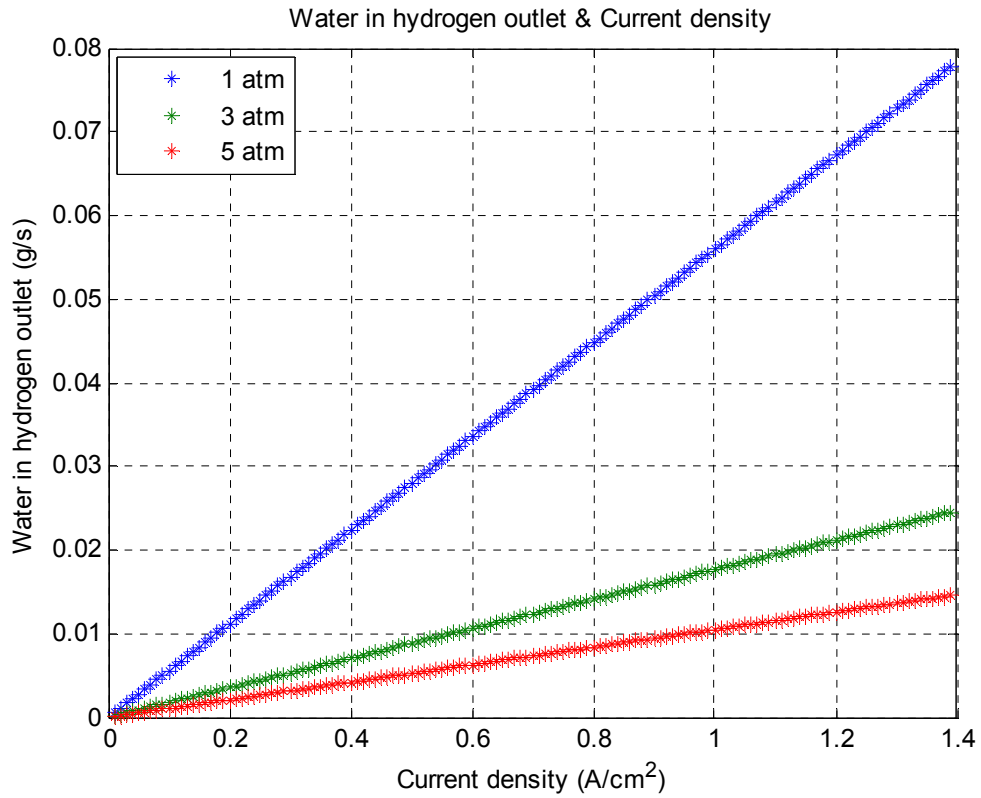


Figure VI.38. Water in hydrogen outlet at different pressures

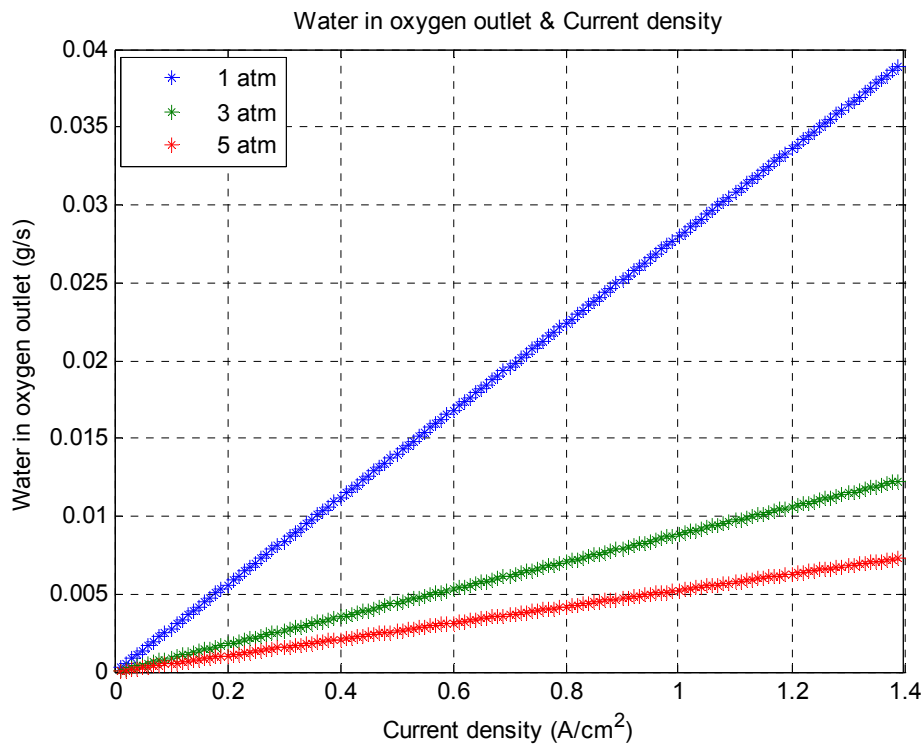


Figure VI.39. Water in oxygen outlet at different pressures

Water production: Since changing pressure does not affect hydrogen and oxygen consumptions, water production becomes constant at changing pressure conditions (Figure VI.40).

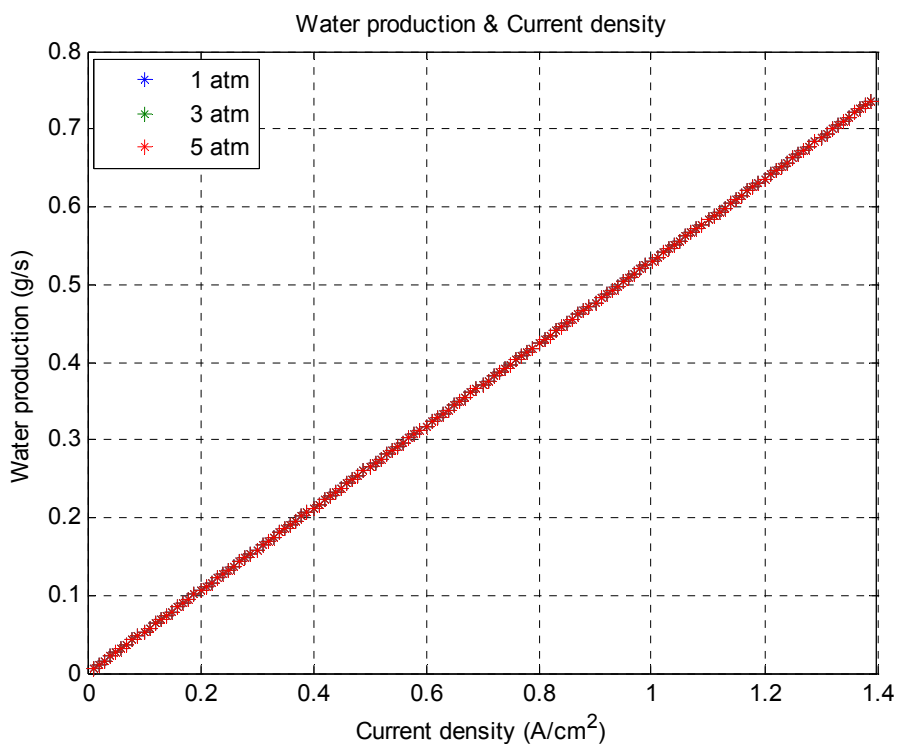


Figure VI.40. Water production at different pressures

Cooling water mass flow rate (Hydrogen only): Cooling water takes the heat which is heat generation considering only change of enthalpy of fuel cell reaction minus heat dissipated from the stacks of the fuel cell. At constant temperatures, heat dissipation from the stacks is constant. Therefore, the Figure VI.41 is linearly proportional to heat generation figure. When pressure is changed, cooling water mass flow rate is not changed much especially between 0-0.6 A/cm² current densities because there are not many heat differences at these current densities. Furthermore, like Figure VI.28, mass flow rate of cooling water decreases when pressure increases.

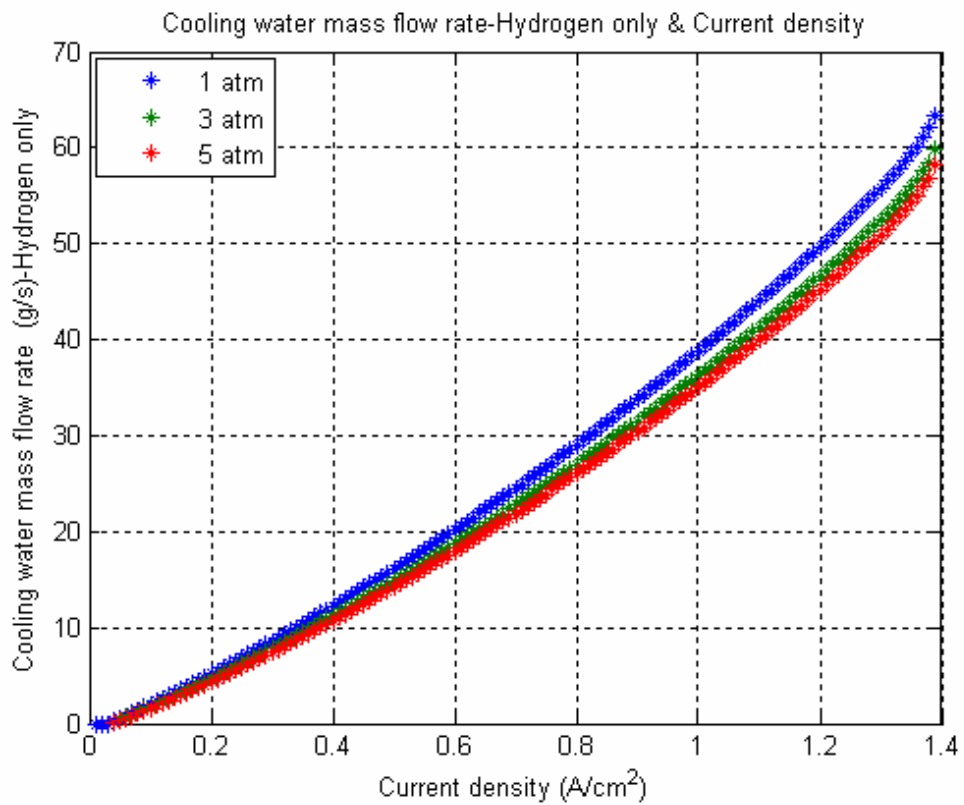


Figure VI.41. Cooling water mass flow rate (Hydrogen only) at different pressures

Cooling water mass flow rate (All inlets): Cooling water takes the heat which is heat generation considering enthalpies of all inlets minus heat dissipated from the stacks which is constant at constant temperature. Therefore, the Figure VI.42 is very similar to the Figure VI.29. For this reason, when pressure increases cooling water mass flow rate decreases.

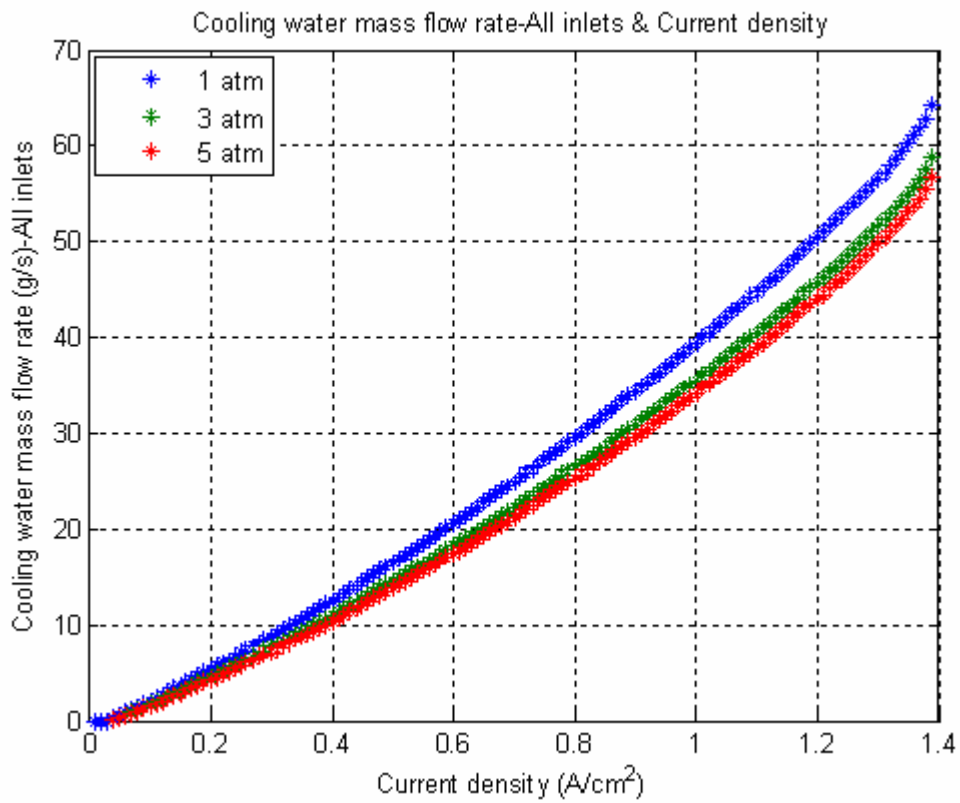


Figure VI.42. Cooling water mass flow rate (All inlets) at different pressures

Efficiency of electricity - TD1 (Hydrogen only): The figure of electrical efficiency according to thermodynamics first law considering change of enthalpy of fuel cell reaction is same as the figure of output voltage. Electrical efficiency according to thermodynamics first law according to hydrogen's HHV increases as pressure increases (Figure VI.43). The reason is higher pressure higher electrical power with constant hydrogen's HHV. Increment of efficiency between 1 and 3 atm pressures is higher than 3 and 5 atm pressure like figure of output voltage.

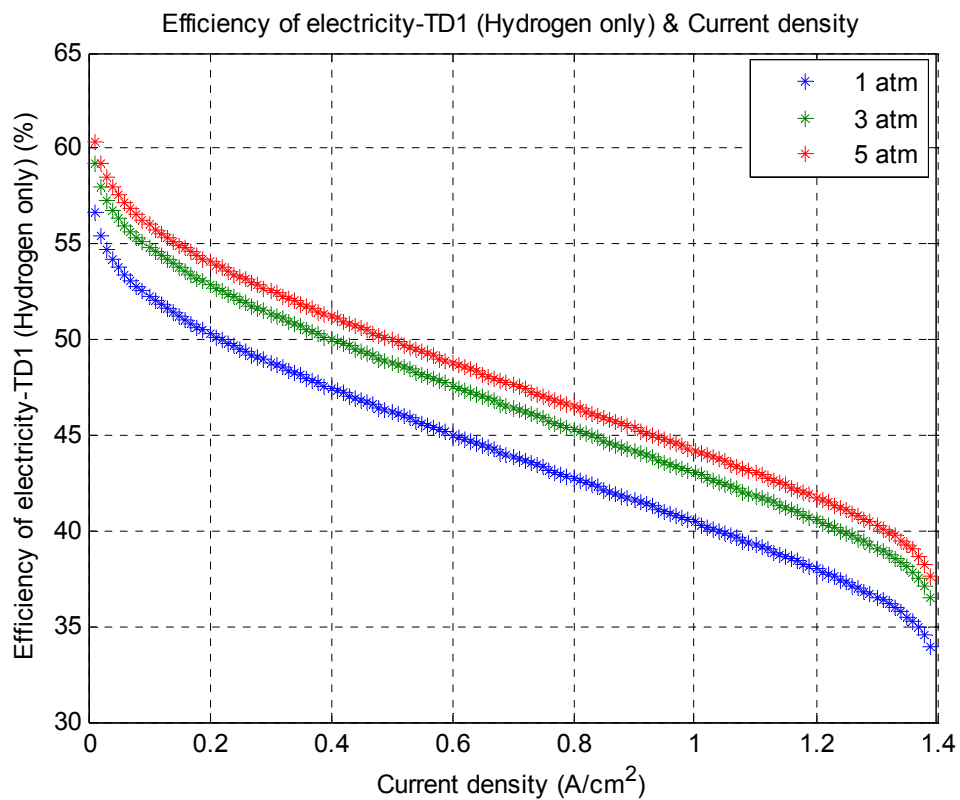


Figure VI.43.Electrical efficiency according to thermodynamics first law (Hydrogen only) at different pressures

Efficiency of electricity - TD2 (Hydrogen only): Electrical efficiency according to thermodynamics second law considering only exergy of hydrogen increases as pressure increases (Figure VI.44). Higher pressure increases both electrical power and exergy of hydrogen. However, increment of power is higher than exergy of hydrogen results this figure. Also increment of efficiency between 1 and 3 atm pressures is higher than between 3 and 5 atm pressures.

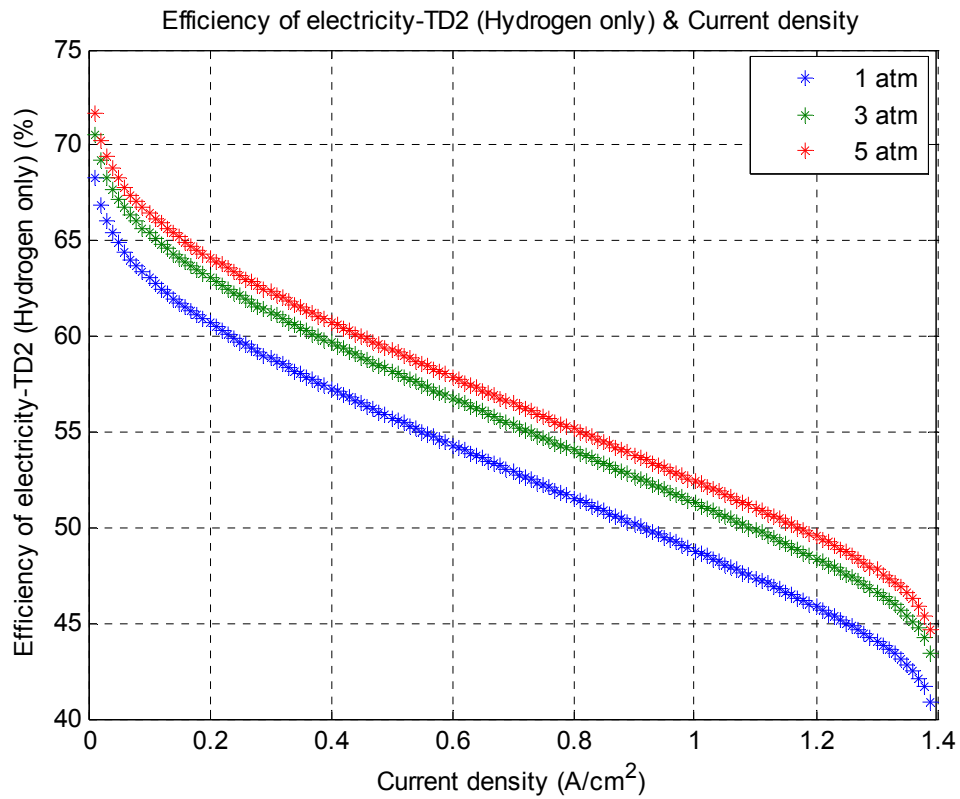


Figure VI.44.Electrical efficiency according to thermodynamics second law (Hydrogen only) at different pressures

Efficiency of electricity - TD1 (All inlets): The figure of electrical efficiency according to thermodynamics first law considering enthalpies of all inlets (Figure VI.45) is similar to previous two figures. However, efficiency differences between different pressures are higher than previous two figures. Increasing pressure increases electrical power and decreases enthalpies of all inlets results the Figure VI.45.

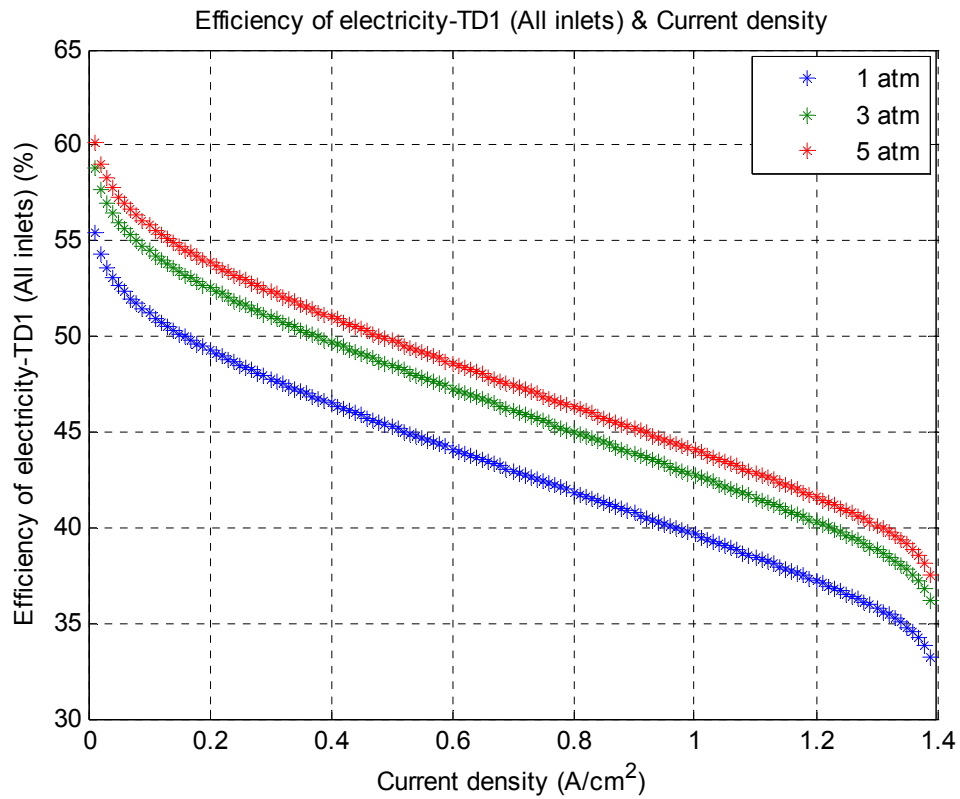


Figure VI.45.Electrical efficiency according to thermodynamics first law (All inlets) at different pressures

Efficiency of electricity - TD2 (All inlets): Electrical efficiency according to thermodynamics second law considering exergies of all inputs increases when pressure increases (Figure VI.46) as previous electrical efficiency figures. Both electrical power and all inlet exergies increase at increasing pressure but ratio of electrical power to exergies of all inlets is higher when pressure is higher.

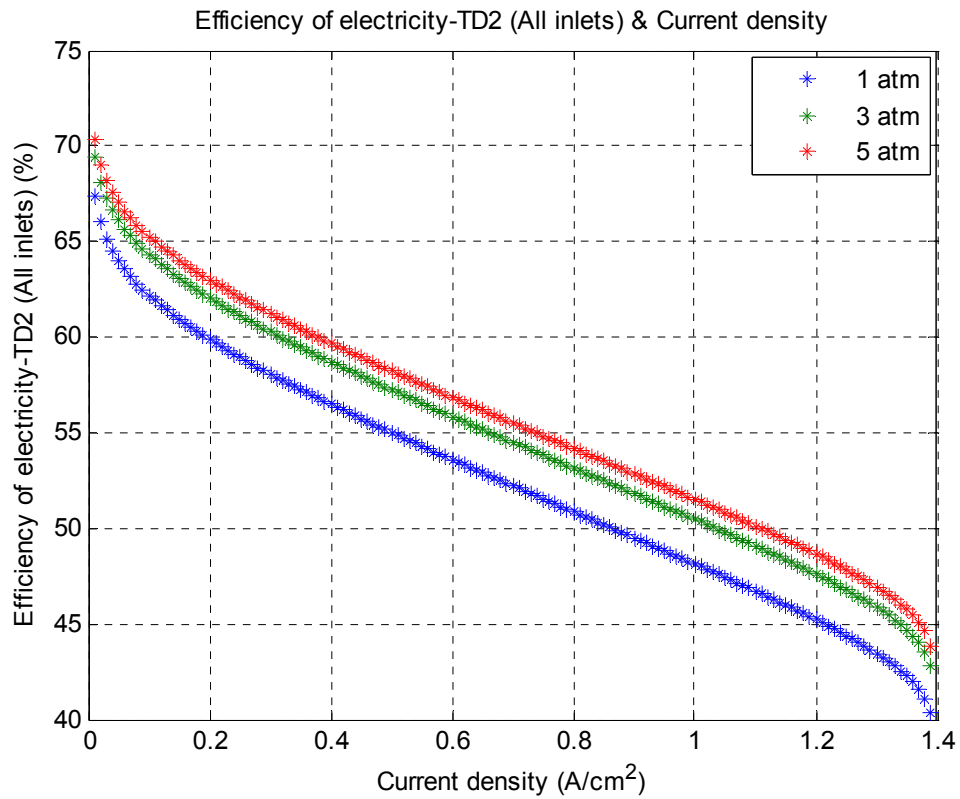


Figure VI.46.Electrical efficiency according to thermodynamics second law (All inlets) at different pressures

Total efficiency -TD1 (Hydrogen only): Total efficiency including electrical and thermal efficiency according to thermodynamics first law considering change of enthalpy of fuel cell reaction is almost constant at different pressure conditions (Figure VI.47). From the Figure VI.47, it is seen that pressure affects the efficiency very slightly that can be negligible. The reason is that increment of total electrical and thermal power is very small that can be negligible when pressure increases at constant hydrogen's HHV and so ratio of total power to hydrogen's HHV becomes almost constant.

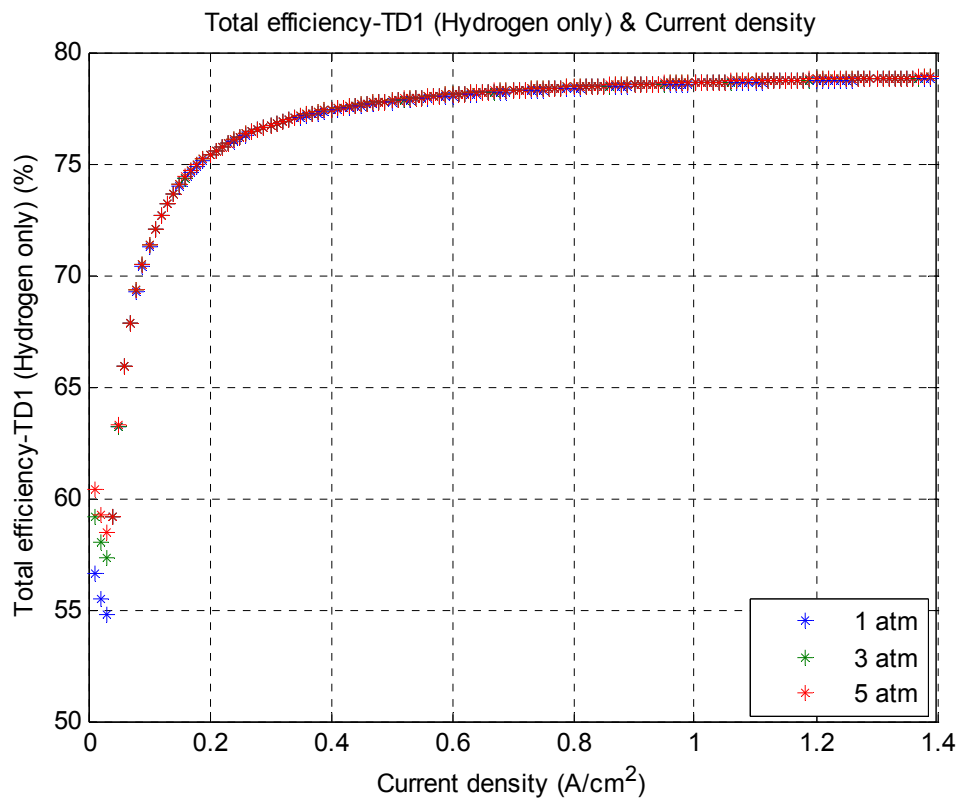


Figure VI.47. Total efficiency according to thermodynamics first law (Hydrogen only) at different pressures

Total efficiency - TD2 (Hydrogen only): Total efficiency according to thermodynamics second law considering exergy of hydrogen increases as pressure increases (Figure VI.48). This curve is similar to electrical efficiency curves because exergy of useful heat is very small value. Up to 0.4 A/cm² current density, there is unsteadiness. The reason is that useful heat generation is zero up to 0.4 A/cm² current density. Both exergy of total power and exergy of hydrogen increase when pressure increases but increment of exergy of total power is higher than exergy of hydrogen. Therefore, when pressure increases, ratio of exergy of total power to exergy of hydrogen increases that gives the Figure VI.48.

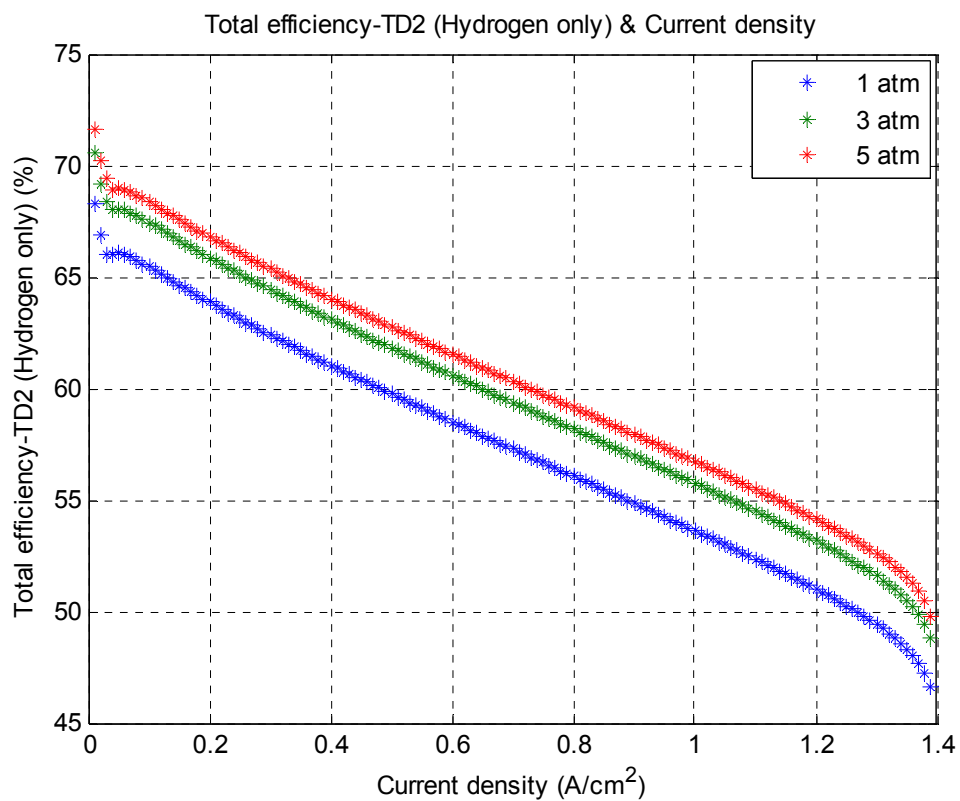


Figure VI.48.Total efficiency according to thermodynamics second law (Hydrogen only) at different pressures

Total efficiency - TD1 (All inlets): Total efficiency according to thermodynamics first law considering enthalpies of all inlets is not affected much when pressure is changed as shown in the Figure VI.49. As pressure increases both total power and enthalpies of all inlets decrease. However, ratio of total power to enthalpies of all inlets is slightly lower at higher pressures.

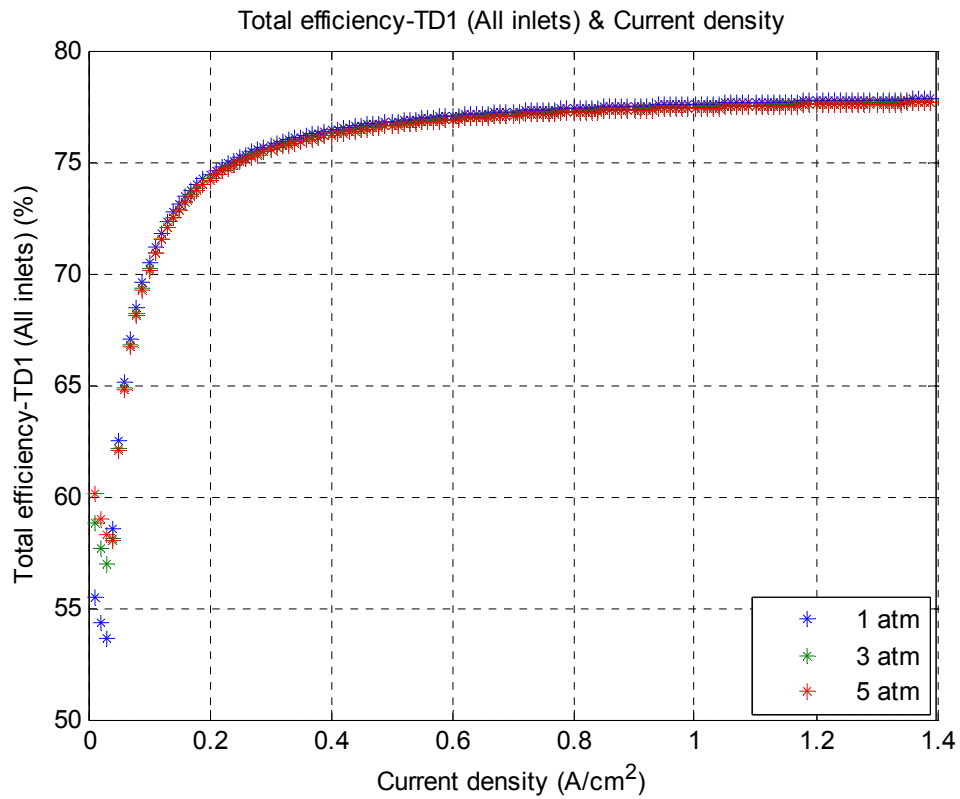


Figure VI.49.Total efficiency according to thermodynamics first law (All inlets) at different pressures

Total efficiency - TD2 (All inlets): Total efficiency according to thermodynamics second law considering all inlets is higher as pressure increases (Figure VI.50). When pressure increases, both exergies of total power and exergies of all inlets increase. However, increment of exergies of total power is higher than all inlets. Therefore, ratio of exergies of total power to all inlets is higher at elevated pressures.

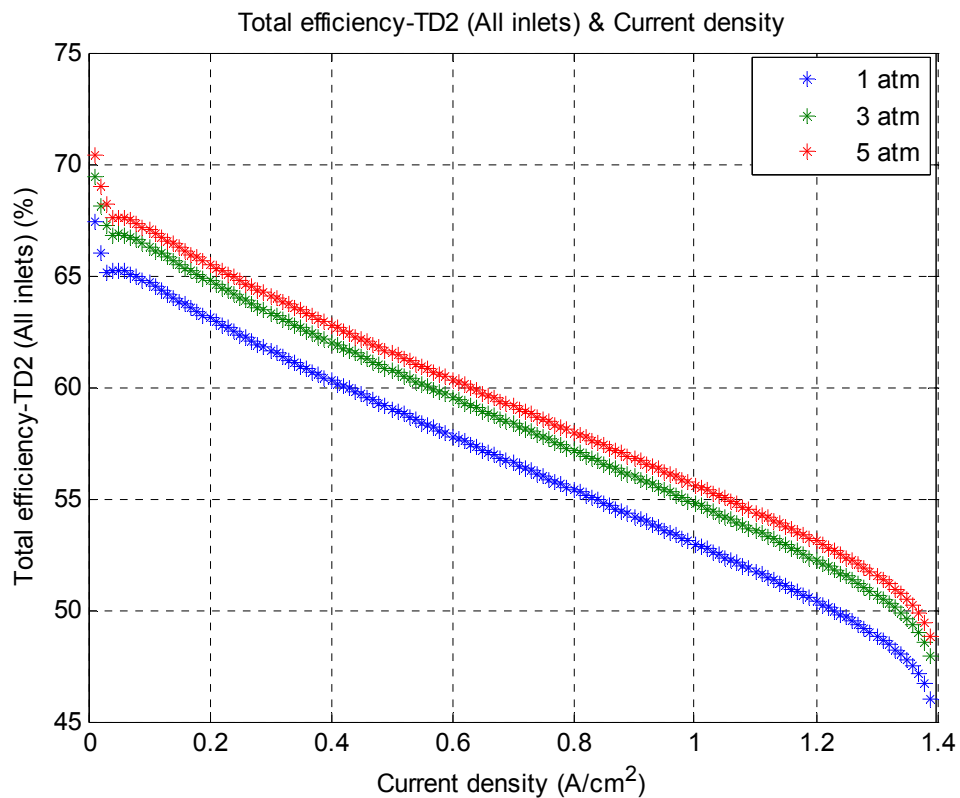


Figure VI.50.Total efficiency according to thermodynamics second law (All inlets) at different pressures

VI.2. COGENERATION

In Chapter V.2, a 90 m² second floor residential house was designed. Heat gain of the residence is 15000 Btu/h (4.4 kW) and heat loss is 19000 Btu/h (5.6 kWh). In summer, electrical consumption is 14 kWh/day and required domestic water heating is 4.4 kWh/day. In winter, electrical consumption 16.3 kWh/day and required domestic hot water is 15.7 kWh/day. We use electrical and thermal energy of the PEM fuel cell modeled within the frame of this study to satisfy the energy requirements of the residence at different cases.

Cases 1-4

For the first four cases, domestic water heating is supplied by thermal energy, and space heating and cooling are supplied by heat pump. Heat pump capacity is chosen according to winter condition. For each case, different types of heat pump model are used. In these cases almost all electrical energy of fuel cell are used and in winter about 82-83 % (Table VI.1) and in summer about 92-93 % (Table VI.3) of thermal energy remains. In general, efficiency values for cases 1-4 are very close to each other.

Winter: Usable energy efficiencies of the first four cases are 74.4 % according to first law of thermodynamics and 52.2 % according to second law of thermodynamics.

Efficiency of used energy is best at case-4 which is 44.19 % for I. law and best at case-2 which is 46.19 % for II. law (Table VI.2).

Summer: Usable energy efficiencies from case-1 to case-4 are 76.79 % for thermodynamics I. law and 52.65 % for II. law of thermodynamics. Efficiencies of used energy for thermodynamics first and second law are best at case-4 which are 41.23 % and 45.96 % respectively (Table VI.4).

Table VI.1.Cases 1-4 in winter

Winter	Space heating	Water heating	Electric cons.	Fuel cell run time (hrs)	Total		Unused energy		Usage of	Usage of	Surplus	
					EE produced (kWh)	TE produced (kWh)	EE (kWh)	TE (kWh)	produced EE (%)	produced TE (%)	EE (%)	TE (%)
Case-1	HP WGH100-WGH142	TE	EE	16.50	89.71	84.68	2.401	69.005	97.32	18.51	2.68	81.49
Case-2	HP WGH200-WGH248	TE	EE	17.75	96.506	91.105	0.997	75.43	98.97	17.21	1.03	82.79
Case-3	HP WH100-WH148	TE	EE	18.50	100.584	94.954	1.475	79.279	98.53	16.51	1.47	83.49
Case-4	HP WH200-WH248	TE	EE	17.25	93.788	88.538	1.159	72.863	98.76	17.70	1.24	82.30

Table VI.2.Efficiencies of cases 1-4 in winter

Winter	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-1	234,45	197,13	74,38	43,93	52,20	45,53
Case-2	252,21	212,06	74,39	44,08	52,20	46,19
Case-3	262,87	221,02	74,39	43,67	52,20	45,95
Case-4	245,11	206,09	74,39	44,19	52,20	46,13

Table VI.3.Cases 1-4 in summer

Summer	Space cooling	Water heating	Electric cons.	Fuel cell run time	Total		Unused energy		Usage of	Usage of	Surplus	
					EE produced	TE produced	EE	TE	produced EE	produced TE	EE	TE
				(hrs)	(kWh)	(kWh)	(kWh)	(kWh)	(%)	(%)	(%)	(%)
Case-1	HP WGH100-WGH142	TE	EE	12.50	67.96	68.428	1.103	64.065	98.38	6.36	1.62	93.64
Case-2	HP WGH200-WGH248	TE	EE	10.25	55.729	56.116	0.447	51.761	99.20	7.76	0.80	92.24
Case-3	HP WH100-WH148	TE	EE	10.75	58.447	58.854	1.295	54.499	97.78	7.40	2.22	92.60
Case-4	HP WH200-WH248	TE	EE	10	54.37	54.748	0.135	50.393	99.75	7.95	0.25	92.05

Table VI.4.Efficiencies of cases 1-4 in summer

Summer	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-1	177,61	149,34	76,79	40,10	52,65	45,22
Case-2	145,64	122,46	76,79	40,95	52,65	45,70
Case-3	152,75	128,43	76,79	40,27	52,65	45,03
Case-4	142,09	119,47	76,79	41,23	52,65	45,96

Cases 5-8

From case-5 to case-8, domestic water heating is supplied by thermal energy, and space heating and cooling are supplied by different types of heat pump as cases 1 to 4. But at cases 5-8 heat pump capacity is chosen according to summer condition. Therefore, heat pump does not compensate required energy of space heating and thermal energy is used to satisfy space heating requirement of the residential in winter. Needed thermal energy is compensated by thermal energy of fuel cell and combustion of unused hydrogen of fuel cell.

Summer: Almost all electrical energy of the fuel cell is used and about 92-93 % of thermal energy remains (Table VI.5). Efficiency of usable energy for I. law of thermodynamics is 76.8 % and for II. law of thermodynamics is 52.65 % which are same as cases 1-4. Usable energy efficiencies are nearly same but case-3 has maximum usable energy efficiencies according to thermodynamics first and second law and efficiency values are 40.65 % and 45.11 %, respectively (Table VI.6).

Winter: There are four scenarios to compensate energy requirement of the residential.

Scenario I: In this scenario, space heating is compensated by heat pump and thermal energy of fuel cell. Almost all thermal energy is consumed as shown in the Table VI.7. Usable energy efficiencies are 74.39 % for I. law and 52.2 % for II. law. Surplus electrical energy efficiencies from case-5 to case-8 are 48.62 %, 66.44 %, 60.48 % and 53 %, respectively (Table VI.7). Maximum used energy efficiencies are at case-5 where minimum unused electrical energy and values are 55.35 % for I. law and 29.99 % for II. law of thermodynamics (Table VI.8).

Scenario II: In this scenario, almost all produced energy of fuel cell consumed (Table VI.9), but to consume all energy, some electrical energy turns to thermal energy in storage tank. Efficiency of usable energy is 74.39 % for I. law at all cases and efficiency of usable energy for II. law for cases 5-8 are 39.88 %, 33.34 %, 35.69 % and 38.61 %, respectively (Table VI.10). Efficiencies of used energy for thermodynamics I. law very close each other (Table VI.10). Case-7 has maximum efficiency of used energy according to I. law which is 74.18 %. Case-5 has maximum efficiency of used energy according to II. law which is 39.65 % because minimum energy conversion value from thermal energy to electrical energy happens at this case.

Scenario III: In this scenario, space heating is compensated by heat pump, thermal energy and combustion of unused hydrogen of the fuel cell, and almost all thermal energy is consumed (Table VI.11). Unused electrical energy efficiencies cases 5-8 are 27.14 %, 53.02 %, 44.80 % and 34.20 %, respectively (Table VI.11). Efficiency of usable energy is 88.96 % for I. law and 54.90 % for II. law of thermodynamics. Unused electrical energy efficiencies directly affect used energy efficiencies. Therefore, used energy efficiencies are best for case-5 and efficiency values are 78.50 % for I. law and 42.54 % for II. law of thermodynamics (Table VI.12).

Scenario IV: In this scenario, space heating is compensated by heat pump, thermal energy and combustion of unused hydrogen of the fuel cell (Table VI.13). Almost all electrical energy and all thermal energy consumed but extra thermal energy required to satisfy thermal energy need of the residential. Usable energy efficiencies are 88.96 % for I. law and 54.90 % for II. law of thermodynamics (Table VI.14). Used energy efficiencies for cases 5-8 are very close to each other both I. and II. law of thermodynamics (Table VI.14). Maximum used energy efficiencies are 88.72 for I. law and 54.61 % for II. law at case-7. Required extra thermal energy values for cases 5-8 per day are 25.059 kWh, 60.778 kWh, 48.945 kWh and 31.283 kWh, respectively (Table VI.13).

Table VI.5.Cases 5-8 in summer

Summer	Space cooling	Water heating	Electric cons.	Fuel cell run time	Total		Unused energy		Usage of	Usage of	Surplus	
					EE produced	TE produced	EE	TE	produced EE	produced TE	EE	TE
				(hrs)	(kWh)	(kWh)	(kWh)	(kWh)	(%)	(%)	(%)	(%)
Case-5	HP WGH100-WGH118	TE	EE	11.25	61.166	61.591	0.984	57.236	98.39	7.07	1.61	92.93
Case-6	HP WGH200-WGH218	TE	EE	10.50	57.088	57.485	1.181	53.13	97.93	7.58	2.07	92.42
Case-7	HP WH100-WH118	TE	EE	11	59.807	60.223	0.63	55.868	98.95	7.23	1.05	92.77
Case-8	HP WH200-WH218	TE	EE	10.25	55.729	56.116	1.252	51.761	97.75	7.76	2.25	92.24

Table VI.6.Efficiencies of cases 5-8 in summer

Summer	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-5	159,85	134,40	76,79	40,37	52,65	45,28
Case-6	149,19	125,44	76,79	40,39	52,65	45,11
Case-7	156,30	131,42	76,80	40,65	52,65	45,55
Case-8	145,64	122,46	76,79	40,39	52,65	45,04

Table VI.7.Cases 5-8 in winter for scenario I

Winter (I)	Space heating	Water heating	Electric cons.	Fuel cell run time (hrs)	Total		Unused energy		Usage of	Usage of	Surplus	
					EE produced (kWh)	TE produced (kWh)	EE (kWh)	TE (kWh)	produced EE (%)	produced TE (%)	EE (%)	TE (%)
Case-5	HP+TE WGH100-WGH118	TE	EE	19.50	106.021	100.087	51.552	1.192	51.38	98.81	48.62	1.19
Case-6	HP+TE WGH200-WGH218	TE	EE	22.75	123.691	116.768	82.182	0.163	33.56	99.86	66.44	0.14
Case-7	HP+TE WH100-WH118	TE	EE	22	119.614	112.919	72.345	0.944	39.52	99.16	60.48	0.84
Case-8	HP+TE WH200-WH218	TE	EE	19.25	104.66	98.802	55.47	0.887	47	99.10	53	0.90

Table VI.8.Efficiencies of cases 5-8 in winter for scenario I

Winter (I)	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-5	277,08	232,97	74,39	55,35	52,20	29,99
Case-6	323,25	271,79	74,39	48,91	52,20	21,96
Case-7	312,60	262,83	74,39	50,94	52,20	24,62
Case-8	273,52	229,98	74,39	53,78	52,20	28,02

Table VI.9.Cases 5-8 in winter for scenario II

Winter (II)	Space heating	Water heating	Electric cons.	Fuel cell run time (hrs)	Total		Unused energy		Usage of	Usage of	Surplus	
					EE produced (kWh)	TE produced (kWh)	EE (kWh)	TE (kWh)	produced EE (%)	produced TE (%)	EE (%)	TE (%)
Case-5	HP+TE WGH100-WGH118	TE	EE	14.75	80.195	75.707	0	2.538	100	97.50	0	2.50
Case-6	HP+TE WGH200-WGH218	TE	EE	15	81.555	76.99	0	0.431	100	99.63	0	0.37
Case-7	HP+TE WH100-WH118	TE	EE	15.25	82.914	78.273	0	1.943	100	98.29	0	1.71
Case-8	HP+TE WH200-WH218	TE	EE	14	76.118	71.857	0	0.871	100	99.12	0	0.88

Table VI.10.Efficiencies of cases 5-8 in winter for scenario II

Winter (II)	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-5	209,58	176,22	74,39	73,18	39,88	39,65
Case-6	213,14	179,21	74,39	74,18	33,34	33,30
Case-7	216,69	182,19	74,39	73,49	35,69	35,52
Case-8	198,93	167,26	74,39	73,95	38,61	38,53

Table VI.11.Cases 5-8 in winter for scenario III

Winter (III)	Space heating	Water heating	Electric cons.	Fuel cell run time (hrs)	Total		Unused energy		Usage of	Usage of	Surplus	
					EE produced (kWh)	TE produced (kWh)	EE (kWh)	TE (kWh)	produced EE (%)	produced TE (%)	EE (%)	TE (%)
Case-5	HP+TE+Hyd. com. WGH100-WGH118	TE	EE	13.75	74.758	99.047	20.289	0.152	72.86	99.85	27.14	0.15
Case-6	HP+TE+Hyd. com. WGH200-WGH218	TE	EE	16.25	88.351	117.056	46.842	0.451	46.98	99.61	53.02	0.39
Case-7	HP+TE+Hyd. com. WH100-WH118	TE	EE	15.75	85.632	113.454	38.363	1.479	55.20	98.70	44.80	1.30
Case-8	HP+TE+Hyd. com. WH200-WH218	TE	EE	13.75	74.758	99.047	25.569	1.132	65.80	98.86	34.20	1.14

Table VI.12.Efficiencies of cases 5-8 in winter for scenario III

Winter (III)	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-5	195,37	164,27	88,96	78,50	54,90	42,54
Case-6	230,90	194,14	88,96	68,48	54,90	30,74
Case-7	223,79	188,17	88,96	71,16	54,90	34,39
Case-8	195,37	164,27	88,96	75,29	54,90	39,23

Table VI.13.Cases 5-8 in winter for scenario IV

Winter (IV)	Space heating	Water heating	Electric cons.	Fuel cell run time (hrs)	Total		Unused energy		Usage of	Usage of	Surplus		Required energy (kWh)
					EE produced (kWh)	TE produced (kWh)	EE (kWh)	TE (kWh)	produced EE (%)	produced TE (%)	EE (%)	TE (%)	
Case-5	HP+TE+Hyd. com. WGH100-WGH118	TE	EE	10.25	55.729	73.836	1.26	0	97.74	100	2.26	0	25.059 TE
Case-6	HP+TE+Hyd. com. WGH200-WGH218	TE	EE	7.75	42.136	55.827	0.627	0	98.51	100	1.49	0	60.778 TE
Case-7	HP+TE+Hyd. com. WH100-WH118	TE	EE	8.75	47.573	63.03	0.304	0	99.36	100	0.64	0	48.945 TE
Case-8	HP+TE+Hyd. com. WH200-WH218	TE	EE	9.25	50.292	66.632	1.103	0	97.81	100	2.19	0	31.283 TE

Table VI.14.Efficiencies of cases 5-8 in winter for scenario IV

Winter (IV)	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-5	145,64	122,46	88,96	88,10	54,90	53,87
Case-6	110,12	92,59	88,96	88,39	54,90	54,23
Case-7	124,33	104,54	88,96	88,72	54,90	54,61
Case-8	131,43	110,51	88,96	88,12	54,90	53,91

Case-9

Space heating is supplied by WGH100 model of heat pump according to winter condition as case-1. However, unlike case-1, domestic water heating is supplied by electrical energy of fuel cell. Consequently, thermal energy is not used in this case and all electrical energy of fuel cell is consumed.

Winter: The results are shown in tables VI.15 and VI.16. Production of 97.52 kWh heat per day is not used. Usable energy efficiencies are 74.39 % for I. law and 52.20 % for II. law of thermodynamics as at cases 1-4. Used energy efficiencies are 38.26 % and 45.50 % for I. law and II. law of thermodynamics, respectively. These efficiency values are lower than at case-1.

Summer: The results of case-9 in summer are shown in tables VI.17 and VI.18. 72.54 kWh thermal energy per day is not used. Usable energy efficiencies for case-9 are 76.79 % for thermodynamics I. law and 52.65 % for thermodynamics II. law as cases 1-4. Efficiencies of used energy are 37.82 % for I. law and 44.99 % for II. law of thermodynamics. Like in winter, used energy efficiency values are lower than at case-1.

Case-10

In winter, there are four scenarios. Space heating is supplied by thermal energy of fuel cell in scenario I and II. In scenario III and IV, heat of combustion of unused of hydrogen in fuel cell is added to thermal energy of the fuel cell for space heating. In summer, space cooling is supplied by WH200 model of heat pump. Domestic hot water requirement is supplied by electrical energy of the fuel cell.

Winter: There are four scenarios for case-10. The results are shown in tables VI.15 and VI.16.

Scenario I: In scenario I, fuel cell works all day. All thermal energy is used but 10.36 kWh/day thermal energy is needed for space heating. Needed thermal energy is compensated by electrical energy of fuel cell. Surplus electrical energy, including energy conversion of electrical energy to thermal energy, is 73.38 % of electrical energy of the fuel cell. Efficiencies of usable energy are 74.39 % for I. law and 49.15 % for II. law of thermodynamics. Used energy efficiencies according to I. and II. law of thermodynamics are 48.54 % and 18.41 %, respectively. Used energy efficiency for II. law is very small because of remaining unused electrical energy. Used energy efficiency for I. law is higher than at cases 1 and 9 but for II. law is lower than at cases 1 and 9 (Table VI.16).

Scenario II: All electrical and thermal energy are consumed. 53.646 kWh/day electrical energy is turned to thermal energy in storage tank. Efficiency of usable energy does not change according to scenario I for I. law but for II. law it decreases to 28.13 %. Efficiencies of used energy are 73.96 % and 28.06 % according to I. and II. law of thermodynamics. Usable and used energy efficiencies are very close because of consumption of almost all energy of fuel cell and Used energy efficiencies are higher than at scenario I of case-10 (Table VI.16).

Scenario III: Space heating is supplied by thermal energy of the fuel cell and combustion of unused of hydrogen in fuel cell. Almost all thermal energy is consumed and 68.63 % surplus electrical energy remains (Table VI.16). Usable energy efficiencies are 88.96 % and 54.90 % for I. and II. law of thermodynamics, respectively. Used energy efficiencies are 62.13 % for I. law and 23.57 % for II. law. Used energy efficiencies are better than at scenario I but worse than at scenario II. Also I. law efficiency of used energy is higher than at cases 1 and 9 but II. law efficiency of used energy is lower than at cases 1 and 9 (Table VI.16).

Scenario IV: Space heating is supplied as scenario III (Table VI.15). Almost all electrical and all thermal energies are used. However, 90.32 kWh/day extra thermal energy is needed for space heating. Usable energy efficiencies are same as scenario III. Used energy efficiencies are 88.21 % and 54.01 % according to I. and II. law of thermodynamics, respectively. Used energy efficiencies for both I. and II. law are better than at other scenarios and cases 1 and 9 (Table VI.16).

Summer: Energy requirement of the residential is only electrical energy (Table VI.17). Therefore, almost all electrical energy of the fuel cell is used and 60.22 kWh/day heat is not used. Usable energy efficiencies are 76.79 % for I. law and 52.65 % for II. law of thermodynamics. Used energy efficiencies according to I. and II. Law of thermodynamics are 37.64 % and 44.77 %, respectively. Used energy efficiency values are lower than at cases 1 and 9. However, there are not much differences between at case-9 and case-10 for I. law, and between at cases 1, 9 and 10 for II. law (Table VI.18).

Case-11

Space heating and cooling methods are same as case-10 except domestic water heating is supplied by thermal energy.

Winter: There are four scenarios for case-10.

Scenario I: Space heating is supplied only thermal energy of the fuel cell. Fuel cell works 24 hours a day. All thermal energy is consumed and 26.035 kWh/day extra heat is needed (Table VI.15). Required thermal energy is compensated by electrical energy of fuel cell. Unused electrical energy including energy conversion is 84.39 %. Efficiencies of usable energy according to I. and II. law of thermodynamics are 74.39 % and 44.54 %, respectively. Used energy efficiencies are 48.54 % for I. law and 13.80 % for II. law of thermodynamics. II. law efficiencies are lower than at case-10 (scenario I), because in this scenario more electrical energy is changed to thermal energy than at scenario I of case-10 (Table VI.16).

Scenario II: Space heating is supplied by thermal energy of the fuel cell. All electrical and thermal energies are consumed. 69.321 kWh/day electrical energy is changed to thermal energy in storage tank. Because of conversion of electrical energy to thermal energy, II. law efficiencies become low. Usable energy efficiencies for thermodynamics I. and II. law are 74.39 % and 21.10%, respectively. Used energy efficiencies are 73.96 % for I. law and 21.02 % for II. law of thermodynamics. Used energy efficiency value for I. law is same as at scenario I of case-10 and higher than at scenario I of case-11 and at cases 1 and 9. For II. law used energy efficiency is better than at scenario I of case-11 and worse than at scenario II of case-10 and at cases 1 and 9 (Table VI.16).

Scenario III: Space heating is supplied by thermal energy of the fuel cell and combustion of unused of hydrogen in fuel cell. Almost all thermal energy is consumed. 85.54 % of produced electrical energy remains (Table VI.15). Usable energy efficiencies are 88.96 % for I. law and 54.90 % for II. law of thermodynamics. According to I. and II. law of thermodynamics, used energy efficiencies are 56.14 % and 15.96 %, respectively. Used energy efficiency for I. law is worse but for II. law of thermodynamics better than at scenario III of case-10 (Table VI.16).

Scenario IV: Space heating is supplied as scenario III. Almost all electrical and all thermal energies are consumed but 127.606 kWh/day thermal energy needed (Table VI.15). Efficiencies of usable energy are same as at scenario III (Table VI.16). Used energy efficiencies are also same as efficiencies of usable energy. Efficiency values are higher than other scenarios but this scenario does not satisfy all thermal energy

requirements of the residential with three hours run time of the PEM fuel cell and 127.606 kWh thermal energy is required (Table VI.15).

Summer: Space cooling is supplied by WH200 model of heat pump as at case-10. However, unlike at case-10, domestic water heating is supplied by thermal energy of fuel cell. Almost all electrical energy of the fuel cell is used and 92.24 % of produced heat remains (Table VI.17). Usable energy efficiencies are same as at case-10. According to thermodynamics I. and II. law, used energy efficiencies are 40.39 % and 45.04 %, respectively. Used energy efficiencies are almost same as at case-1 and better than at cases 9 and 10 (Table VI.18).

Table VI.15. Case-1 and Cases 9-11 in winter

Winter	Space heating	Water heating	Electric cons.	Fuel cell run time (hrs)	Total		Unused energy		Usage of	Usage of	Surplus		Required energy (kWh)
					EE produced (kWh)	TE produced (kWh)	EE (kWh)	TE (kWh)	produced EE (%)	produced TE (%)	EE (%)	TE (%)	
Case-1	HP WGH100-WGH142	TE	EE	16.50	89.71	84.68	2.401	69.005	97.32	18.51	2.68	81.49	
Case-9	HP WGH100-WGH142	EE	EE	19	103.303	97.52	0.019	97.52	99.98	0	0.02	100	
Case 10 (I)	TE	EE	EE	24	130.488	123.18	88.144	0	26.62	100	73.38	0	
Case 11 (I)	TE	TE	EE	24	130.488	123.18	88.144	0	15.61	100	84.39	0	
Case 10 (II)	TE	EE	EE	15.75	85.63	80.84	0	0.946	100	99.30	0	0.70	
Case 11 (II)	TE	TE	EE	15.75	85.63	80.84	0	0.946	100	99.37	0	0.63	
Case 10 (III)	TE+Hyd. com.	EE	EE	18.75	101.943	135.065	69.959	1.525	31.37	98.87	68.63	1.13	
Case 11 (III)	TE+Hyd. com.	TE	EE	20.75	112.817	149.472	96.509	0.257	14.46	99.83	85.54	0.17	
Case 10 (IV)	TE+Hyd. com.	EE	EE	6	32.622	43.22	0.638	0	98.04	100	1.96	0	90.32 TE
Case 11 (IV)	TE+Hyd. com.	TE	EE	3	16.311	21.609	0	0	100	100	0	0	127.606 TE

Table VI.16.Efficiencies of case-1 and cases 9-11 in winter

Winter	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-1	234,45	197,13	74,38	43,93	52,20	45,53
Case-9	269,97	226,99	74,39	38,26	52,20	45,50
Case 10 (I)	341,02	286,73	74,39	48,54	49,15	18,41
Case 11 (I)	341,02	286,73	74,39	48,54	44,54	13,80
Case 10 (II)	223,79	188,17	74,39	73,96	28,13	28,06
Case 11 (II)	223,79	188,17	74,39	73,96	21,10	21,02
Case 10 (III)	266,42	224,01	88,96	62,13	54,90	23,57
Case 11 (III)	294,84	247,90	88,96	56,14	54,90	15,96
Case 10 (IV)	85,25	71,68	88,96	88,21	54,90	54,01
Case 11 (IV)	42,63	35,84	88,96	88,96	54,90	54,90

Table VI.17.Case-1 and cases 9-11 in summer

Summer	Space cooling	Water heating	Electric cons.	Fuel cell run time	Total		Unused energy		Usage of	Usage of	Surplus	
					EE produced	TE produced	EE	TE	produced EE	produced TE	EE	TE
				(hrs)	(kWh)	(kWh)	(kWh)	(kWh)	(%)	(%)	(%)	(%)
Case-1	HP WGH100-WGH142	TE	EE	12.50	67.96	68.428	1.103	64.065	98.38	6.36	1.62	93.64
Case-9	HP WGH100-WGH142	EE	EE	13.25	72.04	72.54	0.828	72.54	98.85	0	1.15	100
Case 10	HP WH200-WH218	EE	EE	11	59.807	60.22	0.975	60.22	98.37	0	1.63	100
Case 11	HP WH200-WH218	TE	EE	10.25	55.729	56.116	1.252	51.761	97.75	7.76	2.25	92.24

Table VI.18.Efficiencies of case-1 and cases 9-11 in summer

Summer	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-1	177,61	149,34	76,79	40,10	52,65	45,22
Case-9	188,27	158,30	76,79	37,82	52,65	44,99
Case 10	156,30	131,42	76,79	37,64	52,65	44,77
Case 11	145,64	122,46	76,79	40,39	52,65	45,04

Case-12

In this case, all energy requirements of the residential are supplied by electrical energy.

Summer: Summer energy requirements and results of case-12 are same as at case-10 (Tables VI.19 and VI.20). For I. and II. law of thermodynamics, used energy efficiency values are lower than at case-8 but for II. law efficiency value is almost same as at case-8 (Table VI.20).

Winter: Space heating is supplied by both WH200 model of heat pump and electrical heater. Fuel cell works all day in winter. All electrical energy of the fuel cell is consumed and 16.616 kWh/day extra electrical energy needed. 123.18 kWh/day heat is not used (Table VI.21). Usable energy efficiencies are 74.39 % for I. law and 52.20 % for II. law of thermodynamics. Used energy efficiencies are 38.26 % and 45.51 % for thermodynamics I. and II. law, respectively. For I. law, used energy efficiency is very low according to scenarios of case-8, but for II. law, efficiency value is better than scenarios of cases-8 except scenario IV (Table VI.22).

Table VI.19.Cases 8 and 12 in summer

Summer	Space cooling	Water heating	Electric cons.	Fuel cell run time (hrs)	Total		Unused energy		Usage of	Usage of	Surplus	
					EE produced (kWh)	TE produced (kWh)	EE (kWh)	TE (kWh)	produced EE (%)	produced TE (%)	EE (%)	TE (%)
Case-8	HP WH200-WH218	TE	EE	10.25	55.729	56.116	1.252	51.761	97.75	7.76	2.25	92.24
Case-12	HP WH200-WH218	EE	EE	11	59.807	60.22	0.975	60.22	98.37	0	1.63	100

Table VI.20.Efficiencies of cases 8 and 12 in summer

Summer	Hydrogen input	Hydrogen input	Usable energy efficiency	Used energy efficiency	Usable energy efficiency	Used energy efficiency
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-8	145,64	122,46	76,79	40,39	52,65	45,04
Case-12	156,30	131,42	76,79	37,64	52,65	44,77

Table VI.21.Cases 8 and 12 in winter

Winter	Space heating	Water heating	Electric cons.	Fuel cell run time (hrs)	Total		Unused energy		Usage of	Usage of	Surplus		Required energy (kWh)
					EE produced (kWh)	TE produced (kWh)	EE (kWh)	TE (kWh)	produced EE (%)	produced TE (%)	EE (%)	TE (%)	
Case-8 (I)	HP+TE WH200-WH218	TE	EE	19.25	104.66	98.802	55.47	0.887	47.00	99.10	53	0.9	
Case-8 (II)	HP+TE WH200-WH218	TE	EE	14	76.118	71.857	0	0.871	100	99.12	0	0.88	
Case-8 (III)	HP+TE+Hyd. com. WH200-WH218	TE	EE	13.75	74.758	99.047	25.569	1.132	65.80	98.86	34.20	1.14	
Case-8 (IV)	HP+TE+Hyd. com. WH200-WH218	TE	EE	9.25	50.292	66.632	1.103	0	97.81	100	2.19	0	31.283 TE
Case-12	HP+EE WH200-WH218	EE	EE	24	130.488	123.18	0	123.18	100	0	0	100	16.616 EE

Table VI.22.Efficiencies of cases 8 and 12 in winter

Winter	Hydrogen input		Usable energy efficiency		Used energy efficiency	
	I. Law (kWh)	II. Law (kWh)	I. Law (%)	I. Law (%)	II. Law (%)	II. Law (%)
Case-8 (I)	273,52	229,98	74,39	53,78	52,20	28,02
Case-8 (II)	198,93	167,26	74,39	73,95	38,61	38,53
Case-8 (III)	195,37	164,27	88,96	75,29	54,90	39,23
Case-8 (IV)	131,43	110,51	88,96	88,12	54,90	53,91
Case-12	341,02	286,73	74,39	38,26	52,20	45,51

VII. CONCLUSIONS AND RECOMMENDATIONS

In this thesis study, a PEM fuel cell was modeled. Using the model, the most important performance parameters of the PEM fuel cell, namely operation temperature and pressure were investigated and their effects were determined on the PEM fuel cell performance. The performance is reflected primarily in the PEM fuel cell output voltage, electrical power output and efficiencies. The basic results of the PEM fuel cell modeling (Table VII.1) are presented below:

- Higher operation temperatures and pressures advance the fuel cell performance; the effect of the pressure increase is more pronounced.
- If higher electrical power is required, increasing pressure gives better results than increasing temperature.
- As the operation temperature and pressure increase, electrical power production increases while useful heat production decreases (taking into account only the electrochemical reaction) (Table VII.1).
- Electrical efficiency values for first and second law of thermodynamics are better with increasing operation pressure and temperature, the effect of the former is more pronounced.
- Total efficiency calculated according to the first law taking into account useful heat and electrical power production slightly decreases with increasing temperature while a slight increase is observed with increasing pressure.
- Total efficiency value calculated according to the second law of thermodynamics is better with both higher temperatures and higher pressures, the effect of the former is more pronounced.

Table VII.1.Results of the PEM fuel cell model at different temperatures and pressures

	Electrical Power (W)			Electrical Efficiency (TD1) (%)			Electrical Efficiency (TD2) (%)		
	Temperatures			Temperatures			Temperatures		
	60°C	80°C	100°C	60°C	80°C	100°C	60°C	80°C	100°C
Pressures									
1 atm	5022	5052	5083	35,52	35,82	36,12	42,85	43,09	43,33
3 atm	5387	5437	5489	37,82	38,26	38,72	45,10	45,50	45,92
5 atm	5556	5617	5679	39,01	39,53	40,06	46,27	46,76	47,26
	Useful Heat Generation (W)			Total Efficiency (TD1) (%)			Total Efficiency (TD2) (%)		
	Temperatures			Temperatures			Temperatures		
	60°C	80°C	100°C	60°C	80°C	100°C	60°C	80°C	100°C
Pressures									
1 atm	6121	5983	5783	78,81	78,23	77,21	48,33	51,03	53,24
3 atm	5845	5703	5555	78,85	78,40	77,90	50,24	52,94	55,26
5 atm	5676	5527	5378	78,86	78,43	77,99	51,24	53,93	56,25

Residential electric and thermal loads are not usually in phase. Moreover, electric and thermal loads may not be closely matched to those produced by the PEM fuel cell. Therefore, it is a difficult decision to choose the right size of PEM fuel cell. Cogeneration applications of the PEM fuel cell in residential buildings may be selected and operated to compensate either the total electrical and thermal demands, or the total thermal demand and part of the electrical demand, or the total electrical demand and part of the thermal demand. Availability of electrical power from the grid, permission to feed back the produced DC power to the grid after conversion to AC will effect the final decision along with other technical and economic factors. To maximize the utilization of the cogeneration heat produced by the residential fuel cell thermal storage media may be a good choice. Results indicate that both first and second law efficiencies decrease as the portion of the unused energies (electrical or thermal) increases. As expected unused electrical energies cause much higher exergy losses than the surplus thermal energies and lead to much lower second law efficiencies. In this study, the best exergetic efficiency is achieved by scenario IV of case-11 with 127.6 kWh/day thermal energy requirement in winter and case-4 in summer.

REFERENCES

- [1] Barbir F.: “PEM Fuel Cells: Theory and Practice”, Elsevier, Academic Press Sustainable World Series, **2005**
- [2] Larminie J.; Dicks A.: “Fuel Cell Systems Explained”, John Wiley & Sons, **2000**
- [3] Avadhanam K. V.: “PEM Fuel Cell Power Plant Simulation”, *MSc Thesis*, Bangalore University, May **2004**
- [4] Güvelioğlu G. H.: “Transport Limitations and Water Management in PEM Fuel Cell”, *PhD Thesis*, Chemical Engineering, Lehigh University, **2005**
- [5] Khan M. J.; Iqbal M. T.: “Modelling and Analysis of Electro-chemical, Thermal, and Reactant Flow Dynamics for a PEM Fuel Cell System”, *Wiley InterScience*, November 5, **2004**
- [6] Steinberg, M.; Cheng H. C.: “Modern and Prospective Technologies for Hydrogen Production from Fossil Fuels”, in T. N. Veziroglu and A. N. Protsenko (editors), *Hydrogen Energy Progress VII, Vol. 2* (Pergamon Press, Oxford, **1998**), 699-740.
- [7] Steeb, H.; Brinner A.; Bubmann H.; Seeger W.: “Operation Experience of a 10 kW PV-Electrolysis System in Different Power Matching Modes”, in T. N. Veziroglu and P. K. Takahashi (editors), *Hydrogen Energy Progress VIII, Vol.2* (Pergamon Press, New York, **1990**) 691-700.
- [8] Çengel Y.; Boles M.: “Thermodynamics—an Engineering Approach” 2nd ed. *Mc Graw-Hill*, **1994**
- [9] Kazim A.: “Exergy Analysis of a PEM Fuel Cell at Variable Operating Conditions”, Department of Mechanical Engineering, Faculty of Engineering, United Arab Emirates University, September 27, 2003, *Energy Conversion & Management* **45**, **2004**, 1949-1961
- [10] Osmanoglu H.; Turan H.: “Modeling of PEM Fuel Cell with a Cogeneration Application”, *Undergraduate Thesis*, Marmara University, Istanbul, Turkey, June **2005**
- [11] Onovwiona H.I.; Ugursal V.I.: “Residential Cogeneration Systems: Review of the Current Technology”, *Renewable & Sustainable Energy Reviews*, **2006**, 389- 431
- [12] Güneş M. B.: “Investigation of a Fuel Cell Based Total Energy System for Residential Applications”, *MSc Thesis*, Faculty of the Virginia Polytechnic Institute, April 30 **2001**
- [13] Fuchs M.; Barbir F.: “Development of Advanced, Low-Cost PEM Fuel Cell Stack and System Design for Operation on Reformate Used in Vehicle Power Systems, Transportation Fuel Cell Power System”, 2000 Annual Progress Report (U.S. Department of Energy, Office of Advanced Automotive Technologies, Washington, D.C., October **2000**), 79-84.

[14] www.sigmaaldrich.com/catalog/search/ProductDetail/ALDRICH/274674,
October 2006

APPENDIX

APPENDIX A. Chemical Exergy Table

Table A.1. Standard molar chemical exergy, (kJ/kmol), of various substances at 298.15 K and P_0

Substance	Formula	Model I ^a	Model II ^b
Nitrogen	N ₂ (g)	639	720
Oxygen	O ₂ (g)	3,951	3,970
Carbon dioxide	CO ₂ (g)	14,176	19,870
Water	H ₂ O(g)	8,636	9,500
Water	H ₂ O(l)	45	900
Carbon (graphite)	C(s)	404,589	410,260
Hydrogen	H ₂ (g)	235,249	236,100
Sulfur	S(s)	598,158	609,600
Carbon monoxide	CO(g)	269,412	275,100
Sulfur dioxide	SO ₂ (g)	301,939	313,400
Nitrogen monoxide	NO(g)	88,851	88,900
Nitrogen dioxide	NO ₂ (g)	55,565	55,600
Hydrogen peroxide	H ₂ O ₂ (g)	133,587	—
Hydrogen sulfide	H ₂ S	799,890	812,000
Ammonia	NH ₃ (g)	336,684	337,900
Oxygen	O(g)	231,968	233,700
Hydrogen	H(g)	320,822	331,300
Nitrogen	N(g)	453,821	—
Methane	CH ₄ (g)	824,348	831,650
Acetylene	C ₂ H ₂ (g)	—	1,265,800
Ethylene	C ₂ H ₄ (g)	—	1,361,100
Ethane	C ₂ H ₆ (g)	1,482,033	1,495,840
Propylene	C ₃ H ₆ (g)	—	2,003,900
Propane	C ₃ H ₈ (g)	—	2,154,000
n-Butane	C ₄ H ₁₀ (g)	—	2,805,800
n-Pentane	C ₅ H ₁₂ (g)	—	3,463,300
Benzene	C ₆ H ₆ (g)	—	3,303,600
Octane	C ₈ H ₁₈ (l)	—	5,413,100
Methanol	CH ₃ OH(g)	715,069	722,300
Methanol	CH ₃ OH(l)	710,747	718,000
Ethyl alcohol	C ₂ H ₅ OH(g)	1,348,328	1,363,900
Ethyl alcohol	C ₂ H ₅ OH(l)	1,342,086	1,375,700

^a J. Ahrendts, "Die Exergie chemisch reaktionsfähiger Systeme", VDI-Forschungsheft, 579, VDI-Verlag, Dusseldorf, 1977, pp. 26-33. Also see, "Reference States", Ebergy-Int. J., Vol. 5, 1980, pp. 667-677. In this model $P_0 = 1.019$ atm.

^b From J. Szargut, D. R. Morris, and F. R. Steward, Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, Hemisphere, New York, 1988, pp. 297-309. In this model, $P_0 = 1.0$ atm

APPENDIX B. Heating and Cooling Load Parameters and Results

Figure B.1.Design conditions

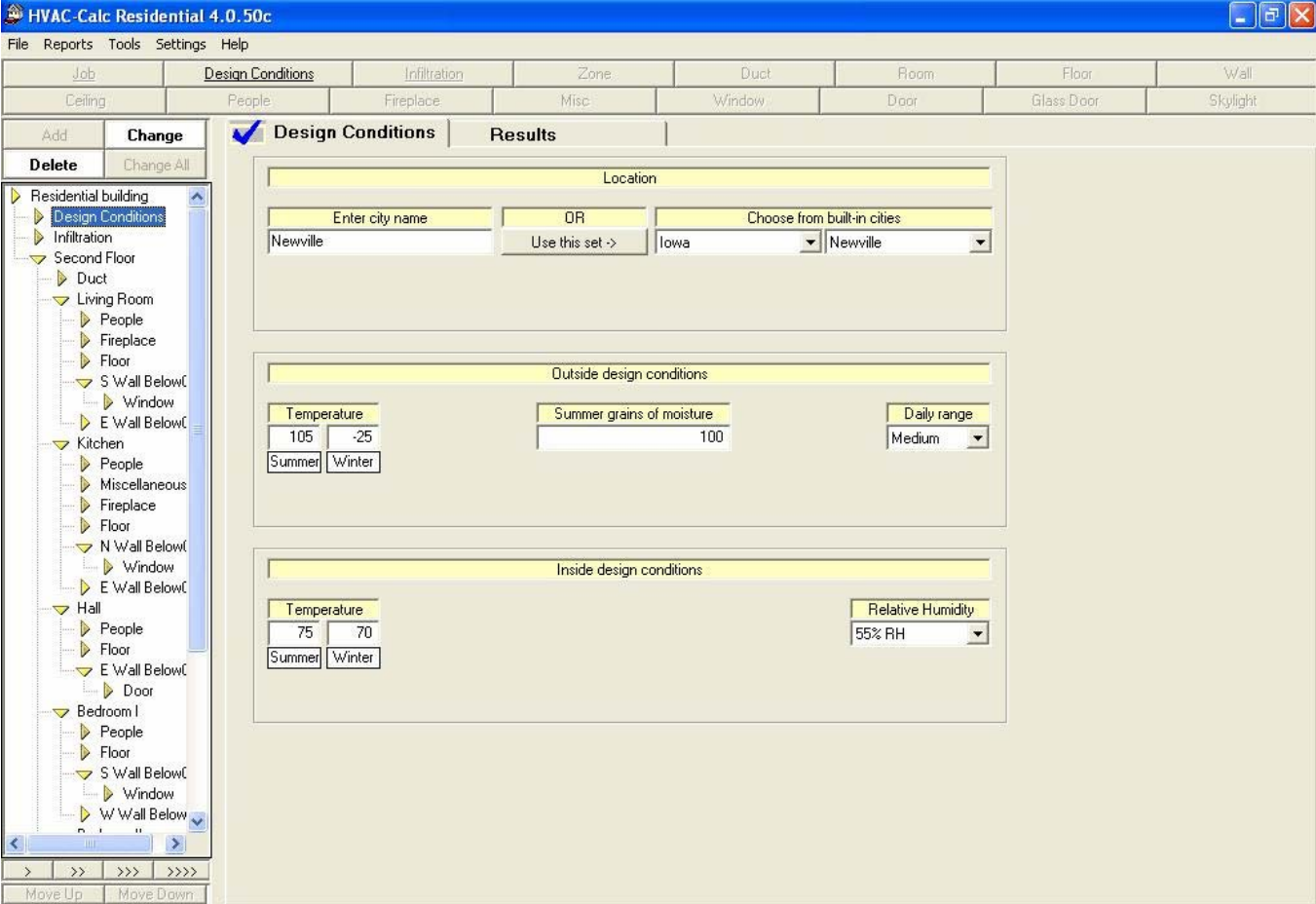


Figure B.2. Infiltration

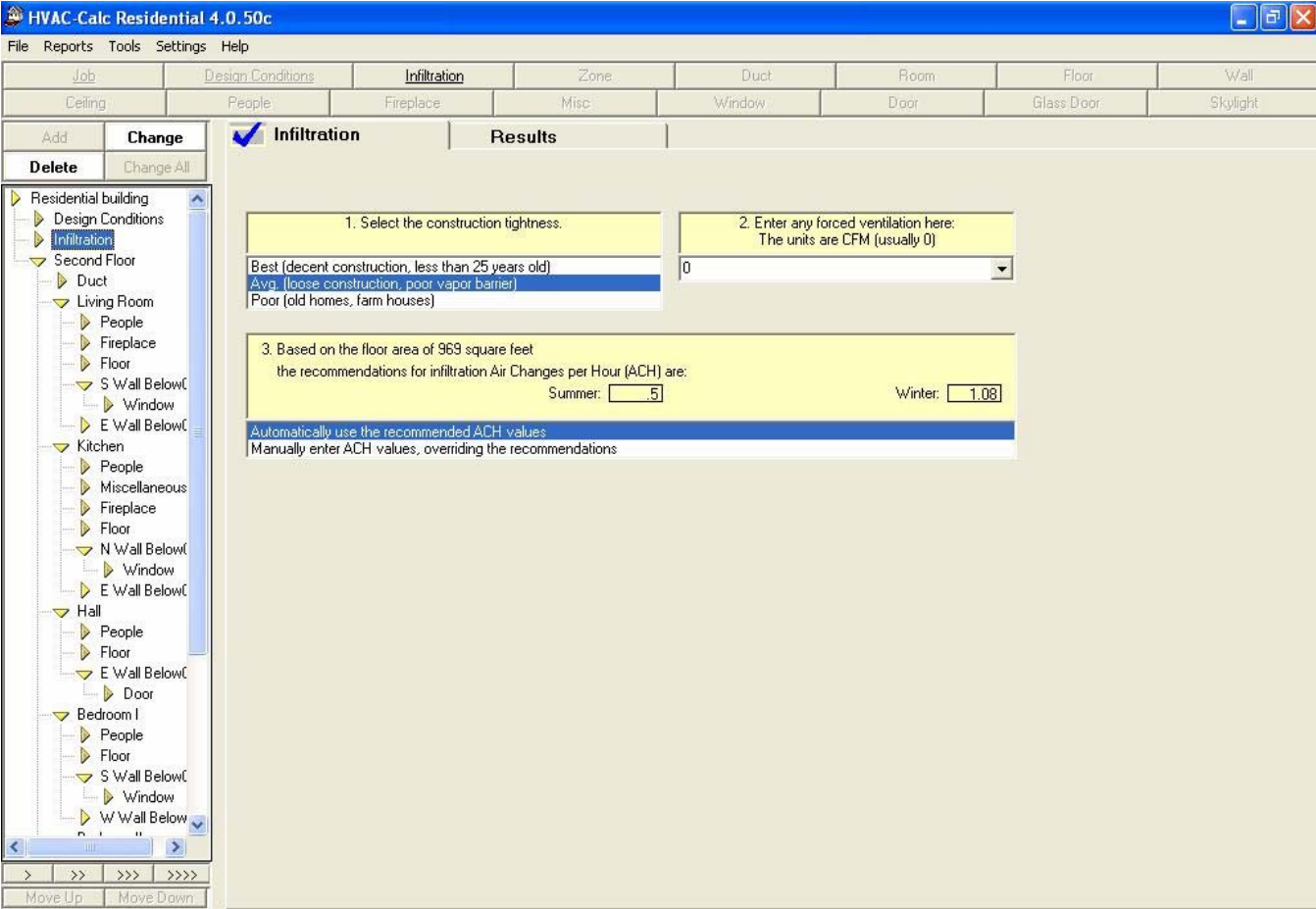


Figure B.3.Duct

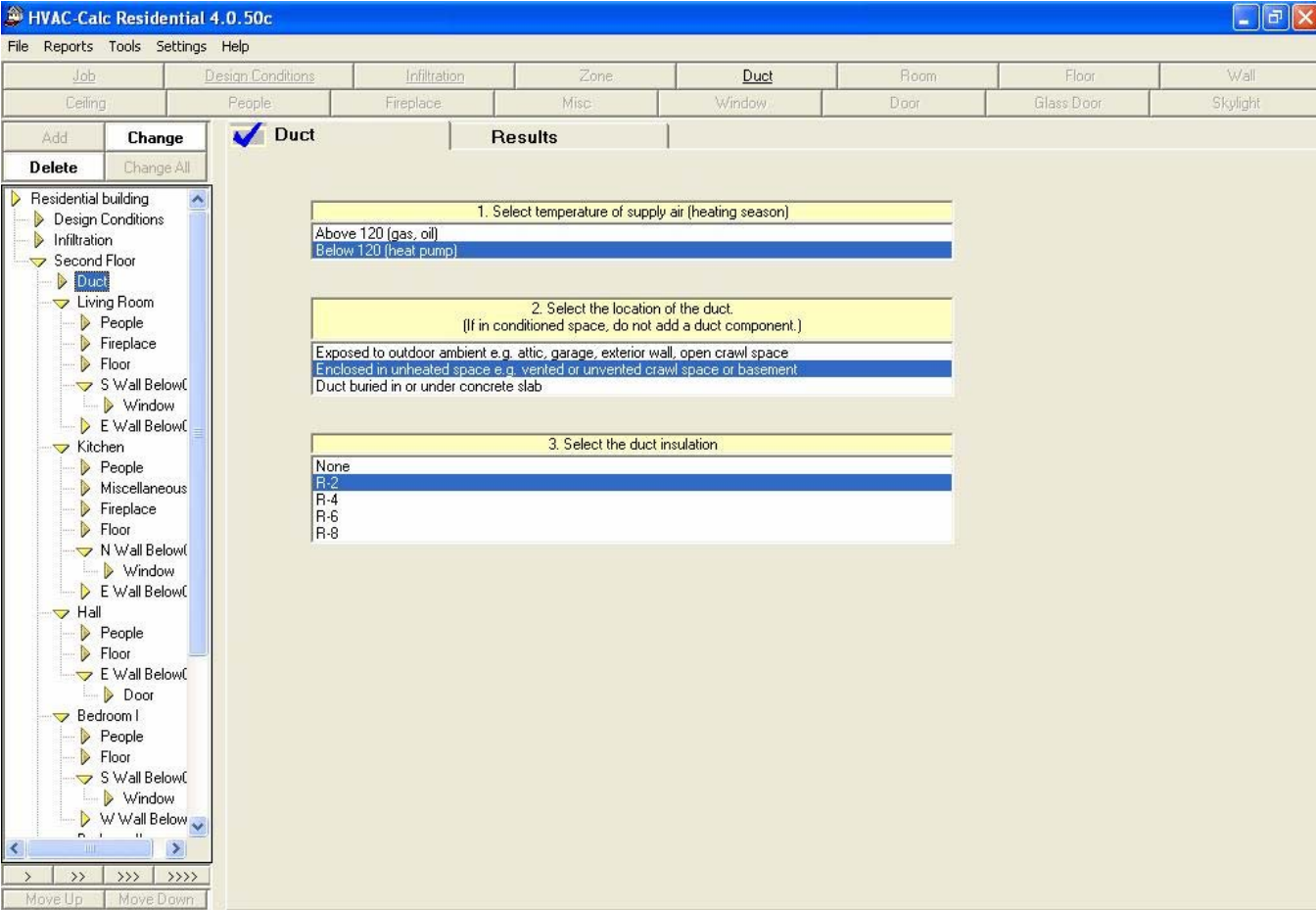


Table B.1.HVAC-Calc Residential 4.0 Report

HVAC-Calc Residential 4.0 Report
X

Print Report
Save to PDF
Close

Page 1 **Residential Heat Loss and Heat Gain Calculation**

In accordance with ACCA Manual J

Report Prepared By:
Unregistered Trial Version

For: Residential building
Newville, Iowa

Design Conditions: Newville

<p>Indoor:</p> <p>Summer temperature: 75</p> <p>Winter temperature: 70</p> <p>Relative humidity: 55</p>	<p>Outdoor:</p> <p>Summer temperature: 105</p> <p>Winter temperature: -25</p> <p>Summer grains of moisture: 100</p> <p>Daily temperature range: Medium</p>
--	---

Building Component	Area	Sensible Gain (BTUH)	Latent Gain (BTUH)	Total Heat Gain (BTUH)	Total Heat Loss (BTUH)
Whole House	969 sq.ft.	11,362	3,450	14,812 (1 tons)	18,567
Second Floor		11,362	3,450	14,812	18,567
Living Room	280 sq.ft.	3,394	920	4,314	5,463
Kitchen	170 sq.ft.	3,344	920	4,264	3,359
Hall	120 sq.ft.	873	460	1,333	831
Bedroom I	150 sq.ft.	1,681	460	2,141	3,237
Bedroom II	172 sq.ft.	1,716	460	2,176	4,032
Bathroom	77 sq.ft.	354	230	584	1,645
Whole House	969 sq.ft.	11,362	3,450	14,812 (1 tons)	18,567

HVAC-Calc Residential 4.0 by HVAC Computer Systems Ltd. 888 736-1101

Load calculations are estimates only, actual loads may vary due to weather and construction differences.

APPENDIX C. Electrical Consumptions of the Residential House

Table C.1. Usage hours of electrical appliances in the living room at different times

Living Room								
Electrical Appliances	Device Energy Requirement (Watts)	Hours of use per day Summer day	Hours of use per day Summer night	Hours of use per day Winter day	Hours of use per day Winter night	Average Hours of use per day	Days of use per week	Number in Room
60W bulb	60	0	3,5	0	6	4,75	7	6
TV (25-inch colour)	150	3	3	2	4	6	6	1
CD/DVD Player	50	1	0	1	3	2,5	2	1
Portable Stereo (average volume)	55	0,5	0	0,5	0,25	0,625	4	1
Hi-Fi Stereo, surr. sound system	500	2	0	0	3	2,5	2	1
Mobile Phone (on standby)	20	14	10	10	14	24	7	1
Total energy requirement (Watts)	1135							

Table C.2. Electrical consumptions of the appliances in the living room at different times

Living Room					
Electrical Appliances	Consumption kWh per day Summer day	Consumption kWh per day Summer night	Consumption kWh per day Winter day	Consumption kWh per day Winter night	Average kWh per day
60W bulb	0,000	1,260	0,000	2,160	1,710
TV (25-inch colour)	0,386	0,386	0,257	0,514	0,771
CD/DVD Player	0,014	0,000	0,014	0,043	0,036
Portable Stereo (average volume)	0,016	0,000	0,016	0,008	0,020
Hi-Fi Stereo, surr. sound system	0,286	0,000	0,000	0,429	0,357
Mobile Phone (on standby)	0,280	0,200	0,200	0,280	0,480

Table C.3.Usage hours of electrical appliances in the kitchen at different times

Kitchen								
Electrical Appliances	Device Energy Requirement (Watts)	Hours of use per day Summer day	Hours of use per day Summer night	Hours of use per day Winter day	Hours of use per day Winter night	Average Hours of use per day	Days of use per week	Number in House
20W Energy efficient light	20	0	1	0	3	2	7	2
Cooker - Small	1250	1	0	0,5	0,5	1	4	1
10.6cu.ft. Fridge Freezer (24 hrs cycling)	180	7	3	6	0	8	7	1
Microwave (standard size)	900	0,5	0,5	0,5	0,5	1	3	1
Fan	140	1	0,5	0,5	1	1,5	5	1
Electric Kettle	2200	0,25	0,25	0,25	0,5	0,625	5	1
Toaster (2 Slice)	1200	0,25	0	0,25	0	0,25	3	1
Coffee Maker	1200	0,1	0	0,1	0,1	0,15	4	1
	Watts per wash cycle	Number of washes per week			Number in house	Average kWh/day		
Washing Machine	2500				3		1	1,071
Washer Dryers	5000				3		1	2,143
Dishwasher	1500				3		1	0,643
Total energy requirement (Watts)	16110							

Table C.4.Electrical consumptions of the appliances in the kitchen at different times

Kitchen					
Electrical Appliances	Consumption	Consumption	Consumption	Consumption	Average
	kWh per day	kWh per day	kWh per day	kWh per day	kWh
	Summer day	Summer night	Winter day	Winter night	per day
20W Energy efficient light	0,000	0,040	0,000	0,120	0,080
Cooker - Small	0,714	0,000	0,357	0,357	0,714
10.6cu.ft. Fridge Freezer (24 hrs cycling)	1,260	0,540	1,080	0,000	1,440
Microwave (standard size)	0,193	0,193	0,193	0,193	0,386
Fan	0,100	0,050	0,050	0,100	0,150
Electric Kettle	0,393	0,393	0,393	0,786	0,982
Toaster (2 Slice)	0,129	0,000	0,129	0,000	0,129
Coffee Maker	0,069	0,000	0,069	0,069	0,103

Table C.5.Usage hours of electrical appliances in the bedroom 1 at different times

Bedroom I								
Electrical Appliances	Device Energy Requirement (Watts)	Hours of use per day Summer day	Hours of use per day Summer night	Hours of use per day Winter day	Hours of use per day Winter night	Average Hours of use per day	Days of use per week	Number in Room
20W Energy efficient light	20	0	1	0	3	2	5	2
Computer - CPU unit (without monitor)	220	2	1	2	3	4	5	1
17" Colour Monitor	120	2	1	2	3	4	5	1
Ink Jet Printer	40	0,2	0	0,1	0,1	0,2	3	1
Fax Machine	500	0,25	0	0,1	0,1	0,225	2	1
Portable Stereo (average volume)	55	1	0,25	0,75	0,75	1,375	4	1
Total energy requirement (Watts)	975							

Table C.6.Electrical consumptions of the appliances in the bedroom I at different times

Bedroom I					
Electrical Appliances	Consumption kWh per day Summer day	Consumption kWh per day Summer night	Consumption kWh per day Winter day	Consumption kWh per day Winter night	Average kWh per day
20W Energy efficient light	0,000	0,029	0,000	0,086	0,057
Computer - CPU unit (without monitor)	0,314	0,157	0,314	0,471	0,629
17" Colour Monitor	0,171	0,086	0,171	0,257	0,343
Ink Jet Printer	0,003	0,000	0,002	0,002	0,003
Fax Machine	0,036	0,000	0,014	0,014	0,032
Portable Stereo (average volume)	0,031	0,008	0,024	0,024	0,043

Table C.7.Usage hours of electrical appliances in the bedroom II at different times

Bedroom II								
Electrical Appliances	Device Energy Requirement (Watts)	Hours of use per day Summer day	Hours of use per day Summer night	Hours of use per day Winter day	Hours of use per day Winter night	Average Hours of use per day	Days of use per week	Number in Room
20W Energy efficient light	20	0	1	0	3	2	5	2
TV	120	0,5	1	0,5	1,5	1,75	2	1
Video Recorder (VCR)	70	0	0,75	0,5	0,75	1	1	1
CD/DVD Player	50	0	1	0	2	1,5	2	1
Electric Iron	1200	0,5	0,5	0,5	0,5	1	3	1
Total energy requirement (Watts)	1480							

Table C.8.Electrical consumptions of the appliances in the bedroom II at different times

Bedroom II					
Electrical Appliances	Consumption kWh per day Summer day	Consumption kWh per day Summer night	Consumption kWh per day Winter day	Consumption kWh per day Winter night	Average kWh per day
20W Energy efficient light	0,000	0,029	0,000	0,086	0,057
TV	0,017	0,034	0,017	0,051	0,060
Video Recorder (VCR)	0,000	0,008	0,005	0,008	0,010
CD/DVD Player	0,000	0,014	0,000	0,029	0,021
Electric Iron	0,257	0,257	0,257	0,257	0,514

Table C.9.Usage hours of electrical appliances in the bathroom at different times

Bathroom								
Electrical Appliances	Device Energy Requirement (Watts)	Hours of use per day Summer day	Hours of use per day Summer night	Hours of use per day Winter day	Hours of use per day Winter night	Average Hours of use per day	Days of use per week	Number in Room
40W bulb	40	2	1	1,5	1,5	3	7	2
Hair Dryer	1500	0	0,25	0,5	0,5	0,625	4	1
Electric Shaver	20	0,25	0	0,25	0	0,25	3	1
Extractor Fan	500	0,75	0,25	0,5	0,5	1	7	1
Total energy requirement (Watts) 2100								

Table C.10.Electrical consumptions of the appliances in the bathroom at different times

Bathroom					
Electrical Appliances	Consumption kWh per day Summer day	Consumption kWh per day Summer night	Consumption kWh per day Winter day	Consumption kWh per day Winter night	Average kWh per day
40W bulb	0,160	0,080	0,120	0,120	0,240
Hair Dryer	0,000	0,214	0,429	0,429	0,536
Electric Shaver	0,002	0,000	0,002	0,000	0,002
Extractor Fan	0,375	0,125	0,250	0,250	0,500

Table C.11.Usage hours of other electrical appliances at different times

About the House								
(in halls, corridors)	Device Energy	Hours of use	Hours of use	Hours of use	Hours of use	Average	Days of use	Number
Electrical Appliances	Requirement	per day	per day	per day	per day	Hours of use	per week	in Room
	(Watts)	Summer day	Summer night	Winter day	Winter night	per day		
20W Energy efficient light	20	0	2	1	3	3	5	2
Fan Heater 1/3hp	700	0,5	0,5	0,5	0,5	1	5	1
Alarm/Security System	5	14	10	10	14	24	7	1
Vacuum Cleaner, average	1000	0,5	0	0,5	0	0,5	3	1
Total energy requirement (Watts) 1745								

Table C.12.Electrical consumptions of the other appliances at different times

About the House					
(in halls, corridors)	Consumption	Consumption	Consumption	Consumption	Average
Electrical Appliances	kWh per day	kWh per day	kWh per day	kWh per day	kWh
	Summer day	Summer night	Winter day	Winter night	per day
20W Energy efficient light	0,000	0,057	0,029	0,086	0,086
Fan Heater 1/3hp	0,250	0,250	0,250	0,250	0,500
Alarm/Security System	0,070	0,050	0,050	0,070	0,120
Vacuum Cleaner, average	0,214	0,000	0,214	0,000	0,214

Table C.13.Total electrical consumptions of the house at different times

Total Household Consumption	Total energy requirement (Watts)	Total Consumption in summer day (kWh per day)	Total Consumption in summer night (kWh per day)	Total Consumption in winter day (kWh per day)	Total Consumption in winter night (kWh per day)	Total average consumption (kWh per day)
Living Room	1135	0,981	1,846	0,487	3,434	3,374
Kitchen	16110	2,857	5,073	2,270	5,481	7,841
Bedroom I	975	0,556	0,279	0,525	0,854	1,107
Bedroom II	1480	0,274	0,342	0,279	0,430	0,663
Bathroom	2100	0,537	0,419	0,801	0,799	1,278
Rest of House	1745	0,534	0,357	0,543	0,406	0,920
Household Total	23545	5,741	8,316	4,905	11,404	15,183

APPENDIX D. Performance of Heat Pump for Different Models

Table D.1. Performance of WH100 model of Whirlpool heat pump

Cooling Performance - Extended Ratings

Outdoor Model	Indoor Model	Indoor Temp DB/WB °F	Outdoor Temp - DB°F														
			65			82			95			105			115		
			Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW
WH118	WM24N/WM25N WEC,WUC24A,B,C	85/72	22,000	.65	1.52	20,000	.67	1.73	18,500	.72	1.88	17,500	.73	1.98	16,500	.75	2.13
		80/67	21,000	.68	1.50	19,000	.70	1.70	17,500	.75	1.85	16,500	.76	1.95	15,500	.78	2.10
		75/63	20,000	.72	1.49	18,000	.73	1.67	16,500	.78	1.82	15,500	.79	1.92	14,500	.81	2.07
WH124	WM24N/WM25N WEC,WUC24A,B,C	85/72	27,500	.67	2.18	25,500	.71	2.43	24,000	.74	2.58	23,000	.75	2.68	22,000	.77	2.78
		80/67	26,500	.70	2.20	24,500	.74	2.40	23,000	.77	2.55	22,000	.78	2.65	21,000	.80	2.75
		75/63	25,500	.73	2.22	23,500	.77	2.37	22,000	.80	2.52	21,000	.81	2.62	20,000	.83	2.72
WH130	WM36N/WM37N WEC,WUC36A,B,C,D	85/72	32,000	.70	2.57	30,000	.73	2.78	28,500	.75	3.03	27,500	.77	3.13	26,500	.79	3.23
		80/67	31,000	.72	2.55	29,000	.76	2.75	27,500	.78	3.00	26,500	.80	3.10	25,500	.82	3.20
		75/63	30,000	.74	2.53	28,000	.79	2.72	26,500	.81	2.97	25,500	.83	3.07	24,500	.85	3.17
WH136	WEC,WUC36A,B,C,D	85/72	40,500	.65	3.42	38,500	.67	3.63	36,000	.72	3.88	35,000	.74	3.98	34,000	.76	4.08
		80/67	39,500	.68	3.40	37,500	.70	3.60	35,000	.75	3.85	34,000	.77	3.95	33,000	.79	4.05
		75/63	38,500	.72	3.80	36,500	.73	3.57	34,000	.78	3.82	33,000	.80	3.92	32,000	.82	4.02
WH136	WM36N/WM37N	85/72	39,321	.62	3.33	37,399	.64	3.54	34,952	.69	3.78	33,980	.71	3.88	33,088	.73	3.97
		80/67	38,420	.65	3.31	36,380	.67	3.51	34,000	.72	3.75	33,027	.74	3.85	32,059	.76	3.94
		75/63	37,267	.69	3.69	35,289	.70	3.47	32,980	.75	3.71	32,010	.77	3.81	31,041	.79	3.91
WH142	WM42N WEC,WUC46B,C,D	85/72	45,500	.67	3.96	43,500	.69	4.13	41,000	.73	4.33	40,000	.75	4.43	39,000	.77	4.43
		80/67	44,500	.69	3.95	42,500	.72	4.10	40,000	.76	4.30	39,000	.78	4.40	38,000	.80	4.40
		75/63	43,500	.72	3.94	41,500	.75	4.07	39,000	.79	4.27	38,000	.81	4.37	37,000	.83	4.37
WH148	WM48N WEC,WUC58C,D	85/72	55,000	.62	4.13	52,000	.65	4.33	48,000	.70	4.73	47,000	.72	5.13	46,000	.75	5.73
		80/67	53,000	.65	4.10	50,000	.68	4.30	46,000	.73	4.70	45,000	.75	5.10	44,000	.78	5.70
		75/63	51,000	.68	4.07	48,000	.71	4.27	44,000	.76	4.67	43,000	.78	5.07	42,000	.81	5.67
WH160	WM60N WEC,WUC60D	85/72	65,500	.65	5.73	62,500	.67	6.03	58,500	.70	6.53	56,500	.72	6.83	54,500	.75	7.03
		80/67	63,500	.68	5.70	60,500	.70	6.00	56,500	.73	6.50	54,500	.75	6.80	52,500	.78	7.00
		75/63	61,500	.71	5.67	58,500	.73	5.97	54,500	.76	6.47	52,500	.78	6.77	50,500	.81	6.97

Heating Performance - Extended Ratings

Outdoor Model	Indoor Model	Outdoor Temp. DB/WB°F														
		0/0			17/15			35/33			47/43			62/56		
		Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW
WH118	WM24N/WM25N WEC,WUC24A,B,C	5,300	1.40	1.29	9,700	2.00	1.42	14,400	2.70	1.56	17,500	3.10	1.65	21,400	3.70	1.70
WH124	WM24N/WM25N WEC,WUC24A,B,C	6,800	1.40	1.63	13,000	2.10	1.81	19,600	2.80	2.05	24,000	3.30	2.13	29,500	3.90	2.22
WH130	WM36N/WM37N WEC,WUC36A,B,C,D	12,700	1.70	2.25	18,600	2.30	2.37	24,800	2.90	2.51	29,000	3.30	2.58	34,200	3.80	2.64
WH136	WEC,WUC36A,B,C,D	13,500	1.60	2.67	22,000	2.20	2.93	31,000	2.80	3.24	37,000	3.20	3.39	44,500	3.70	3.52
	WM36N/WM37N	12,894	1.60	2.55	21,000	2.20	2.80	28,560	2.80	2.98	34,000	3.20	3.12	40,800	3.71	3.24
WH142	WM42N WEC,WUC46B,C,D	14,600	1.60	3.00	24,000	2.20	3.26	35,000	2.90	3.54	40,500	3.30	3.73	50,800	3.90	3.82
WH148	WM48N WEC,WUC58C,D	19,100	1.70	3.45	29,000	2.30	3.70	39,500	2.90	3.99	46,500	3.30	4.13	55,300	3.80	4.26
WH160	WM60N WEC,WUC60D	24,000	1.70	4.24	35,000	2.30	4.24	46,700	2.90	4.72	54,500	3.30	4.84	64,300	3.80	4.96

Table D.2. Performance of WH200 model of Whirlpool heat pump

Cooling Performance - Extended Ratings

Outdoor Model	Indoor Model	Indoor Temp DB/WB °F	Outdoor Temp - DB °F														
			65			82			95			105			115		
			Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW
WH218	WM24N/WM25N WEC,WUC30A,B,C	85/72	22,000	.65	1.41	20,000	.67	1.50	19,000	.72	1.63	17,500	.73	1.78	16,500	.75	1.88
		80/67	21,000	.68	1.36	19,000	.70	1.47	18,000	.75	1.60	16,500	.76	1.75	15,500	.78	1.85
		75/63	20,000	.72	1.33	18,000	.73	1.44	17,000	.77	1.57	15,500	.79	1.72	14,500	.81	1.82
WH224	WM24N/WM25N WEC,WUC30A,B,C	85/72	28,000	.67	1.68	26,000	.71	1.93	24,500	.74	2.23	23,500	.75	2.33	22,500	.77	2.43
		80/67	27,000	.70	1.70	25,000	.74	1.90	23,500	.77	2.20	22,500	.78	2.30	21,500	.80	2.40
		75/63	26,000	.73	1.73	24,000	.77	1.87	22,500	.80	2.17	21,500	.81	2.27	20,500	.83	2.37
WH230	WM36N/WM37N WEC,WUC36A,B,C,D	85/72	33,000	.70	2.23	31,000	.73	2.43	30,000	.75	2.63	29,000	.77	2.83	28,000	.79	3.03
		80/67	32,000	.72	2.20	30,000	.76	2.40	29,000	.78	2.60	28,000	.80	2.80	27,000	.82	3.00
		75/63	31,000	.74	2.17	29,000	.79	2.37	28,000	.81	2.57	27,000	.83	2.77	26,000	.85	2.97
WH236	WM42N WEC,WUC46B,C,D	85/72	40,500	.65	3.23	38,500	.67	3.33	37,000	.72	3.43	35,000	.74	3.58	34,000	.76	3.68
		80/67	39,500	.68	3.20	37,500	.70	3.30	36,000	.75	3.40	34,000	.77	3.55	33,000	.79	3.65
		75/63	38,500	.72	3.17	36,500	.73	3.27	35,000	.78	3.37	33,000	.80	3.52	32,000	.82	3.62
WH242	WM42N WEC,WUC46B,C,D	85/72	45,500	.67	3.13	43,500	.69	3.33	41,000	.73	3.73	40,000	.75	3.83	39,000	.77	3.93
		80/67	44,500	.69	3.10	42,500	.72	3.30	40,000	.76	3.70	39,000	.78	3.80	38,000	.80	3.90
		75/63	43,500	.72	3.07	41,500	.75	3.27	39,000	.79	3.67	38,000	.81	3.77	37,000	.83	3.87
WH248	WM60N WEC,WUC60D	85/72	57,000	.62	4.03	55,000	.65	4.33	50,000	.70	4.73	48,000	.72	4.93	46,000	.75	5.23
		80/67	55,000	.65	4.00	53,000	.68	4.30	49,000	.73	4.70	46,000	.75	4.90	44,000	.78	5.20
		75/63	53,000	.68	3.97	50,000	.71	4.27	46,000	.76	4.67	44,000	.78	4.87	42,000	.81	5.17
WH260	WM60N WEC,WUC60D	85/72	67,000	.65	4.73	64,000	.67	5.03	58,000	.70	5.53	55,000	.72	6.03	52,000	.75	6.53
		80/67	65,000	.68	4.70	60,000	.70	5.00	56,000	.73	5.50	53,000	.75	6.00	50,000	.78	6.50
		75/63	63,000	.71	4.67	60,000	.73	4.97	54,000	.76	5.47	51,000	.78	5.97	48,000	.81	6.47

Heating Performance - Extended Ratings

Outdoor Model	Indoor Model	Outdoor Temp. DB/WB °F														
		0/0			17/15			35/33			47/43			62/56		
		Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW
WH218	WM24N/WM25N WEC,WUC30A,B,C	7,300	1.60	1.37	11,000	2.30	1.40	14,900	3.00	1.46	17,500	3.50	1.47	20,800	4.10	1.49
WH224	WM24N/WM25N WEC,WUC30A,B,C	8,900	1.50	1.80	14,000	2.20	1.86	19,400	2.90	1.96	23,000	3.40	1.98	27,500	4.00	2.01
WH230	WM36N/WM37N WEC,WUC36A,B,C,D	10,400	1.60	2.14	17,500	2.20	2.33	25,000	2.90	2.53	30,000	3.30	2.66	36,300	3.90	2.73
WH236	WM42N WEC,WUC46B,C,D	14,500	1.60	2.79	23,000	2.30	2.93	32,000	3.00	3.13	37,000	3.50	3.18	45,500	4.10	3.25
WH242	WM42N WEC,WUC46B,C,D	14,900	1.60	2.89	24,000	2.30	3.06	33,600	3.00	3.28	40,000	3.50	3.35	48,000	4.10	3.43
WH248	WM60N WEC,WUC60D	19,200	1.90	3.18	30,000	2.50	3.52	41,400	3.10	3.91	49,000	3.50	4.10	58,500	4.00	4.29
WH260	WM60N WEC,WUC60D	22,700	1.80	3.94	34,000	2.40	4.15	46,000	3.10	4.35	54,000	3.50	4.52	64,000	4.10	4.57

Table D.3. Performance of WGH100 model of Whirlpool heat pump

Cooling Performance - Extended Ratings

Outdoor Model	Indoor Model	Indoor Temp DB/WB °F	Outdoor Temp - DB°F														
			65			82			95			105			115		
			Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW
WGH118	WEC, WUC24A,B,C	85/72	22,575	.57	1.40	20,650	.63	1.71	20,800	.64	1.91	19,250	.68	2.10	18,400	.71	2.27
		80/67	21,900	.66	1.42	19,900	.72	1.71	18,600	.72	1.90	17,445	.77	2.08	16,350	.80	2.25
		75/63	19,750	.70	1.38	18,125	.76	1.68	17,185	.76	1.86	16,150	.81	2.05	15,250	.84	2.22
	WM24N/WM25N	85/72	21,110	.57	1.30	19,715	.63	1.61	19,235	.65	1.92	17,435	.68	2.11	16,205	.71	2.27
		80/67	21,350	.66	1.32	19,000	.72	1.60	17,200	.74	1.91	15,800	.77	2.09	14,400	.80	2.25
		75/63	19,340	.70	1.28	17,305	.76	1.55	15,890	.77	1.87	14,625	.81	2.06	13,430	.84	2.22
WGH124	WEC, WUC24A,B,C	85/72	29,070	.59	1.82	26,600	.64	2.32	26,400	.67	2.58	24,500	.70	2.90	23,350	.72	3.17
		80/67	29,060	.65	1.83	26,500	.71	2.30	24,000	.74	2.54	22,640	.78	2.85	21,020	.81	3.10
		75/63	25,750	.70	1.80	23,790	.75	2.27	21,600	.79	2.50	20,625	.82	2.81	19,340	.85	3.06
	WM24N/WM25N	85/72	27,000	.59	1.61	24,590	.64	2.06	25,300	.67	2.44	23,480	.70	2.57	21,475	.72	2.81
		80/67	27,000	.65	1.62	24,500	.71	2.04	23,000	.74	2.40	21,700	.78	2.53	20,680	.81	2.75
		75/63	25,750	.70	1.59	21,995	.75	2.01	20,700	.79	2.36	19,770	.82	2.49	19,020	.85	2.71
WGH130	WEC, WUC30A,B,C	85/72	35,500	.58	2.43	32,450	.63	2.95	33,550	.66	3.38	30,845	.69	3.67	29,680	.72	3.98
		80/67	34,095	.64	2.36	31,250	.71	2.94	30,000	.73	3.26	28,050	.78	3.63	26,575	.81	3.95
		75/63	30,830	.67	2.37	28,200	.74	2.90	27,900	.78	3.18	25,900	.83	3.53	24,665	.87	3.81
	WM36/WM37N	85/72	35,220	.57	2.38	32,665	.62	2.85	30,700	.65	3.21	29,200	.67	3.48	27,700	.71	3.76
		80/67	33,825	.64	2.30	31,000	.70	2.87	28,000	.72	3.08	26,515	.77	3.43	24,800	.80	3.73
		75/63	30,585	.66	2.31	28,010	.74	2.75	26,040	.76	3.08	24,525	.82	3.34	23,015	.86	3.60
WGH136	WEC, WUC36A,B	85/72	41,425	.59	2.85	38,435	.64	3.50	39,120	.68	4.09	36,440	.70	4.44	34,625	.74	4.82
		80/67	38,950	.65	2.80	37,020	.72	3.49	35,000	.75	3.94	34,035	.78	4.37	32,910	.83	4.78
		75/63	36,250	.60	2.81	33,425	.75	3.44	32,560	.79	3.84	30,490	.84	4.24	28,805	.88	4.61
	WEC, WUC36C,D	85/72	42,679	.59	2.87	40,500	.61	3.54	41,580	.64	4.19	38,730	.66	4.55	36,800	.70	4.93
		80/67	42,510	.62	2.83	39,000	.69	3.53	37,200	.71	4.04	36,175	.74	4.48	35,000	.78	4.89
		75/63	39,560	.65	2.80	35,200	.72	3.48	34,600	.75	3.94	32,400	.80	4.35	30,600	.83	4.72
WM36N/WM37N	85/72	41,425	.59	2.85	38,435	.64	3.50	39,120	.68	4.09	36,440	.70	4.44	34,625	.74	4.82	
	80/67	38,950	.65	2.80	37,020	.72	3.49	35,000	.75	3.94	34,035	.78	4.37	32,910	.83	4.78	
	75/63	36,250	.60	2.81	33,425	.75	3.44	32,560	.79	3.84	30,490	.84	4.24	28,805	.88	4.61	
WGH142	WEC, WUC46B,C,D	85/72	51,870	.58	3.51	48,325	.66	4.35	45,610	.72	5.00	43,525	.70	5.49	41,440	.72	5.99
		80/67	50,625	.64	3.48	46,550	.74	4.34	44,500	.76	4.90	41,800	.78	5.43	39,390	.81	5.94
		75/63	45,925	.67	3.47	42,035	.76	4.24	39,060	.78	4.83	36,775	.82	5.28	34,485	.86	5.73
	WM42N	85/72	49,895	.57	3.38	46,350	.65	4.17	43,635	.71	4.78	41,550	.70	5.24	39,465	.71	5.70
		80/67	48,650	.63	3.34	44,575	.73	4.16	42,500	.75	4.68	39,825	.77	5.17	37,415	.80	5.64
		75/63	43,950	.66	3.32	40,060	.75	4.39	37,085	.77	4.58	34,800	.80	5.00	32,510	.85	5.40
WEC, WUC36C,D	85/72	49,560	.52	3.40	46,150	.59	4.22	42,600	.65	4.75	41,100	.66	5.21	38,275	.68	5.67	
	80/67	48,375	.57	3.36	44,500	.66	4.20	41,500	.69	4.66	39,500	.73	5.15	36,400	.76	5.62	
	75/63	43,890	.59	3.35	40,180	.68	4.10	36,500	.71	4.58	34,760	.77	5.00	31,875	.81	5.42	
WGH148	WEC, WUC58C,D	85/72	50,900	.60	3.70	50,215	.65	4.38	51,050	.68	4.84	48,235	.71	5.36	46,200	.74	5.85
		80/67	49,650	.67	3.66	49,400	.73	4.27	47,000	.77	4.83	43,030	.81	5.25	40,975	.85	5.67
		75/63	47,975	.72	3.62	45,075	.77	4.22	43,850	.80	4.67	40,375	.84	5.05	37,475	.87	5.43
	WM48N	85/72	50,900	.60	3.70	50,215	.65	4.38	51,050	.68	4.84	48,235	.71	5.36	46,200	.74	5.85
		80/67	49,650	.67	3.66	49,400	.73	4.27	47,000	.77	4.83	43,030	.81	5.25	40,975	.85	5.67
		75/63	47,975	.72	3.62	45,075	.77	4.22	43,850	.80	4.67	40,375	.84	5.05	37,475	.85	5.67
WGH160	WEC, WUC58D	85/72	67,940	.59	4.20	60,950	.65	5.06	60,750	.70	5.76	55,275	.73	6.25	52,100	.73	6.76
		80/67	66,375	.65	4.15	58,500	.73	4.98	56,500	.77	5.58	50,800	.82	6.07	46,900	.86	6.55
		75/63	61,900	.67	4.12	54,600	.77	4.90	51,700	.81	5.49	46,700	.88	5.95	42,900	.93	6.41
	WM60N	85/72	67,940	.59	4.20	60,950	.65	5.06	60,750	.70	5.76	55,275	.73	6.25	52,100	.73	6.76
		80/67	66,375	.65	4.15	58,500	.73	4.98	56,500	.77	5.58	50,800	.82	6.07	46,900	.86	6.55
		75/63	61,900	.67	4.12	54,600	.77	4.90	51,700	.81	5.49	46,700	.88	5.95	42,900	.93	6.41

Heating Performance - Extended Ratings

Outdoor Model	Indoor Model	Outdoor Temp. DB/WB°F														
		0/0			17/15			35/33			47/43			62/56		
		Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW
WGH118	WEC, WU24A,B,C	7,160	1.59	1.32	11,600	2.25	1.52	13,300	2.34	1.67	18,600	3.25	1.68	20,950	3.52	1.74
	WM24N/WM25N	7,115	1.70	1.23	10,800	2.15	1.47	14,700	2.63	1.62	17,300	2.95	1.72	20,550	3.35	1.80
WGH124	WEC, WUC24A,B,C	9,705	1.63	1.74	15,775	2.30	1.99	18,650	2.54	2.15	25,500	3.35	2.25	29,000	3.70	2.30
	WM24N/WM25N	8,700	1.53	1.67	14,775	2.20	1.85	20,040	2.44	2.05	24,300	3.15	2.26	28,000	3.50	2.34
WGH130	WEC, WUC30A,B	12,590	1.76	2.10	20,600	2.30	2.62	22,830	2.32	2.89	33,000	3.10	3.05	36,800	3.29	3.27
	WM36N/WM37N	14,410	1.88	2.25	21,600	2.25	2.81	22,400	2.64	2.49	32,400	2.90	3.27	35,185	3.23	3.19
WGH136	WEC, WUC36A,B	14,860	1.59	2.74	23,275	2.20	3.12	26,325	2.34	3.30	36,500	3.10	3.47	40,860	3.38	3.54
	WEC, WUC36C,D	15,450	1.58	2.83	24,200	2.20	3.22	26,600	2.41	3.24	37,600	3.15	3.49	42,100	3.43	3.56
WGH142	WM36N/WM37N	14,860	1.59	2.74	23,275	2.20	3.12	26,325	2.34	3.30	36,500	3.10	3.47	40,860	3.38	3.54
	WEC, WUC36B,C,D	20,500	1.83	3.28	32,000	2.40	3.91	34,000	2.62	3.81	46,000	3.10	4.35	50,300	3.28	4.49
WGH148	WEC, WUC46B	20,180	1.91	3.10	31,500	2.50	3.67	34,000	2.62	3.81	46,000	3.25	4.15	50,300	3.44	4.29
	WEC, WUC46C,D	20,180	1.91	3.10	31,500	2.50	3.67	34,000	2.62	3.81	46,000	3.30	4.09	50,300	3.49	4.22
WGH160	WM42N	20,715	1.75	3.47	29,500	2.20	3.93	38,800	2.68	4.21	45,000	3.00	4.39	52,750	3.40	4.55
	WM48N	21,000	2.05	3.00	33,375	2.65	3.69	34,000	2.47	4.03	50,000	3.60	4.07	54,000	4.10	3.86
WGH148	WEC, WUC58C,D	20,500	2.03	2.96	32,000	2.60	3.61	32,600	2.42	3.95	49,000	3.50	4.10	53,000	4.10	3.79
	WM60N	24,850	1.62	4.49	38,600	2.35	4.81	41,050	2.60	4.63	59,500	3.50	4.98	65,300	3.87	4.94
WGH160	WEC, WUC58D	23,260	1.70	4.01	39,000	2.40	4.76	44,200	2.52	5.15	60,500	3.20	5.54	68,015	3.47	5.75

Table D.4.Performance of WGH200 model of Whirlpool heat pump

Cooling Performance - Extended Ratings

Outdoor Model	Indoor Model	Indoor Temp DB/WB °F	Outdoor Temp - DB°F														
			65			82			95			105			115		
			Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW	Btuh	S/T	kW
WGH218	WEC,WUC30A,B,C	85/72	22,625	.58	1.23	21,255	.66	1.52	19,790	.68	1.63	18,370	.74	1.73	16,865	.74	1.99
		80/67	21,815	.65	1.23	19,620	.72	1.50	18,000	.77	1.62	16,690	.81	1.80	15,410	.85	1.95
		75/63	21,295	.69	1.22	18,110	.80	1.51	16,750	.81	1.61	15,545	.83	1.80	14,070	.88	1.94
	WM24N/WM25N	85/72	21,500	.64	1.26	20,394	.65	1.48	17,320	.67	1.57	17,360	.67	1.72	16,745	.68	1.85
		80/67	20,465	.66	1.23	18,825	.71	1.46	17,200	.76	1.56	16,335	.78	1.71	15,300	.78	1.83
		75/63	19,125	.78	1.22	17,375	.79	1.47	16,005	.80	1.55	14,995	.80	1.69	13,970	.81	1.81
WGH224	WEC,WUC30A,B,C	85/72	25,605	.60	1.63	27,315	.67	1.90	26,390	.67	2.13	24,435	.72	2.26	23,310	.71	2.55
		80/67	24,690	.67	1.63	25,215	.73	1.88	24,000	.76	2.11	22,200	.79	2.35	21,300	.82	2.53
		75/63	24,100	.71	1.56	23,275	.81	1.83	22,335	.80	2.03	20,680	.81	2.29	19,450	.85	2.42
	WM24N/WM25N	85/72	26,840	.66	1.58	25,595	.68	1.90	26,390	.67	2.13	24,435	.72	2.26	23,310	.71	2.55
		80/67	25,750	.69	1.56	23,625	.74	1.87	22,500	.76	2.17	21,120	.79	2.34	19,960	.81	2.53
		75/63	23,910	.70	1.59	21,810	.82	1.88	20,935	.80	2.16	19,475	.83	2.31	18,225	.84	2.48
WGH230	WEC,WUC36A,B,C,D	85/72	36,400	.64	2.18	33,800	.66	2.49	31,700	.64	2.75	30,600	.68	3.01	29,000	.70	3.27
		80/67	33,400	.71	2.15	31,200	.72	2.46	30,000	.72	2.70	27,800	.75	2.97	26,500	.81	3.24
		75/63	33,900	.73	2.15	28,800	.80	2.47	26,700	.77	2.70	25,900	.77	2.97	24,600	.79	3.23
	WM36N/WM37N	85/72	35,190	.65	2.12	32,680	.70	2.46	30,645	.65	2.69	29,375	.69	2.96	28,035	.71	3.21
		80/67	32,285	.72	2.09	30,240	.75	2.43	29,000	.73	2.64	27,215	.78	2.92	25,615	.82	3.18
		75/63	29,870	.74	2.09	27,675	.71	2.43	25,810	.78	2.64	24,850	.78	2.92	23,780	.80	3.17
WGH236	WEC,WUC58C,D	85/72	45,950	.62	2.73	43,000	.63	3.05	40,290	.64	3.37	38,200	.64	3.71	36,350	.67	4.05
		80/67	42,275	.68	2.70	39,500	.69	3.02	36,000	.75	3.19	35,200	.71	3.66	33,500	.73	4.00
		75/63	39,400	.70	2.67	36,800	.71	3.00	34,650	.72	3.28	32,800	.73	3.62	31,250	.74	3.96
	WM42N	85/72	43,934	.65	2.85	42,444	.65	3.23	41,040	.69	3.52	37,941	.75	3.82	34,894	.73	4.36
		80/67	40,793	.67	2.77	39,300	.69	3.08	38,000	.72	3.44	34,808	.74	3.75	31,540	.76	4.27
		75/63	37,652	.69	2.69	36,156	.71	3.00	34,846	.74	3.36	31,640	.72	3.67	28,386	.78	4.19
WGH242	WEC,WUC58C,D	85/72	50,600	.65	2.94	47,400	.66	3.29	44,300	.67	3.61	42,200	.69	3.97	40,200	.70	4.32
		80/67	46,500	.71	2.91	43,500	.73	3.27	40,500	.77	3.52	39,000	.75	3.90	37,200	.76	4.24
		75/63	43,300	.73	2.89	40,600	.74	3.24	38,000	.75	3.52	36,400	.77	3.86	34,000	.84	4.20
	WM48N	85/72	49,850	.66	2.62	46,475	.68	3.22	44,300	.68	3.64	42,190	.70	4.01	40,200	.71	4.36
		80/67	45,450	.75	2.62	42,650	.75	3.20	40,500	.78	3.55	38,850	.77	3.92	37,200	.77	4.27
		75/63	41,460	.70	2.60	39,810	.76	3.17	38,000	.76	3.55	37,200	.81	3.90	36,235	.85	4.24
WGH248	WEC,WUC58C,D	85/72	59,825	.64	3.32	55,835	.64	4.05	53,600	.65	4.52	51,000	.64	4.98	48,640	.64	5.41
		80/67	54,550	.70	3.31	51,240	.71	4.03	49,000	.75	4.41	46,960	.74	4.88	45,005	.74	5.31
		75/63	51,640	.72	3.30	47,825	.72	3.99	45,975	.73	4.41	43,400	.76	4.85	41,135	.82	5.26
	WM48N	85/72	60,340	.69	3.42	56,105	.68	4.17	52,500	.66	4.65	50,125	.66	5.12	47,640	.65	5.56
		80/67	55,030	.75	3.40	51,490	.75	4.14	48,000	.76	4.53	46,160	.73	5.02	44,090	.75	5.46
		75/63	52,075	.70	3.38	48,060	.76	4.10	45,035	.74	4.53	42,660	.79	4.99	40,295	.83	5.41
WGH260	WEC,WUC60D	85/72	67,000	.65	3.83	63,100	.67	4.63	59,450	.68	5.22	56,700	.68	5.69	48,700	.77	6.15
		80/67	61,700	.71	3.75	58,200	.73	4.56	56,000	.76	5.28	52,300	.75	5.64	49,700	.77	6.11
		75/63	57,400	.73	3.69	54,200	.74	4.50	51,100	.75	5.12	48,685	.77	5.60	46,300	.78	6.07
	WM60N	85/72	67,500	.65	4.13	63,400	.67	4.85	58,390	.67	5.18	52,886	.64	4.98	47,830	.76	6.10
		80/67	63,000	.71	4.10	58,475	.73	4.78	55,000	.75	5.24	51,840	.74	4.88	48,815	.76	6.06
		75/63	58,730	.73	3.98	54,450	.74	4.72	50,188	.74	5.08	47,975	.76	4.85	45,475	.77	6.02

Heating Performance - Extended Ratings

Outdoor Model	Indoor Model	Outdoor Temp. DB/WB°F														
		0/0			17/15			35/33			47/43			62/56		
		Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW	Btuh	COP	kW
WGH218	WM24N/WM25N	7,040	1.37	1.50	11,200	2.10	1.56	13,650	2.55	1.56	18,000	3.30	1.60	20,650	3.78	1.60
	WEC,WUC30A,B,C	4,640	1.30	1.05	9,700	2.00	1.42	12,800	2.50	1.50	18,000	3.40	1.55	21,280	3.85	1.62
WGH224	WM24N/WM25N	9,445	1.68	1.65	15,100	2.30	1.91	17,200	2.45	2.05	24,000	3.25	2.17	26,950	3.55	2.22
	WEC,WUC30C	8,910	1.54	1.70	14,400	2.30	1.83	16,300	2.57	1.86	23,000	3.50	1.93	25,800	3.80	1.99
WGH230	WM36N/WM37N	13,485	1.61	2.45	19,500	2.20	2.60	21,850	2.33	2.75	29,000	3.10	2.74	32,210	3.36	2.81
	WEC,WUC36A,B,C,D	13,800	1.74	2.32	20,000	2.40	2.47	26,000	2.90	2.63	31,000	3.30	2.73	35,000	3.58	2.86
WGH236	WM42N	13,850	1.50	2.71	24,000	2.10	3.23	24,940	2.14	3.41	37,500	3.00	3.61	41,000	3.22	3.74
	WEC,WUC58C,D	16,000	1.64	2.86	26,000	2.40	3.08	32,600	2.88	3.31	37,000	3.20	3.47	42,500	3.40	3.66
WGH242	WM48N	14,140	1.46	2.84	25,000	2.20	3.33	26,900	2.25	3.50	41,500	3.30	3.68	46,065	3.57	3.78
	WEC,WUC58C,D	17,200	1.64	3.08	26,000	2.30	3.28	35,300	2.97	3.48	41,500	3.30	3.62	49,200	3.80	3.79
WGH248	WM48N	18,830	1.66	3.32	31,000	2.30	3.95	34,950	2.50	4.11	50,000	3.30	4.44	56,070	3.62	4.54
	WEC,WUC58C,D	19,030	1.69	3.30	32,000	2.40	3.91	35,325	2.61	3.96	52,000	3.50	4.35	58,000	3.84	4.43
WGH260	WM60N	23,400	1.67	4.11	37,140	2.35	4.64	39,510	2.39	4.84	58,000	3.25	5.23	63,750	3.50	5.34
	WEC,WUC60D	23,400	1.48	4.62	35,000	2.15	4.77	43,500	2.58	4.93	56,000	3.25	5.04	66,000	3.74	5.17

VITA

Halil Osmanoglu was born in Istanbul in 1982. After completion of his high school study at Pertevniyal High School in 2000, he started intensive English program in Language School of Marmara University for one year. Then, he started mechanical engineering studies at Engineering Faculty of Marmara University in 2001. After graduated from mechanical engineering department in 2005, he was approved of Master of Science degree for mechanical engineering at Marmara University.