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Investigation Of Working Temperature Effect On Micro-Cogeneration Application Of Proton Exchange Membrane Fuel Cells

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ABSTRACT

In this study, micro-cogeneration application is used to increase the efficiency of Proton Exchange Membrane Fuel Cell (PEMFC) systems and effect of different operation temperatures on system performance is observed. For this reason, two different PEMFC systems were comparatively studied operating at 70°C and 160°C, respectively. Micro-cogeneration system design has done considering experimentally determined current density, power and temperature values. Since the amount of heat extracted from each PEMFC system is different related to the operating temperatures, different heat transfer fluids have been used for the cooling systems. These systems are designed for utilization of electricity and hot water for Atılım University Hydrogen Energy Laboratory. Heat loss calculation is made for the laboratory and thermal energy needed for heating the laboratory is calculated. Parallel to the design calculations, simple payback times for PEMFCs with micro-cogeneration applications were determined. LT-PEMFC and HT-PEMFC systems have 402 W and 456 W thermal powers respectively and 87.4 % and 92.8 % total cogeneration efficiencies were calculated for each system respectively. For each system maximum water temperatures and flow rates are calculated as a result of micro-cogeneration application. HT-PEMFC system has found to be capable of higher amount of heating. Even LT-PEMFC system has a lower thermal power and efficiency; it is determined to be more economical and has a lower pay pack time then HT-PEMFC system. For both systems, necessary number of stacks to be used for laboratory heating is calculated as four.

Keywords: Proton Exchange Membrane Fuel Cell, Micro-cogeneration, Hydrogen energy

INTRODUCTION

With the increasing population and developing technology, energy demand is increasing more and more. Nowadays, most of the energy required is provided from primary resources which are called as fossil fuels like petroleum and natural gas and as a result of the use of these limited and declining resources, environmental pollution and global warming occurs. In this extent, use of clean, environmentally friendly, low price, natural renewable energy resources are spreading. Hydrogen, which is a clean energy carrier, is one of the most important renewable energy resources. Fuel cell systems are electrochemical systems which use hydrogen energy to produce electrical energy. Fuel cell technology is reliable and is capable of achieving higher efficiencies, with lower emissions among the renewable energy technologies. Among all fuel cells, proton exchange membrane type fuel cells (PEMFC) gain the highest interest because of their high performances, high power densities, modular structures, small size and low operating temperatures [1]. Besides mobile and stationary applications of PEMFC's in industry and defense sector, recently household or mobile co-generation applications have become a current issue. PEMFC's are classified into two categories; operation temperatures between 60- 80 °C are called low temperature PEMFC's (LT-PEMFC) and operation temperatures above 100°C are called high temperature PEMFC's (HT-PEMFC) [2]. HT-PEMFCs have high CO tolerances, easy heat removal and have developed electrode kinetics and they do not need to be humidified [3]. LT-PEMFCs have low operation temperatures, high gas impermeability and they are more economical [4].

Heat released during electricity production in PEMFC's should be removed with the help of cooling

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fluid or air cooling systems for high performance and a stable operation [5]. For especially HT-PEMFCs, where air cooling is less effective, liquid cooling fluid is pumped among the cell via cooling channels to remove the excess heat [6]. The utilization of removed heat simultaneously with the electrical energy of the PEMFC system enables to recover the heat otherwise should be wasted and increase the total efficiency of the system as to about 85-90%. This way the system utilizes energy more economically and effectively. Such applications are named as micro-cogeneration applications [2]. To supply the necessary thermal load (heating requirement) of a building or a space, first the heat loss and the corresponding heat demand should be calculated. During calculations, wall structural components, window and door properties and all relevant dimensions have great importance.

One of the most important issues for operation of fuel cells is the feasibility of the fuel cell system. Simple payback time calculation is a simple but effective methodology for determination of feasibility of a fuel cell system. This method simply shows how fast the investment pays its initial cost back and is a means for comparing different systems but inflation, or changes in electricity and natural gas prices are not considered [2].

MATERIAL AND METHODS

In this study, comparison of micro-cogeneration applications of a LT-PEMFC system with 480 W of electrical power and a HT-PEMFC system with 480 W electrical power has been done operating on 0.6 V cell voltage. Different types of membranes are used for the different systems. The excess heat produced by the fuel cells is used for heating Hydrogen Energy Laboratory in Atılım University. For that, heat loss calculations have been done for determination of the necessary heat load of the laboratory.

To see the economic advantage of micro-cogeneration system, simple pay back times (SPT) for LT-PEMFC and HT-PEMFC systems were calculated before and after cogeneration applications.

Schematically representations of LT-PEMFC and HT-PEMFC systems are shown in Fig. 1. In Figure 1.a flow diagram of the LT-PEMFC system can be seen where air first passes through the filter then with the help of the compressor air is flown into the humidifier.

Fig. 1.b shows HT-PEMFC system. In this system, air firstly passes through the filter, then through the compressor and then to the pre heater. In both systems, hydrogen is fed to the PEMFC via hydrogen tanks. In HT-PEMFC system, hydrogen is heated in the pre-heater before being fed to the system. Properties of the PEMFC systems can be seen in Table 1.

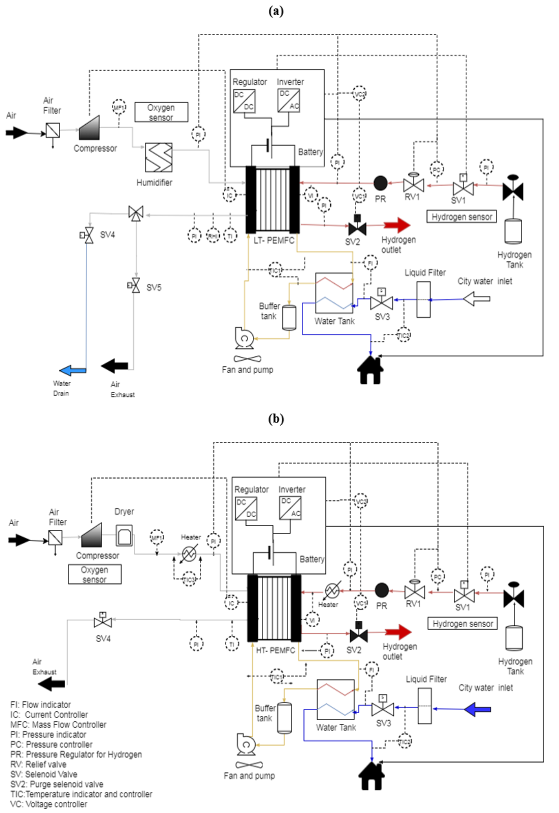

Figure 1. a) LT-PEMFC and b) HT-PEMFC micro-cogeneration applications flow diagrams

Excess heat of the fuel cell system is removed by using heat transfer oil 32 (Petrol Ofisi) and water in the water tanks are heated by the heat transfer oil. This heat is used for space heating purposes and the cooled heat transfer oil passes through circulation tank equipped with a fan and pumped back to the cell. All flows are controlled by valves and control equipment.

Table 1. LT-PEMFC and HT-PEMFC stack properties

PEMFC type	*Parameters*	*Value*
	Current Density (0.6 V/cell)	*0.9 A/cm²*
	Membrane	*Nafion 212*
LT-PEMFC	*Active Area*	*150 cm²*
	Cell number	*6*
	Max. Power @0.6 V/cell	*480 W*
	Current Density (0.6 V/cell)	*0.41 A/cm²*
	Membrane	*Polybenzimidazole (PBI)/H_3PO_4*
HT-PEMFC	*Active Area*	*150 cm²*
	Cell number	*13*
	Max. Power @0.6 V/cell	*480 W*

THEORY AND CALCULATIONS

Assumptions used in the calculations are:

- PEMFC micro-cogeneration systems operate in steady state conditions.
- The ideal gas principles are applied to gases.
- One-dimensional flow is assumed.
- The kinetic and potential energy changes are negligible.
- LT-PEMFC stack consist of Nafion® 212 membrane, HT-PEMFC stack consist of PBI membrane
- Working temperature of the LT-PEMFC stack is 70°C at 100% humidity and working temperature of the HT-PEMFC stack is 160°C with dry gas feed.

PEMFC Stack Calculations

H_2 flows into the PEMFC at the anode gas inlet. The H_2 concentration N_{H2} at the inlet depends on the current density I (A/cm^2), stoichiometric ratio H_2, S_{H2}, cell active area A (cm^2) and number of cells N_{cell}. The H_2 concentration at the anode gas inlet of the PEMFC is calculated by Eq. 1. F is the Faraday constant.

$$N_{H_2} = S_{H_2}.\frac{I.A}{2.F}.N_{cell} \tag{1}$$

Air is fed to PEMFC at the anode gas inlet. Oxygen concentration in air is 21 %. NO_2 is concentration of oxygen and N_{air} is concentration of air. The concentration of O_2 depends on the current density I, cell active area A, number of cells N_{cell} and stoichiometry of O_2. The concentration of O_2 and air are calculated as follows:

$$N_{O_2} = S_{O_2}.\frac{I.A}{4.F}.N_{cell} \tag{2}$$

$$N_{air} = \frac{S_{O_2}}{r_{o_2}}.\frac{i.A}{4.F}.N_{cell} \tag{3}$$

The energy balance for a PEMFC stack system is expressed with the following equation:

$$\sum \dot{E}_{mass,in} - \sum \dot{E}_{mass,out} + \dot{Q} - \dot{W}_{net} = 0 \tag{4}$$

In Equation 4, $\Sigma\dot{E}_{mass,in}$ is the total enthalpy of the inlet gasses and $\Sigma\dot{E}_{mass,out}$ is the total enthalpy of the outlet gasses. For the low temperature cell, air is humidified at the inlet; and there is also water vapor among the inlet gases. $\dot{Q}$ refers to the heat dissipation from the PEMFC stack to the ambient, $\dot{W}_{net}$ denotes the net power of the cell stack.

PEMFC Heat Loss Calculations

Maximum heat loss from the cell stack by natural convection and radiation is calculated by Eq. 5.

$$\dot{Q}_{loss} = \frac{T_s - T_o}{R_{th}} \tag{5}$$

In Eq. 5, Q_{loss} denotes the heat loss, T_s is the stack surface temperature, T_o is the ambient temperature (room temperature) and R_{th} is the thermal resistance. Heat losses from the low temperature cells can be neglected but for the high temperature cells, heat loss is too high to be neglected. To prevent this much heat loss from the cell surface, HT-PEMFC stack is insulated by means of an insulation material. The optimum thickness of the insulation material which was chosen to be glass wool is calculated by the following equation.

$$\Delta x = \frac{k.\Delta T.A}{Q_{loss}} \tag{6}$$

Here, k is the thermal conductivity, ΔT is the difference between T_s and T_o and A is the heat transfer area of the HT-PEMFC stack.

Micro- Cogeneration System Calculations

PEMFC System efficiency given in Eq. 9 is the sum of electrical efficiency of the stack (Eq. 7) and thermal efficiency of the stack (Eq. 8)

$$\eta_{el} = \frac{P_{exit}}{\dot{n}_{H2} \times LHV} \tag{7}$$

$$\eta_{th} = \frac{P_{cooler}}{P_{H2}} = \frac{\dot{m}_{ss}.c_{p,cl}.\Delta T_{cl}}{P_{H2}} \tag{8}$$

$$\eta_{cogeneration} = \eta_{el} + \eta_{th} \tag{9}$$

In this equation; $\dot{n}_{H2}$ is the hydrogen molar flow rate and LHV is the lower heating value of hydrogen gas (241.83 kJ/mol).

Energy balance in the water tank can be calculated by Eq. 10.

$$\dot{m}_{cl} c_{p,cl} \Delta T_{cl} \Delta\eta = \dot{m}_w c_{p,w} \Delta T_w \tag{10}$$

In this equation, $\dot{m}_{cl}$ and $\dot{m}_w$ are mass flow rates of cooling liquid and heating water respectively. $c_{p,cl}$ and $c_{p,w}$ are constant specific heat values of cooling liquid and heating water respectively. ΔT_{cl} and ΔT_w are cooling liquid inlet and exit temperature difference and heating water inlet and exit temperature difference respectively. η denotes the PEMFC system heat exchange effectiveness and in this study, it is estimated that about 10% of the heat is lost to the surrounding.

Simple Payback Time Calculations

For application of cogeneration, PEMFC system is estimated to be operating 10 hours per day for 6 months. Electrical production is calculated based on this estimation. Annual electrical production (AEP) is calculated in Eq.11.

$$AEP = 8760 \text{ x } CF \text{ x } P_{fc} \quad (11)$$

In Eq.11, CF is the capacity factor which is the ratio of produced power in a specified time to maximum possible power production of the system operating on its rated power during same period and P_{fc} is the PEMFC system nominal power. PEMFC systems are estimated to operate at their rated (maximum) power during the studied time.

Payback time of the PEMFCs is calculated by Equation 12 seen below.

$$SPT = \frac{P_{fc}.C_{fc}}{AEP.\left[C_{el} - \frac{C_h}{\overline{\eta_{fc}}}\right]} \quad (12)$$

In this equation; C_{fc} is fuel cell price, C_{el} (TL/kWh) is the cost of produced electricity. C_{ng} is natural gas price in TL/kWh, $\overline{\eta_{fc}}$ is average annual efficiency of the cell stack system. Since the produced power is constant for PEMFC system, average annual efficiency is equal to the system efficiency. The cost of the PEMFC is determined upon an amount of 1000 production annually which decreases the unit price [4].

Ratio between the heat actually utilized in cogeneration and the heat produced by a PEMFC system is called heat utilization factor and is very important for SPT calculations of PEMFC. It can be seen in Eq. 13.

$$\frac{Q_{cogeneration}}{Q_{heat\ production}} \quad (13)$$

Simple payback time of the micro-cogeneration application of PEMFCs is calculated by Eq. 14;

$$SPT_{chp} = \frac{C_{fc}.P_{fc}}{AEP.\left[C_{el} - \frac{C_{fuel}}{\eta_{el}} + \left(\frac{\eta_{tot}}{\eta_{el}} - 1\right).f_{hu}.\frac{C_{fuel}}{\eta_{heat}}\right]} \quad (14)$$

where , η_{tot} is the total PEMFC efficiency, f_{hu} is the heat utilization factor and η_{heat} is the natural gas combustion efficiency.

Calculation of Heat Loss and Necessary Thermal Load For the Laboratory

Thermal energy needed for heating the laboratory where micro-cogeneration is applied is calculated using computer software called; NZN. There are 4 different temperature zones in Turkey regarding the average seasonal temperatures and Ankara is in the 3rd temperature zone.

Constructional components of the Hydrogen Energy Laboratory located at the -1st floor of Atılım University in İncek, Ankara can be seen in Table 2. Each component has different value of thermal conductivity. In Figure 2, Laboratory schematically representation can be seen with the required dimensions.

Table 2. Constructional components of walls

External wall	*Internal wall*
Ferroconcrete	*Reinforced concrete wall*
Pumice Concrete	*Rough cast*
Rough cast	*Gypsum plaster*
Condensed XPS	
Carbon based foam material	*Exterior Paint*
Stucco	
Exterior Paint	

Thermal load calculations have been done considering the temperature differences between the laboratory and the adjacent rooms, corridors or outside. Also regarding the directions, external and internal wall areas, doors and windows play an important role on calculation of heat loss through a room. Besides that, thickness of constructional components of walls has a great impact on the thermal resistance thus the heat loss as well.

All important properties of constructional components are given in Table 3. For the calculations of areas of the wall, doors and windows are excluded for a more precise solution of thermal energy needed for heating the laboratory.

RESULTS AND DISCUSSION

PEMFC Results

Firstly, for performance characteristics LT-PEMFC and HT-PEMFC systems were studied and relevant results were given in Fig. 3a and 3b respectively. For both systems, design power value of 480 W at 0.6 V cell voltage have successfully obtained.

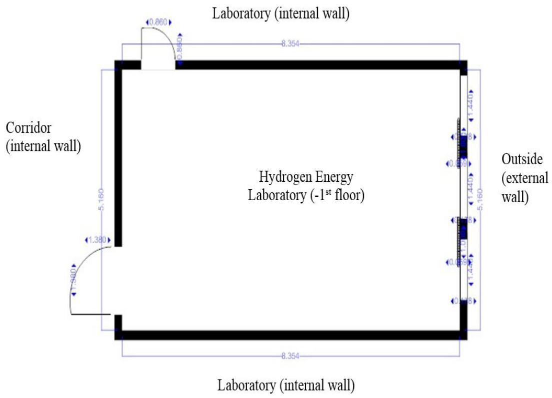

Figure 2. Hydrogen Energy Laboratory schematically representation with dimensions in meters

Table 3. Properties of Constructional Components

Constructional Component	Direction[1]	Thickness (m)	Length (m)	Width (m)	Number	Neighbor ambient temperature (°C)	Excluded area[2]	Area to exclude (m^2)
External window (S_w)	NW	0.010	1.44	1.43	3	-12		
External Wall (E_w)	NW	0.300	2.85	5.16	1	-12	S_w	2.89
Inner door (I_d1)	W	0.042	2.12	0.86	1	18		
Inner door (I_d2)	S	0.042	2.31	1.38	1	18		
Internal Wall (I_w1)	W	0.170	2.85	8.36	1	18	I_k1	2.2
Internal Wall (I_w2)	S	0.210	2.85	5.16	1	18	I_k2	3.19
nternal Wall (I_w3)	E	0.210	2.85	8.36	1	18		
Roof	SE	0.500	5.16	8.36	1	18		
Floor	NW	0.500	5.16	8.36	1	18		

The higher current densities and power values can be achieved by using lower cell voltages. However, when working with the HT-PEMFC system in low voltage regions, the water generated on the cathode side causes the acid leaching in the membrane and performance loss in long term operation.

In addition to this, although the membrane used in the LT-PEMFC system is different, the water formed on the cathode side of the cells is returned to the membrane and can cause the electrodes and the membrane to be drowned by water due to excessive moisture. When all of these is taken into consideration, it has been chosen as a 0.6 V operating voltage per cell in order to provide long term performance.

Design parameters and experimental results of low temperature and high temperature PEMFC systems can be seen in Table 4. Because of the property of the membrane used for low temperature PEMFC, air with 100% humidity is fed to the system. For high temperature PEMFC on the other hand, to prevent acid loss in the PBI membrane, and also because of the nature of high temperature, dried gases are fed to the system. Thermal power outputs for LT-PEMFC and HT-PEMFC systems are found to be 402 W and 456 W respectively.

Table 4. LT-PEMFC and HT-PEMFC design parameters

PEMFC Type	H_2 flow rate (slpm)[1]	Air flow rate V(slpm)	Gas humidifying ratio (%)	Thermal output (W)
LT-PEMFC	5.1	30.3	100	402
HT-PEMFC	6.7	30.3	0	456

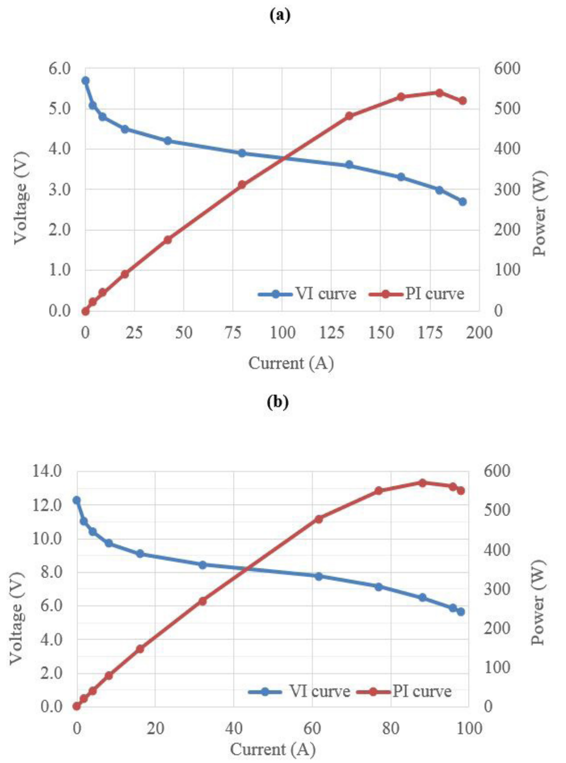

Figure 3. a) LT-PEMFC and b) HT-PEMFC systems performance curves

Micro-Cogeneration Application Results

For micro-cogeneration application of PEMFCs, as heat transfer fluid deionized water is used in LT-PEMFC system and heat transfer oil is used for cooling HT-PEMFC system.

In Table 5, physical properties, temperature differences and mass flow rates of cooling fluid and water can be seen for both systems. Because of high operation temperature

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Table 5. Micro-cogeneration Application Results of PEMFC's

PEMFC Type	$C_{p,ss}$ (Kj/kg.°C)	ΔT^1 (°C)	$\dot{m}_{ss}$ (kg/s)	η el	η_{th}	η_{cogen}	ΔTw^{2} (°C)	$\dot{m}_W$ (kg/s)
LT-PEMFC	4.187	6	0.016	47.8	40	87.4	40	0.0022
HT-PEMFC	2.400	10	0.019	47.8	45	92.8	40	0.0025

[1] PEMFC cooling liquid inlet and exit temperature difference

[2] Heating water inlet and exit temperature difference for winter month average

Table 6. Thermal energy needed for heating the laboratory

Constructional Component		Heat Dissipation Calculation				Total heat requirement
Constructional Component	Width (cm)	Heat Dissipation[1] q_o (W)	Calculated area A (m²)	Total heat transfer coefficient U (W/m²K)	Temperature difference DT (°C)	q_h (W)
Location	B01	-	-	-1	-	Room Temperature: 22°C-
Sw	-	441	6.18	2.100	34	
Ew	-	216	1.82	0.538	34	
Id1	-	15	1.82	2.000	4	
Id2	-	26	3.19	2.000	4	
Iw1	0.2	153	21.63	1.770	4	
Iw2	0.2	82	11.52	1.770	4	
Iw3	0.2	240	23.83	2.513	4	
Roof	0.5	22	43.14	0.128	4	
Floor	0.5	67	43.14	0.390	4	
TOTAL		1262	66.27			1578[2]

[1] Calculation of the amount of heat requirement of the laboratory not including direction, location, etc. [2] Calculation of the amount of heat requirement of the laboratory including direction, location, etc.

of HT-PEMFC, to prevent heat loss, stack was insulated by glass wool of 1 cm thickness.

In Fig. 4, maximum water temperature-flowrate graphics of both PEMFC systems can be seen. In both systems, water is heated by means of a radiator (heat exchanger).

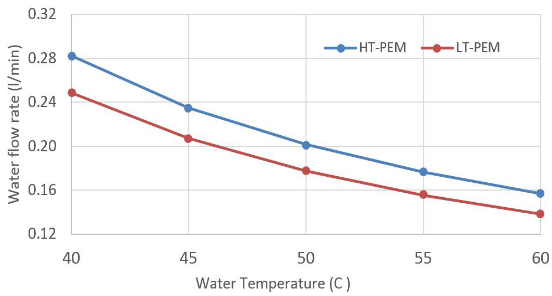

Figure 4. LT-PEMFC and HT-PEMFC cogeneration systems, water flowrate-water temperature graph

When examined, it can be concluded that for same temperature difference, HT-PEMFC system is capable of heating a higher amount of water per unit time.

Determination of Heating Load of the Laboratory

After all values are inputted to NZN software program, thermal energy needed for heating the laboratory is calculated and details can be seen in Table 6 below.

For heating the laboratory, necessary number of PEM fuel cells for HT-PEMFC system is calculates as 4 and total thermal power is determined as 1820 W. For LT-PEMFC cogeneration application, again a total of 4 cells are to be used but total thermal power is determined to be 1608 W. During the year, operational capacity of the systems can be arranged by changing the flow rate for cold months. In Table 7, maximum water temperature values for different flow rates are given for both systems.

Table 7. Flow rates required for water heating for both systems

LT-PEMFC			*HT-PEMFC*		
Water temperature (°C)	*Water flow rate (kg/s)*	*Water flow rate (l/m)*	*Water temperature (°C)*	*Water flow rate (kg/s)*	*Water flow rate (l/m)*
40	0.035	0.25	40	0.0039	0.28
45	0.0029	0.21	45	0.0033	0.24
50	0.0025	0.18	50	0.0028	0.20
55	0.0022	0.16	55	0.0025	0.18
60	0.0019	0.14	60	0.0022	0.16

Table 8. Simple pay back times for LT- PEMFC and HT -PEMFC systems.

PEMFC type	f_{hu}	*SPT (year)*	SPT_{chp} *(year)*
LT- PEMFC	0.596	3.3	2.4
HT-PEMFC	0.848	7	5.1

Pay Back Time Calculation Results

Simple pay back times for PEMFC systems and micro-cogeneration application of the systems are given in Table 8. Even though HT-PEMFC cogeneration system is more efficient, LT-PEMFC and its equipment are cheaper which makes this system more economical and advantageous with a SPT of 2.4 years.

RESULTS

In this study, effects of different operation temperatures on PEMFC system micro-cogeneration applications are examined. Firstly design of the LT-PEMFC and HT-PEMFC systems has been done and these systems have been experimentally tested. As heat transfer fluid deionized water is used in LT-PEMFC system and heat transfer oil is used for cooling HT-PEMFC system because of high oxidation durability.

LT-PEMFC and HT-PEMFC systems have 402 W and 456 W thermal powers respectively and by using this excess heat of the PEMFC systems simultaneously with electricity production, 87.4 % and 92.8 % total cogeneration efficiencies are calculated for LT-PEMFC and HT-PEMFC system respectively. For each system maximum water temperatures and flow rates are calculated as a result of micro-cogeneration application and HT-PEMFC system is found to be capable of higher amount of heating. Although LT-PEMFC system has a lower thermal power and efficiency, it is determined to be more economical and has a lower pay pack time then HT-PEMFC system. For both systems, necessary number of cells to be used for laboratory heating is calculated as four and both systems are found technically convenient for micro-cogeneration applications.

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SYMBOLS

A	Cell area [cm^2]
C_p	Specific heats [J/gK]
C_{fc}	Cost of fuel cell power system per kW of nominal power [$/kW]
CF	Capacity factor
C_{el}	Cost of electricity [$/kW]
C_{h2}	Cost of hydrogen [$/kW]
C_{fuel}	Cost of natural gas [$/kW]
$\dot{E}$	Enthalpy [J/s]
f_{hu}	Heat utilization factor
F	Faraday constant [96485 A.s/mol]
I	Current density [A/cm^2]
$\dot{m}$	Mass flow rate [g/s]
$\dot{n}$	Rates of consumed and generated gases [mol/s]
N_{cell}	Number of cell
Q	Heat dissipation [W]
P_{fc}	Fuel cell system nominal power [W]
r_{O2}	Oxygen volume in air
R_{th}	Thermal resistance K/W]
S	Stoichiometric ratio
T	Temperature [°C or K]
W_{net}	Net power [W]
η	Water heating efficiency
η_{el}	Electrical efficiency of fuel cell
η_{fc}	Average annual efficiency
η_{tot}	Total fuel cell efficiency
η_{heat}	Efficiency of conventional heat gene ration
AEP	Annual electric production
Δh	Low heating value of H2 gas
$\dot{m}_{cl}$	Mass flow rate of cooling liquid
$\dot{m}_W$	Mass flow rate of city water
$C_{p,cl}$	Specific heat of cooling liquid
$C_{p,w}$	Specific heat of city water
ΔT_{cl}	Inlet and outlet temperature differen ce of cooling liquid
ΔT_w	Inlet and outlet temperature differen ce of city water

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