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Clean Source of Energy for Pollution Restraining: Performance Evaluation of PEM Fuel Cell

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Abstract:

Clean source of energy is the essential requirement of coming future to maintain a stable ecosystem on the earth, distressed by the global warming due to steep increase in the pollution. A step moving towards this urgent need is the Fuel Cell operating by the use of hydrogen and its continuous improvement in performance. In this paper an investigation was made on the performance of Proton Exchange Membrane (PEM) Fuel Cell with 25 cm^2 Nafeon-117 membrane area, serpentine channels, with 0.8 mm deep by 1 mm wide every 0.9 mm. The performance was identified to be influenced by number of operating parameters such as temperature, humidification of gas streams; anode hydrogen flow rate and cathode oxygen flow rate. The PEM fuel cell under consideration was given the highest voltage at 75 ^{0}C temperature of fuel cell, 75 ^{0}C temperature of anode humidification, 50 x 10^{-6} m^3 min^{-1} of anode flow rate. The maximum open circuit voltage was obtained at cathode flow rate of 150 x 10^{-6} m^3 min^{-1}. Also, the current density and voltage characteristics were observed and experimental data obtained was validated by using co-relation given by Khazaee.

Keywords — **PEM Fuel Cell, Nafion Membrane, Hydrogen, Open Circuit Voltage, Fuel Cell Stack**.

I INTRODUCTION

Fuel Cell (FC) and Hydrogen technologies have been presented a track to allow the use of renewable and clean energy systems to trim down the polluting emissions, recover energy efficiency and empower the economy [1,2]. Lot of efforts and studies have been done on the improvement of conventional combustion-based energy system, showing that efficiency can be achieved with huge efforts in terms of plant difficulty [3-7] and still with CO_2 and other polluting components. To uphold the priority of clean energy source, Fuel cell by the use of hydrogen can substantially fulfils the load of clean energy. Though, till hydrogen could not stand on the basis of economics, if compares with the cost of fossil fuels (cost of H_2/Kg ≈ 2 x cost of fossil fuel/kg for large scale production of H_2) [8] due to some technological hurdles such as hydrogen storage and its transportation, [9-12] continuous research efforts can stand the fuel cell and hydrogen in the global economic era of energy sector.

The objective of this research work was to investigate and optimization of performance of the PEM fuel cell by observing the effect of temperature on open circuit voltage (OCV), effect of humidification on OCV, effect of anode flow rate (hydrogen flow rate) on OCV, effect of cathode flow rate (oxygen flow rate) on OCV and voltage current characteristics of PEM fuel cell.

FC has number of benefits over conventional combustion-based technologies existing in many power plants; greenhouse gases such CO_2, SOx, NOx and other air pollutants responsible for the global warming, environmental pollution and health problems which can be evaded at the position of FC operation. On the assessment of life-cycle basis, if pure H_2 is used as a fuel, FC leave only heat and water as byproducts [2]. With number of FC technologies, Proton Exchange Membrane (PEM) FC achieved greater attention particularly for the large characteristic power density, low operating temperature but still with CHP potential (for example for residential applications [13, 14]), and safe operation. Considerable efforts have been

made in the direction of making PEMFC systems able to achieve the optimum balance of cost, efficiency, reliability and durability. The major obstacle in the development and commercialization of this power generation system is a short life time. The lifetime outputs of FC vary significantly, for vehicle purpose ranging from 3000 to 5000 operating hours and for stationary applications up to 40,000 operating hours [15 17]. The quantification of long-term performance and durability of FC is currently still difficult. Indeed, all the mechanisms of FC component deterioration, affecting FC performance degradation, are not yet fully understood. The rate of degradation of the stack voltage is taken as a parameter indicative of the health status of an FC. Generally the range of voltage reduction rate is of 1e20 [mVh^{-1}] [16 17].

The water management is a phenomenon which particularly affects the long life of a PEM-FC. Generally, the reduced conductivity in the membrane is observed if insufficient water content, within the stack or at definite positions within the unit cell [18] and in any ions present in the catalyst layer, resulting in increased ohmic losses and in a drop in cell voltage [15-17]. A balance must be realized between reactants (hydrogen and oxygen) delivery and water supply and removal [19]. St-Pierre et al. [20] confirmed that the life and durability of an FC is strongly affected by the water management in the PEM-FC. The proper management of water within the cell ensures high efficiency, maintaining power density and stable operating conditions in the face of long periods of operation [21]. To stay with this view, it is necessary to keep the membrane humidified with relative water content to have high proton conductivity. On the other hand, disproportionate buildup of water may harmfully impact on the performance and lifetime of fuel cell.

II EXPERIMENTAL PEM FUEL CELL

The experimental set-up consists of a single PEM fuel cell with active surface area 0.05 m x 0.05 m of membrane electrode assembly sandwiched between flow field plates, current collector plates as shown in Fig. 1 and geometric parameters of this fuel cell are given in Table I.

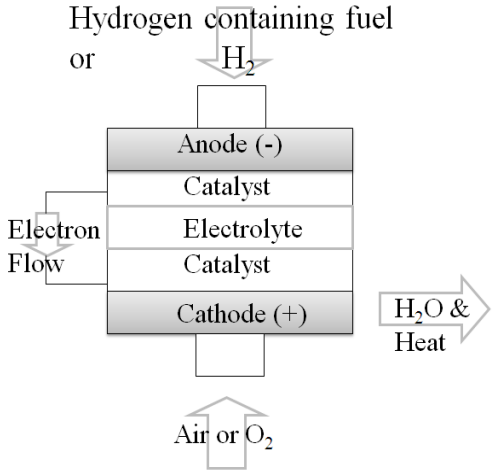


Fig 1. Diagram of experimental set-up for testing PEM fuel cell

The structure of the PEM fuel cell is a composite of two porous electro catalytic electrodes on either side of a solid polymer electrolyte (SPE) membrane. The thermodynamic reversible potential for the overall cell reaction is 1.214 V, which compares favourably to 1.23 V for the hydrogen fuel cell and, consequently has generated the interest in the PEM fuel cell as an alternative power source. The cells were fitted with a membrane electrode assembly (MEA) sandwiched between two graphite blocks with flow beds cut out for hydrogen and oxygen–air flow as shown in Fig. 2.

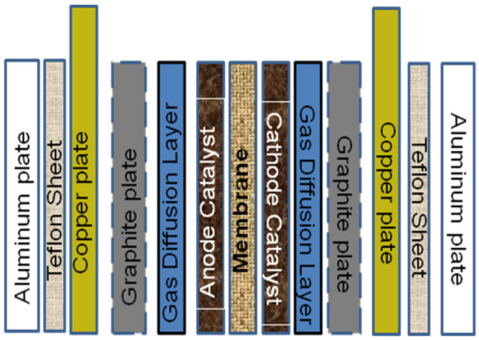


Fig. 2 Schematic Single Stack Fuel Cell

Flow field plates made of graphite are pressed to MEA on both sides. These plates are grooved to create flow channels in them, through which the gases flow. Hydrogen passes through the flow channel in the plate on the anode side. Oxygen

flows through the passages in the plate on the cathode side. Different flow arrangements have been tested by researchers with the aim of achieving good diffusion of hydrogen ion across the membrane. This experimental studies is conducted with 4-serpentine (4-S). A photograph of the 4-serpentine flow field is shown in Fig. 3.

Fig. 3 Photograph serpetine channel

The cell was held together between two aluminium backings plates provided with small holes to accommodate thermocouples, using a set of retaining bolts positioned around the periphery of the cell as shown in the photograph of side views of PEM fuel cell Fig. 4. The graphite blocks were also provided with electrical contacts and small holes to accommodate thermocouples.

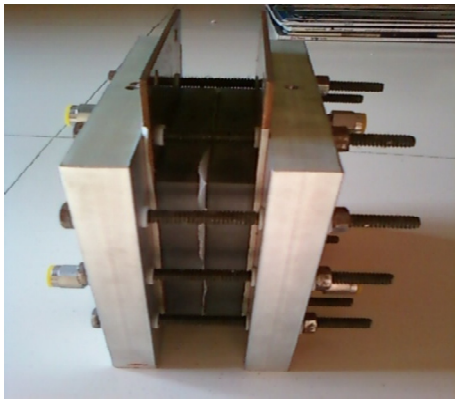
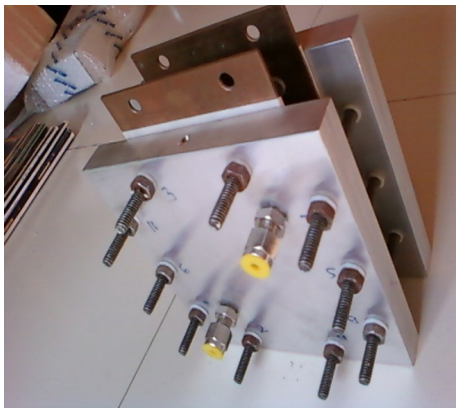


Fig. 4 Side views of PEM Fuel Cell

Hydrogen, Oxygen and air were supplied from cylinders at ambient temperature, and the pressure regulated at inlet by pressure regulating valves. All connections between the cells and equipment were with PTFE tubing, fittings and valves as shown in the working experimental set-up of single fuel cell stack in Fig. 5. The gas diffusion layers used are carbon cloth at the anode and cathode for electrical connection with the catalyst and good mass transport of reactants. Copper plates are used as current collectors.



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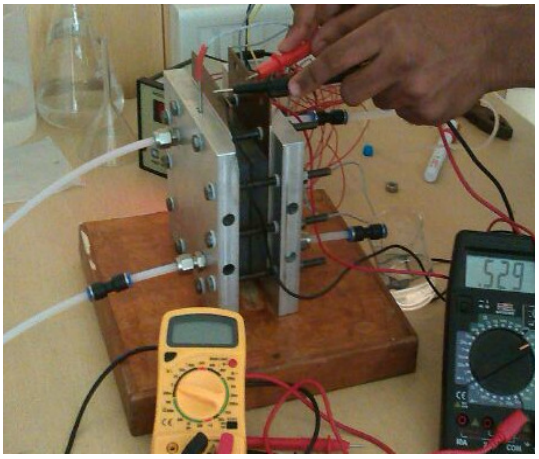

Figure 5. Working Set-up of PEM fuel cell

TABLE I
GEOMETRIC PARAMETERS OF THE PEM FUEL CELL

Parameter	Values
Electrolyte membrane	Nafion 117
Effective electrode area	25 cm^2 (5 cm × 5 cm)
Membrane area	64 cm^2 (8 cm × 8 cm)
Anode catalyst	Pt-Ru 4.0 mg/cm^2
Cathode catalyst	Pt-black 4.0 mg/cm^2
Channel rib width	0.9 mm
Channel Width (mm)	1 mm
Channel Depth (mm)	0.8 mm
Membrane Thickness (mm)	179 µm
Gasket	Teflon

III RESULT AND DISCUSSION

The commercial N-117 MEA was operated with anode feed of Hydrogen 50 x 10^{-6} m^3 min^{-1} and cathode feed oxygen 100 x 10^{-6} m^3 min^{-1}. The cell open circuit voltage at different temperature was recorded at zero current. The cathode and anode humidifier is used to maintain moisture in the oxygen stream in order to keep the membrane humidified. Oxygen is fed continuously through the cathode humidifier. The humidification temperature of all gases was kept 75°C. The active MEA area used was 25 x 10^{-4} m^2.

A Effect of Temperature on Open Circuit Voltage (OCV)

As temperature increases the OCV value also increases as reaction kinetics speed up at higher temperature. But at same time on further increasing the performance decreases as at higher temperatures the N117 membrane losses it conductivity. It is observed that at 75°C the open circuit voltage was maximum for given operating conditions as shown in figure 6. The cell was operated at different temperatures and OCV values are recorded.

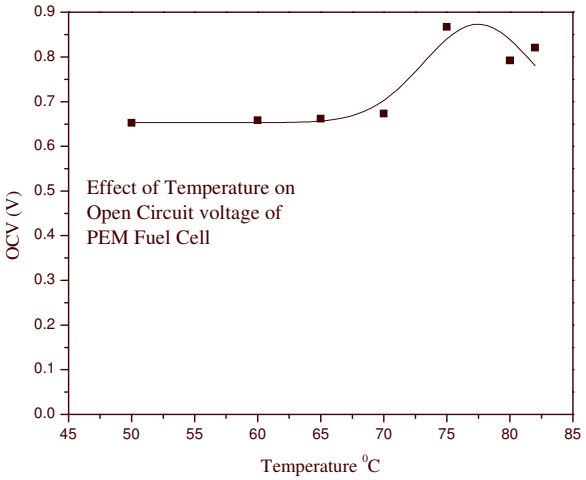

Fig. 6 Effect of temperature on OCV

B Effect of Anode Humidification Temperature on OCV

Hydrogen gas is humidified by bubbling it through water which is present in a bottle. A heater is placed in the bottle to heat the water to a required temperature. The humidity acquired by hydrogen is controlled by either increasing or decreasing the temperature of water in the bottle. Open circuit voltage curves with different anode humidification temperatures in the range of 65-85 °C are presented in Fig. 7. The data obtained by keeping the cathode flow rate at 100 x 10^{-6} m^3 min^{-1}, anode flow rate 50 x 10^{-6} m^3 min^{-1} and cell operating temperature at 75 °C It can be found from Fig. 7, the voltage decreases as the humidification temperature increases due to an increase in the saturation humidity of hydrogen gas. The mole fraction of hydrogen decreases and mole fraction of water increases with an increase in anode humidification temperature resulting in decrease in performance.

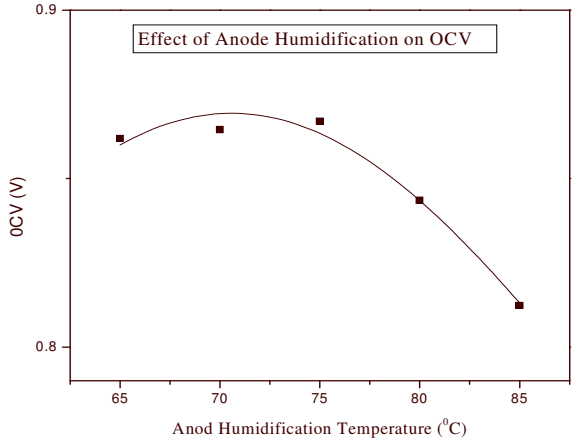

Figure 7. Effect of Anode Humidification Temperature on OCV of Fuel Cell

C Effect of Anode Flow rate on OCV

N-117 anode feed hydrogen was used with different flow rate and keeping cathode feed oxygen flow rate at 100 x 10^{-6} m^3 min^{-1}. The temperature of cell was kept at 75°C, and humidifier temperature was also at 75°C. At 50 x 10^{-6} m^3 min^{-1} the OCV value is higher. Higher flow rate may cause the higher fuel crossover through the membrane as shown in Fig. 8. The thermodynamic reversible potential for the overall cell reaction is 1.23 V for the hydrogen. Fuel cell Open circuit voltage (OCV) usually does not reach the theoretical value at the given pressure and temperature. The reason for lowering of the OCV from the theoretical voltage could be the diffusion of fuel across the membrane. OCV is an indicator of the degree of fuel crossover via diffusion.

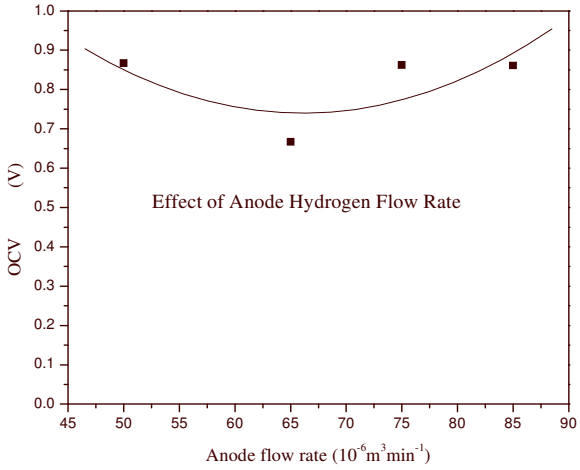

Fig. 8 Effect of anode flow rate on OCV.

D Effect of Cathode Flow rate on OCV

To study this effect anode feed hydrogen flow rate was kept constant at 50 x 10^{-6} m^3 min^{-1}. Cathode feed oxygen flow rate was varied at 75°C operating temperature of the cell. The cell performance decreases slightly by the increase of the cathode flow rate after 150 x 10^{-6} m^3 min^{-1}.

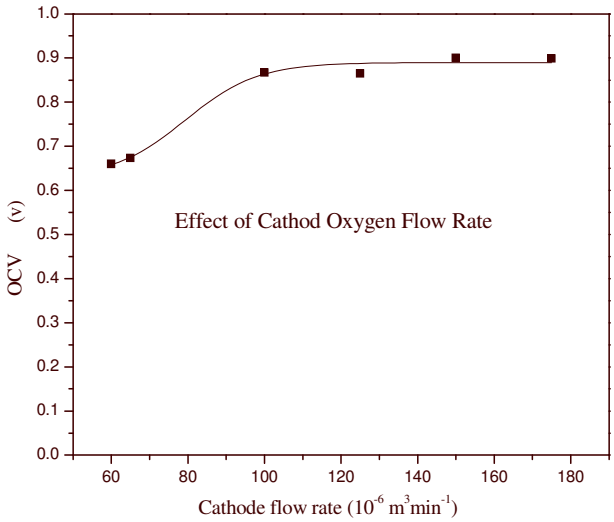

Fig. 9 Effect of cathode flow rate on OCV on hydrogen fuel cell

The product of reaction on cathode side is water, if the water production increased it interferes the movement of oxygen, blocks cathode flow channels and also blocks pores of electrode and GDL so that an optimum cathode flow rate is necessary to minimize the voltage loss at the cathode. At oxygen flow rate of 150 x 10^{-6} m^3 min^{-1} maximum open circuit was obtained. The same oxygen flow rate was used here after for performance evaluation of all composite membranes.

E Current density and voltage characteristics

N-117 membrane with anode feed hydrogen 50 x 10^{-6} m^3 min^{-1}; cathode feed oxygen 150 x 10^{-6} m^3 min^{-1}, operating temperature and humidification temperature at 75°C. Current density and voltage data were obtained by applying load, the potential difference was applied across the cell and stabilized current value was measured. Same procedure was repeated by changing the voltage.

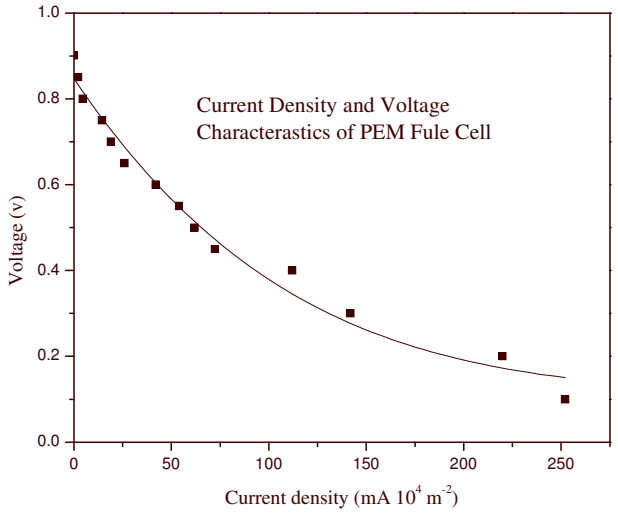

Fig. 10 Voltage-current characteristics of Fuel Cell for N117 with $H2/O_2$ feed

Above current density and voltage characteristics (polarization data) were fitted in correlation given by Khazaee et al. (Equ. 1) [22].

$$V = a + bi^k + ciZ^n \left(\frac{T_{H2}}{T_{cell}}\right)^d \left(\frac{T_{O2}}{T_{cell}}\right)^e \left(\frac{\dot{Q}_{O2}}{\dot{Q}_{H2}}\right)^f P^g + lZ^h [\exp(m + pi)]^j \quad (1)$$

In this equation current density is in $Ax10^4 m^{-2}$, temperatures are in $^\circ C$, flow rates are in $L/\min$, ambient pressure is in *bar* and Z=2 for serpentine channel. In Eq (1) the constants a, b, c, d, e, f, g, h, j, k, l, m and n are undefined and by using software as Data fit which fits the results of experiment from one to more independent variables given in Table 6. Hence, by substituting the values of constants given in Table II, Eq (1) converts into Eq (2) as given below.

TABLE II
VALUES AND LIMITS OF CONSTANT IN EQ 1

Variables	Value	Lower Limit	Upper Limit
A	0.87265	0.868892869	0.876415133
B	-0.9	-0.199909826	-0.182112449
C	-0.27134189	-0.284603833	-0.258079947
D	-9.97 E-02	-0.13058875	-6.87E-02
E	-0.1375614	-0.173141973	-0.101980824
F	-2.69 E-02	-3.41E-02	-1.97E-02
G	0.132698922	-0.153154262	-0.112243582
H	13.856425	-3.472674784	31.18552528
M	-6.228078322	-124161.6701	124149.2139
J	1.775427703	-59501.80159	59505.35244
K	0.368901517	0.33917133	0.398631704
L	7.89E-04	-137.8906155	137.8921933
N	0.216711724	0.195475458	0.23794799
P	0.548819575	-18393.17559	18394.27323

$$V = 0.8726 - 0.191i^{0.369} + 11.2024\exp(-11.055 + 0.974i) - \quad (2)$$

$$- \frac{0.3152i}{P^{0.1327}\left(\frac{T_{H2}}{T_{cell}}\right)^{0.0996}\left(\frac{T_{O2}}{T_{cell}}\right)^{0.1375}\left(\frac{\dot{Q}_{O2}}{\dot{Q}_{H2}}\right)^{0.0269}}$$

Fig. 11 shows the comparison between the experimental results and the predicted results by the correlated equation (1) of voltage-current characteristics for $T_{O2} = 55\ ^\circ C$, $T_{H2} = 55\ ^\circ C$, $T_{cell} = 75\ ^\circ C$, P=2.905 bar, $\dot{Q}_{O2} = 0.15\ L/\min$, $\dot{Q}_{H2} = 0.05\ L/\min$

The model given by Khazaee et. al. shows the good agreement of predicted results with experimental results for low current values, but as the current increases the error between the predicted and experimental results was increased as shown in Fig. 11

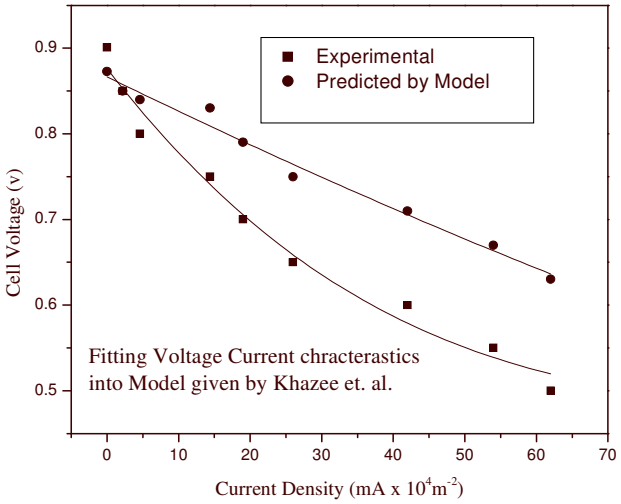

Fig. 11 Comparison of experimental and predicted voltage-current characteristics predicted by the model of Fuel Cell for N117 with $H2/O_2$ feed

IV CONCLUSIONS

In this work, the performance of fuel cell has been studied by observing the effect of various parameters such as temperature of fuel cell, anode humidification temperatures, anode hydrogen flow rate, and cathode oxygen flow rate and voltage current characteristics. The PEM fuel cell under consideration has given the highest voltage at 75 ^{0}C temperature of fuel cell, 75 ^{0}C temperature of anode humidification, 50 x 10^{-6} m^3 min^{-1} of hydrogen anode flow rate. The maximum open circuit voltage was obtained at cathode oxygen flow rate of 150 x

10^{-6} m^3 min^{-1}. The product of reaction on cathode side is water, if the water production increased it interferes the movement of oxygen, blocks cathode flow channels and also blocks pores of electrode and GDL so that an optimum oxygen cathode flow rate is necessary to minimize the voltage loss at the cathode. The data obtained for voltage current characteristics was fitted in the model given by Khazee et al. and the model gives the best fitting for the initial current density values with near about 20 % error in the latter values of current density.

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REFERENCES

1. *European Commission. EUR 20719 EN e hydrogen energy and fuel cells a vision of our future, http://ec.europa.eu/research/energy/; (2003).*
2. *Andersson M., Sundén B., Fuel cell handbook. 7th ed. US: DOE; (2004).*
3. *Bhargava R.K., Bianchi M., Campanari S., Pascale A., Montenegro G., Peretto A. A parametric thermodynamic evaluation of high performance gas turbine based power cycles. Transaction of the ASME. Journal of Engineering for Gas Turbines and Power, 132 (2), (2009).*
4. *Bianchi M., Branchini M., De Pascale A., Melino F., Peretto A., Bhargava R.K., Gas turbine power augmentation technologies: a systematic comparative evaluation approach. Proceedings of ASME Turbo Expo, 5, pp 99-107, (2010).*
5. *Bagnoli M., Bianchi M., Melino F., Peretto A., Spina P.R., Bhargava R., Application of a computational code to simulate interstage injection effects on Ge frame 7ea gas turbine. Transaction of the ASME. Journal of Engineering for Gas Turbines and Power 130 (1), (2007)*
6. *Bianchi M., Melino F., Peretto A., Spina, P.R., Ingistov S., Influence of water droplets size and temperature on wet compression, Proceedings of ASME Turbo Expo 2007, 3, pp 651-662, (2007).*
7. *De Pascale A., Ferrari C., Melino F., Morini M., Pinelli M., Integration between a thermo-photo-voltaic generator and an organic rankine cycle, Applied Energy September, 97, pp. 695-703, (2012).*
8. *Antonia H., Marika T., A Hydrogen Future? An Economic and Environmental Assessment of Hydrogen Production Pathways, Natural Resources Defence Council Issue paper: November (2005).*
9. *Balat M., and Kirtay E., 'Major Technical Barriers to a "Hydrogen Economy"', Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 32 (9), pp 863 —876, (2010).*
10. *Sirous N. and Tuan A., Ethanol Reforming For Hydrogen Production In High Pressure Condition: Effect Of Different Support On Cobalt Based Catalyst, Rasayan J. Chem 2 (3), pp 543-554, (2009).*
11. *Llorca J., Homs N., Sales J., Fierro J., L. G. de la Piscina, P.R., Effect of sodium addition on the performance of Co-ZnO-based catalysts for hydrogen production from bioethanol, J. Catal., 222, pp 470-480, (2004).*
12. *Llorca J., Pilar R.P., Jean-Alain D., Joaquim S., Narcıs H., CO-free hydrogen from steam-reforming of bioethanol over ZnO- supported cobalt catalysts Effect of the metallic precursor, Applied Catalysis B: Environmental, 43, pp 355–369, (2003).*
13. *Bianchi M., De Pascale A., Spina P.R., Guidelines for residential micro-CHP systems design. Applied Energy, 88(5), pp 1500-9, (2010).*
14. *Bagnoli M, De Pascale A. Performance evaluation of a small size cogenerative system based on a PEM fuel cell stack, Proceedings of the ASME Turbo Expo 2005, 4, pp. 143-50, (2005).*
15. *Knights S.D., Colbow K.M., St-Pierre J., Wilkinson D.P., Aging mechanisms and lifetime of PEFC and DMFC. Journal of Power Sources, 127, pp 127-34, (2004).*
16. *Schmittinger W., Vahidi A., A review of the main parameters, influencing long-term performance and durability of PEM fuel cell, Journal of Power Sources, 180, pp 1-14, (2008).*
17. *Hinds G., Performance and durability of PEM fuel cells: a review, NPL report DEPC- MPE 002, pp 25-42, (2004).*
18. *Zawodzinski T., Derouin C., Radzinski S., Sherman R., Smith V., Springer T., Water uptake by and transport through napheon-117 membranes, Journal of Electrochemical Society, 140(4), pp 1041-7, (1993).*

19. *McKay D.A., Siegel J.B., Ott W., Stefanopoulou A.G.,Parameterization and prediction of temporal fuel cell voltage behavior during flooding and drying conditions. Journal of Power Sources, 178 (1), pp 207-22, (2008).*

20. *St-Pierre J., Wilkinson D.P., Knights S., Bos M., Relationship between water management, contamination and lifetime degradation in PEFC, Journal of New Materials for Electrochemical Systems, 3, pp 99-106, (2000).*

21. *Mokmeli A., Asghari S., An investigation into the effect of anode purging on the fuel cell performance, International Journal of Hydrogen Energy, 35 pp 9276-82, (2010).*

22. *Khazaee I., Ghazikhani M., Experimental characterization and Correlation of a triangular channel geometry PEM fuel cell at different operating conditions, The Arabian Journal for Science and Engineering*