CHEMICAL ENGINEERING TRANSACTIONS Volume 21, 2010
Editor J. J. Klemeš, H. L. Lam, P. S. Varbanov

DOI: 10.3303/CET1021147

Multi-Objective Optimisation of a PEM Fuel Cell System

Suha Orçun Mert*, Zehra Özçelik, Yavuz Özçelik, Ibrahim Dinçer
Dept. Chemical Enginnering, Ege University Bornova, İzmir, Turkey
orcun.mert@ege.edu.tr

The multi-objective optimisation of fuel cell systems is conducted in this study with the objective functions for maximizing the power output and both energy and exergy efficiencies, and minimizing the emissions and cost generation (through exergoeconomics). The cases are investigated parametrically using varying operating conditions, such as temperature, pressure, surrounding temperature and pressure, current density, humidity and etc. The interface of the computer program is developed and genetic algorithm based solver is implemented to the program for dealing the multi-objective problems. It is seen that the cost of production is inversely proportional to the maximum produced work, and the selection of the optimum value depends on the needs of the system that the fuel cell (FC) system will be used, the best value from cost point of view is 3.35 $/GW at 0.5 work fraction.

1. Introduction

The phenomena of FC systems are complicated due to the FC elements and reactions, and their modelling and optimisation is essential for better performance. Nowadays with the increasing pollution and the decrease of the fossil fuel resources a movement has occurred towards more environmentally benign and more efficient power production, and this has shifted the priority from the conventional fuels and internal combustion engines and increased the interest on alternative fuels and power sources. In this study, the optimisation problem includes cost, emission and efficiency objectives. The aim of this study is to apply a multi-objective optimisation scheme to a PEM FC system used for transportation purposes. FCs are considered as one of the most promising alternative power sources especially for sub-megawatt scale applications like light-duty transportation. FCs convert chemical energy into electrical energy by a well known electrochemical process. Since the electrochemical processes are not governed by Carnot law relatively low operating temperatures does not leads to efficiency losses. Contrary to internal combustion engines, the efficiency of FCs is not strongly dependent on the operating power. FCs has an increasing demand with its high efficiency and used in many areas including transportation applications, domestic uses, heat production etc.

2. The PEM Fuel Cell Engine System Studied

For the investigation The Ballard's Xcellsis™ HY-80 Fuel Cell Engine is taken as an example (Figure 1). Since the Xcellsis™ HY-80 fits beneath the floor of the vehicle; the size of the passenger compartment is not affected. The engine is lightweight, 68 kW

Please cite this article as: Mert S. O., Ozcelik Z., Ozcelik Y. and Dincer I., (2010), Multi-objective optimisation of a PEM fuel cell system, Chemical Engineering Transactions, 21, 877-882 DOI: 10.3303/CET1021147

hydrogen-fuelled FC engine. The hydrogen stored in tank at 10 atm and 298 K. After a pressure regulation depending on the system pressure, the hydrogen is fed to the system. The FC stack is composed of 97 cells of each having a 900 cm^2 effective area. The cooling system is used in order to maintain the operating temperature constant inside the FC stack. (Ballard, 2005)

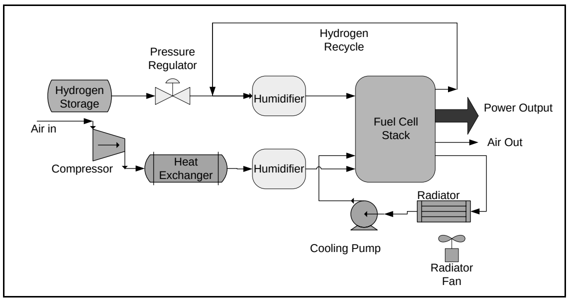

Figure 1: Flow chart of Ballards XcellsisTM HY-80 fuel cell engine.

2.1 Modeling

The maximum voltage that can be produced by a cell without any irreversibility is called as the reversible cell voltage. A form of the Nernst equation is used. Since this specific equation derived by using Ballard fuel cell and is a function of environment temperature, system pressure and the partial pressures of both hydrogen and oxygen.

$$V_{rev} = 1.229 - 8.5 \cdot 10^{-4} (T_{FC} - 298.25) + 4.3085 \cdot 10^{-5} \cdot T_{FC} \left[\ln\left(p_{H_2}\right) + \frac{1}{2} \ln\left(p_{O_2}\right) \right] \tag{1}$$

where, x_{H2O} is the water mole fraction that is P_{sat}/P respectively both for anode and cathode. x_A and x_c are anode and cathode dry gas mole fractions, respectively and ξ_A and ξ_C are anode and cathode stoichiometries respectively. (Amphlett et al., 1995)

2.1.1 Operating Cell Voltage

The operating cell voltage is less than the reversible cell voltage because of the irreversibilities and overpotentials. Since the overpotentials depend on the system operating parameters the operating cell voltage is not constant while the reversible cell voltage is constant for general cases. The operating cell voltage may be expressed by;

$$V_{operating} = V_{rev} - V_{irrev} \tag{2}$$

Activation losses, ohmic losses, mass transport or concentration losses are the overpotentials that are taken to account in this study. (Rowe and Li, 2001)

$$V_{irrev} = V_{act} + V_{ohm} + V_{con} \tag{3}$$

After calculating the irreversibilities the power produced by the stack can is calculated via,

$$\dot{W}_{Stack} = V_{operating} \cdot i \cdot A_{cell} \cdot n_{cell} \tag{4}$$

where, n_{cell} is the number of FCs inside the stack; A_{cell} is the area of the each cell; *i* is the current density. (Ay et al., 2006)

2.1.2 Exergoeconomic Analysis & Efficiency

The overall exergy balance is;

$$\dot{I}_{FC} = \sum \dot{E}_{mass,in} - \sum \dot{E}_{mass,out} - \sum \dot{E}_{Heat} - \sum \dot{E}_{work} \tag{5}$$

Also the balance equation for the entire system to get the net work output, and both energy and exergy efficiencies for the entire system as follows:

$$\dot{W}_{net} = \dot{W}_{FC} - \dot{W}_{comp} - \dot{W}_{cool,pump,act} - \dot{W}_{fan,act} \tag{6}$$

$$\eta_{sys,exergy} = \frac{\dot{W}_{net}}{\dot{E}_{in}} \tag{7}$$

where E_{in} is calculated from the exergy of the inlet streams of the system. The overall exergetic cost balance is used as; (Mert et al., 2007)

$$\sum \left(\dot{E}_{in,i} \cdot C_{in,i}\right) + \dot{Z}_{tot} = \sum \left(\dot{E}_{out,i} \cdot C_{out,i}\right) + \dot{W}_{net} \cdot C_W \tag{8}$$

3. Multi-Objective Optimisation

Multi-objective optimisation (or programming), also known as multi-criteria or multi-attribute optimisation, is the process of simultaneously optimizing two or more conflicting objectives subject to certain constraints. This may include maximization of all objective functions or minimization of all functions or a combination of maximization and minimization of objective functions.

If a multi-objective problem is well formed, there should not be a single solution that simultaneously minimizes each objective. Finding such a solution, and quantifying how much better this solution is compared to other such solutions is the goal when setting up and solving a multi-objective optimisation problem. (Zitzler, 2004)

In mathematical terms, the multi-objective problem can be written as:

$$\begin{gathered} \min_x [f_1(x), f_2(x), f_3(x), \ldots, fn(x),] \\ \text{s.t.} \\ g(x) \leq 0 \\ h(x) = 0 \\ x_l \leq x \leq x_u \end{gathered} \tag{9}$$

where $f_i(x)$ is the i-th objective function, g(x) and h(x) are the inequality and equality constraints, respectively, and x is the vector of optimisation or decision variables.

3.1 Solution Methods

A common difficulty with a multi-objective optimisation problem is the conflict between the objectives: in general, none of the feasible solutions is optimal with respect to all the objectives. One of the most classical methods is the method of objective weighting. The multiple objective functions are combined in one function such as;

$$F(x) = \sum_{i=1}^{N} w_i f_i(x) \tag{10}$$

where $x \in X$, X is the feasible region, and $0 \leq w_i \leq 1$ and $\sum_i^N w_i = 1$. By changing the corresponding weight (w_i) the importance given to a objective can be changed easily.
A genetic algorithm (GA) which is a search technique used in computing to find exact or approximate solutions to optimisation and search problems is used as solver. (Özçelik, 2007)Genetic algorithms are a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (Ehrgott, 2005).

4. Multi-Objective Optimisation of a PEM Fuel Cell System

In order to apply a multi-objective optimisation technique to the derived model an objective function is to be prepared for the solution. In this study so far the weighing method is used, that a weighing factor is given to the objective function parameters which are the produced work (WFC) , energy efficiency $\eta_{sys,exergy}$, exergy efficiency $\eta_{sys,exergy}$, and the cost of produced work C_W . It must also considered that C_W must be minimized where as the other parameters has to be maximized in the optimum. In weighing method each of these parameters are given a factor which is between 0 and 1. In this study a selection for the weighing factors is not made, beside a parametric study for different weighting factors are applied and the multi-objective problem is separately solved for each case. So the results are tried to be discussed with the light of these studies. The optimisation depends on a fitness function. In this study fitness function is formed depending on the objective function derived. The parameters are normalized to form the fitness function between 0 and 1. (Weise, 2007) The normalization is done by dividing each parameter with its maximum value which is obtained by single optimisation of that parameter. So the fitness function is changed as in the equation 11. (Konak et al., 2006)

$$Z = w_1 \frac{W_{FC}}{W_{FC,max}} + w_2 \frac{\eta_{energy}}{1} + w_3 \frac{\eta_{exergy}}{1} - w_4 \frac{C_w}{C_{w,max}} \tag{11}$$

4.1 Evaluation of the Results

For understanding the behavior of the multi-objective structure of the PEM FC system 48 different sets with different weights are calculated by the Mulop Computer Program. If the fitness values of the set are investigated (Figure 2), it is seen that the sets that in the higher work fraction the fitness value is much higher than the other sets. This situation is expected since when the normalization is considered the values of the work contribution reaches to 1 so the solutions tends to values for better optimizing produced work.
In Figure 3 the change of produced work and energy and exergy efficiencies with respect to the weight of work in the objective function is seen. It is seen that the work and efficiencies are proportional with each other which is an expected result since these values are all maximized. It is seen that the best values for efficiencies lies in the lower values of contribution but in these values the produced work values are low since the values between 0.5-0.6 is much more acceptable.

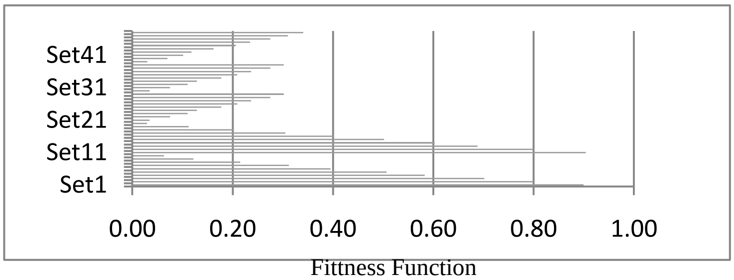

Figure 2: The fitness values of the sets

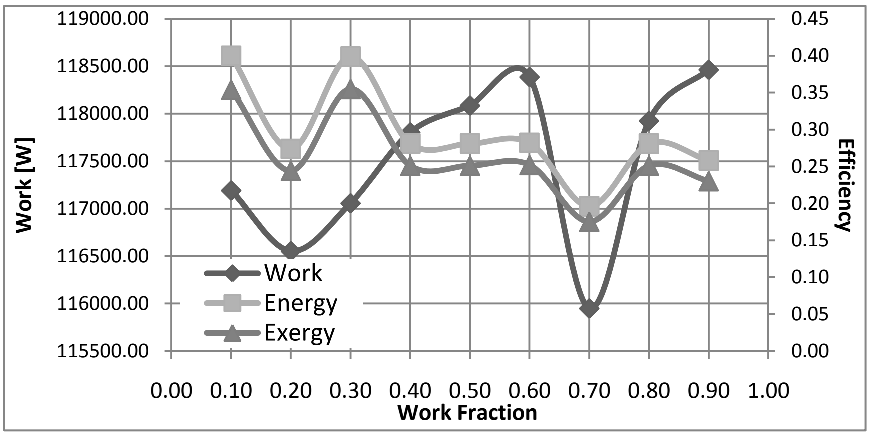

Figure 3: The variation of produced work and efficiencies wrt to the weight of work

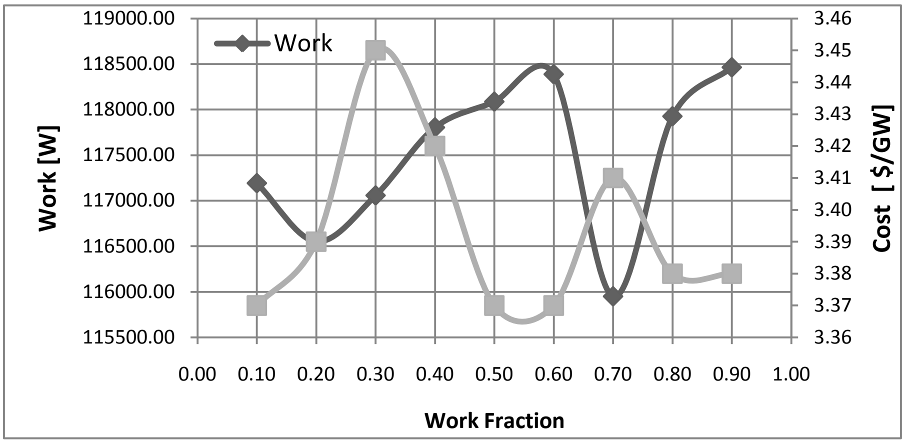

Figure 4: The variation of produced work and cost wrt to the weight of work in the objective function

Differing from Figure 3, the Figure 4 represents the one maximization one minimization objectives which are produced work and cost of production respectively. It is seen that when the produced work amount increases the cost of production decreases, that is also an expected result and the optimum values in the figure is seen between 0.5-0.6 which is in a harmony with the efficiency values.

5. Conclusion

The phenomena of FC systems are complicated due to the FC elements and reactions, and their modeling and optimisation is essential for better performance. In this study, the optimisation problem includes cost, emission and efficiency objectives. This study covers a multi-objective optimisation scheme to a PEM FC system used for transportation purposes. Weighted sum of objectives method is used in order to unify the objective function and a computer program is developed based on a hybrid genetic algorithm for the solution of this complex model. The results of parametric investigation are mostly expected when the tendencies of the variables and objectives are investigated. In order to determine a certain optimum working condition further studies that includes optimisation of the weighting factors in addition to the objective parameters will be studied in following periods.

References

Amphlett J.C., Baumert R.M., Mann R.F., Peppley B.A., Roberge P.R., 1995, Performance Modeling Of The Ballard Mark IV, Journal of Electrochemical Society 142 (1), 9-15 .

Ay M., Midilli A., Dincer I., 2006, Exergetic Performance Analysis of a PEM Fuel Cell, Int. J. Energy Res 30, 307–320.

Ballard, 2005, Product Bulletin, Xcellsistm HY-80 Fuel Cell Engine, <www.ballard.com>, (last accessed 04/2005).

Konak A., Coit D.W., Smith A.E., 2006, Multi-Objective Optimization Using Genetic Algorithms: A Tutorial, Reliability engineering & systems safety 91, 992-1007.

Mert S.O., Dincer I., Özçelik Z., 2007, Exergoeconomic Analysis of A Vehicular PEM Fuel Cell System, Journal of Power Source 165 (1), 244-252.

Özçelik Y., 2007, Exergetic optimization of shell and tube heat exchangers using a genetic based algorithm, Applied Thermal Engineering 27, 1849–1856.

Rowe A., Li X., 2001, Mathematical Modeling of Proton Exchange Membrane Fuel Cells, Journal of Power Sources 102, 82-96.

Weise T, 2007, Global Optimization Algorithms - Theory and Application, <www.it-weise.de/projects/book.pdf >, (last accessed 20/01/2010).

Zitzler E., Laumanns M., and Bleuler S., 2004 A Tutorial on Evolutionary Multiobjective, Metaheuristics for Multiobjective Optimization, Springer, USA.