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# Thermodynamic Investigation and Optimization of a Power Generation System Based Solid Oxide Fuel Cell Using Taguchi Approach

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*ABSTRACT*

Fuel cells directly convert chemical energy into electrical power using electrochemical reactions. Solid oxide fuel cell (SOFC) is one of the high-temperature fuel cells that propose a promising future from the standpoint of power generation. In this study, optimization of an SOFC system is performed using Taguchi approach after verification of the model in compare with experimental results. Current density, inlet temperature of SOFC, and utilization factor are considered as input parameters and the electrical power is selected as the output response. The analysis of variance (ANOVA) results indicate that the current density is the most effective parameter on electrical power which has 52% of contribution followed by inlet temperature of SOFC and utilization factor by 25 and 20% of contributions, respectively. The electrical power enhances by increasing current density and inlet temperature of SOFC and reducing utilization factor. Signal to noise ratio (S/N) analysis elucidate that the current density of 9500 A/m$^2$, the inlet temperature of SOFC of 850 °C, and the utilization factor of 75% is the optimum condition in order to achieve the highest electrical power. The results show that the electrical power is 644.3 kW at the optimum condition.

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## 1. INTRODUCTION[1]

Fuel cell is a device that directly converts the chemical energy as a fuel into electrical power through a process of electrochemical reactions. Therefore, it produces electrical power without any high-temperature combustion of fuel normally occurs in conventional power plants. It does not required to convert the chemical energy of fuel into mechanical energy and then drive an electric generator as conventional power plants [1-3].

Fuel cells are most commonly classified by the type of electrolyte being used, with very different properties and possible applications. These include [2, 4, 5]:

- Proton exchange membrane fuel cell (PEMFC)
- Alkaline fuel cell (AFC)
- Direct methanol fuel cell (DMFC)
- Molten carbonate fuel cell (MCFC)
- Phosphoric acid fuel cell (PAFC)
- Zinc-air fuel cell (ZAFC)
- Microbial fuel cell (MFC)
- Photonic ceramic fuel cell (PCFC)
- Solid oxide fuel cells (SOFC)

High-temperature fuel cells (i.e. MCFC and SOFC) proposed the most promising future from the power generation point of view because they allow for hybrid systems to be engineered. Hence, the generating electricity with higher efficiency is possible [4, 6].

There are many advantages for SOFCs operating at a higher temperature, typically in the range of 600-1000 °C. This high temperature provides two benefits: i) high-quality waste heat and ii) effectively activates the processes of reforming and electrochemical oxidation of hydrocarbon fuels in presence of catalysts [5, 6].

In recent studies, SOFCs have been used as the prime mover of the heat and power systems due to their high performance and low pollution. Several studies have been conducted on this topic. For instance, Ebrahimi et al. [7] analyzed the produced power in a combined

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system of SOFC, micro gas turbine and the organic Rankine cycle. In their proposed system, the exhaust gases from the SOFC entered into micro gas turbine. According to the results, the fuel consumption was reduced by 45% and the total efficiency was increased by 65% using the proposed system. Bang-Moller et al. [8] studied an integrated system consisting of a two-stage gasification concept, an SOFC and a micro gas turbine. The system was examined from energy and exergy points of view. The results revealed that the power and the electrical efficiency of the hybrid system were 290 KW and 58.2%, respectively. Energy and exergy analysis of an internal reforming SOFC (IR-SOFC) combined with gasifier was studied by Ozcan et al. [9]. According to the results, the energy and exergy efficiencies were obtained 42.2 and 36.5% for SOFC and 78 and 50% for the combined system, respectively.

The full trial design is not effective from standpoints of cost and time. Therefore, the design of experiment (DOE) method is a useful tool to minimize time, cost, and number of experiments. DOE methods are more valuable in processes in which different input parameters are affecting various output parameters. Taguchi approach was selected the least number of trials among DOE methods in order to study the effect of input parameters on response variables. Optimization of the process using the signal-to-noise ratio (S/N) analysis is another advantage of Taguchi approach. Nowadays, Taguchi approach is very popular in engineering researches [10-12].

Several systems have been investigated and optimized using Taguchi approach for instance studying and optimization of diesel engine working on biodiesel [13], performance analysis and optimization of a thermoelectric generator (TEG) [14], optimization of an SI engine used pure gasoline, ethanol, and methanol [15], optimization of ground heat exchangers (GHX) for space heating and cooling applications [16].

In the present study, a SOFC system is modeled and validated in comparison to experimental results. Although several studies were reported using Taguchi approach in different engineering problems; application of the Taguchi method in performance evaluation and optimization of the SOFC system is scarce, which offers another scope of the present study.

## 2. SOFC MODELLING

The methane fueled SOFC system is presented in the following and the schematic is illustrated in Figure 1. Where, $\dot{a}_{\mathrm{r}}$, $\dot{b}_{\mathrm{r}}$, and $\dot{c}_{\mathrm{r}}$ are the molar conversion rate for the reforming, shifting, and electrochemical reactions, respectively. These reactions occur in the anode and cathode electrodes of the SOFC as shown in Equations (1) to (3) [17].

$$\dot{a}_{\mathrm{r}} \rightarrow (\mathrm{CH_4 + H_2O \rightarrow CO + 3H_2}) \quad \text{Reforming} \quad (1)$$

$$\dot{b}_{\mathrm{r}} \rightarrow (\mathrm{CO + H_2O \rightarrow CO_2 + H_2}) \quad \text{Shifting} \quad (2)$$

$$\dot{c}_{\mathrm{r}} \rightarrow (\mathrm{H_2 + 1/2O_2 \rightarrow H_2O}) \quad \text{Overall} \quad (3)$$

Inlet and outlet molar flow rates at the SOFC can be calculated by applying mass balances to Equations (1)-(3) as Equation (4):

$$\begin{aligned}
&\dot{n}_{CH_4,4} = \dot{a}_r \\
&\dot{n}_{H_2O,4} = R_{STCR}(\dot{n}_{CH_4,4}) \\
&\dot{n}_{H_2,5} = 3\dot{a}_r + \dot{b}_r - \dot{c}_r \\
&\dot{n}_{CO,5} = \dot{a}_r - \dot{b}_r \\
&\dot{n}_{CO_2,5} = \dot{b}_r \\
&\dot{n}_{H_2O,5} = \dot{n}_{H_2O,4} - \dot{a}_r - \dot{b}_r + \dot{c}_r \\
&\dot{n}_{O_2,12} = \dot{n}_{O_2,11} - (\dot{c}_r/2) \\
&\dot{n}_{N_2,12} = \dot{n}_{N_2,11} = (79/21).\dot{n}_{O_2,11} \\
&\dot{n}_4 = \dot{n}_{CH_4,4} + \dot{n}_{H_2O,4} \\
&\dot{n}_5 = \dot{n}_{H_2,5} + \dot{n}_{CO,5} + \dot{n}_{CO_2,5} + \dot{n}_{H_2O,5} \\
&\dot{n}_{11} = \dot{n}_{O_2,11} + \dot{n}_{N_2,11} \\
&\dot{n}_{12} = \dot{n}_{O_2,12} + \dot{n}_{N_2,12}
\end{aligned} \quad (4)$$

where the index numbers refer to numbers in Figure 1. $\dot{n}_i$ corresponds to the mole components at *i* points and $R_{STCR}$ is the steam to carbon ratio.

The extent of electrochemical reaction ($\dot{c}_r$) is defined as Equation (5):

$$\dot{c}_r = U_f \cdot (3\dot{a}_r + \dot{b}_r) \quad (5)$$

where $U_f$, $\dot{a}_r$, and $\dot{b}_r$ are the fuel utilization ratio, the extent of reforming, and shifting reactions.

$K_{shift}$ is the equilibrium constant for shifting which is obtained as Equation (6):

$$ln(K_{shift}) = -\frac{\Delta\bar{g}^0_{shift}}{\bar{R}.T_{FC,e}} = ln\left(\frac{\dot{n}_{CO_2}.\dot{n}_{H_2}}{\dot{n}_{CO}.\dot{n}_{H_2O}}\right) \quad (6)$$

The current density is calculated by Equation (7):

$$j = \frac{2 \cdot F \cdot \dot{c}_r}{N_{FC}.A_a} \quad (7)$$

where, $A_a$, $N_{FC}$, and $F$ are the effective surface area, the cell number, and Faraday constant, respectively.

Electricity ($V_c$) is generated by moving electrons along the circuit space when the equilibrium reactions occur that is obtained using Equation (8):

$$V_c = V_N - V_{loss} \quad (8)$$

where $V_N$ is the Nernst voltage which is obtained as Equation (9):

$$V_N = -\frac{\Delta\bar{g}^{\circ}}{2.F} + \frac{\bar{R}.T_{FC,e}}{2.F} ln\left(\frac{a_{H_2,e}.\sqrt{a_{O_2,e}}}{a_{H_2O,e}}\right) \quad (9)$$

$V_{loss}$ is the voltage losses and is calculated as Equation (10):

$$V_{loss} = V_{ohm} + V_{act} + V_{conc} \quad (10)$$

It is noteworthy that $V_{loss}$ includes ohmic ($V_{ohmic}$), activation ($V_{act}$), and concentration ($V_{conc}$) losses.
$V_{ohm}$ is calculated using Equations (11) to (15) [18]:

$$V_{ohm} = (R_c + \Sigma_i \rho_i \delta_i).j \quad (11)$$

$$\rho_e = \left(3.34 \times 10^4 exp(-10300/T_{FC,e})\right)^{-1} \quad (12)$$

$$\rho_a = \left(95 \times 10^6/T_{FC,e}\ exp(-1150/T_{FC,e})\right)^{-1} \quad (13)$$

$$\rho_c = \left(42 \times 10^6/T_{FC,e}\ exp(-1200/T_{FC,e})\right)^{-1} \quad (14)$$

$$\rho_{int} = \left(9.3 \times 10^6/T_{FC,e}\ exp(-1100/T_{FC,e})\right)^{-1} \quad (15)$$

where $R_c$ is the resistivity contact, ρ is the electrical resistivity of SOFC components including electrolyte (e), anode (a), cathode (c), interconnect (int), and $\delta$ is thickness of a SOFC component. These values and other information of the SOFC system are summarized in Table 1.
$V_{act}$ is the sum of activation voltages in the anode and cathode sections which is computed by Equation (16) [19].

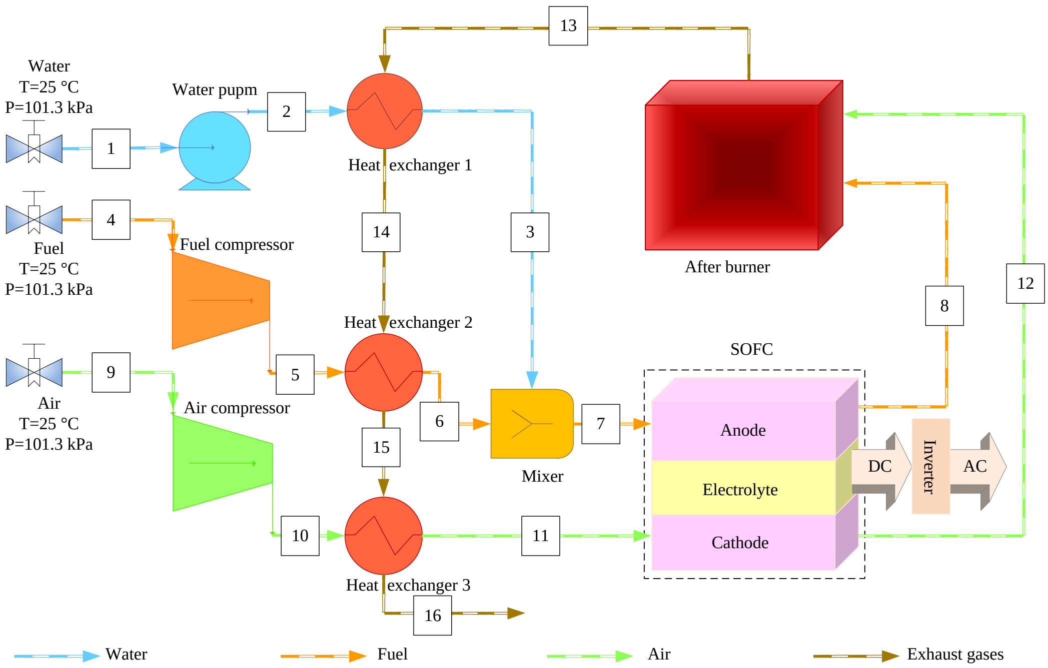


**Figure 1.** Schematic diagram of SOFC system

**TABLE 1.** Overall data of SOFC [18]

| Parameter | Value |
|---|---|
| Thickness of anode | 500 μm |
| Thickness of cathode | 50 μm |
| Thickness of electrolyte | 10 μm |
| Thickness of interconnect | 300 μm |
| Number of cells ($N_{FC}$) | 11,000 |
| Active surface area ($A_a$) | 0.01 $m^2$ |
| Temperature difference between inlet and outlet of SOFC | 100 |
| Steam to carbon ratio | 2.5 |
| SOFC DC-AC inverter efficiency ($\eta_{inv}$) | 0.97 |
| Water pump isentropic efficiency ($\eta_{is,WP}$) | 0.85 |
| Fuel compressor isentropic efficiency ($\eta_{is.FC}$) | 0.85 |
| Air compressor isentropic efficiency ($\eta_{is.AC}$) | 0.85 |

$$V_{act} = \frac{\bar{R}.T_{FC,e}}{F}.\left(sinh^{-1}\left(\frac{j}{2j_{oa}}\right)\right) + \frac{\bar{R}.T_{FC,e}}{F}.\left(sinh^{-1}\left(\frac{j}{2j_{oc}}\right)\right) \quad (16)$$

where $j_o$ is the exchange current density which is obtained for anode and cathode as Equations (17) and (18), respectively [20, 21]:

$$j_{oa} = \gamma_{anode}\left(\frac{P_{H_2}}{P_0}\right)\left(\frac{P_{H_2O}}{P_0}\right) exp\left(-\frac{E_{act,a}}{\bar{R}T_{FC,e}}\right) \quad (17)$$

$$j_{oc} = \gamma_{cathode}\left(\frac{P_{O_2}}{P_0}\right)^{0.25} exp\left(-\frac{E_{act,c}}{\bar{R}T_{FC,e}}\right) \quad (18)$$

where $\gamma$ is pre-exponential coefficient defined for anode ($\gamma_{anode}$) and cathode ($\gamma_{cathode}$). $E_{act,a}$ and $E_{act,c}$ are activation energies for anode and cathode, respectively [20, 21].

$V_{conc}$ is the sum of losses related to gas concentration occurring in the anode and cathode according to Equation (19) [22]:

$$V_{conc} = \frac{\bar{R}.T_{FC,e}}{2.F} . \left( ln\left(1 + \frac{P_{H_2}.j}{P_{H_2O}.j_{as}}\right) - ln\left(1 - \frac{j}{j_{as}}\right)\right) - \left(\frac{\bar{R}.T_{FC,e}}{2.F} . ln\left(1 - \frac{j}{j_{cs}}\right)\right) \quad (19)$$

where $j_{as}$ and $j_{cs}$ are limiting current density of anode and cathode, respectively. These quantities are calculated as Equations (20) and (21) [22]:

$$j_{as} = 2.F.P_{H_2}.D_{aeff}/\bar{R}.T_{FC,e}.\delta_a \quad (20)$$

$$j_{cs} = 4.F.P_{O_2}.D_{ceff}/\left(\left(\frac{P_{17} - P_{O_2,e}}{P_{12}}\right)\bar{R}.T_{FC,e}.\delta_c\right) \quad (21)$$

where $D_{eff}$ is the effective diffusivity which is defined for anode and cathode [23, 24].

The electrical power produced by the SOFC ($\dot{W}_C$) is calculated by Equation (22):

$$\dot{W}_C = \eta_{inv}\ (N_{FC}.j.A_a.V_c) \quad (22)$$

where $\eta_{inv}$ is the inverter efficiency introduced in Table 1.

The net electrical power is defined in Equation (23):

$$\dot{W}_{net} = \dot{W}_C - \dot{W}_{WP} - \dot{W}_{FC} - \dot{W}_{AC} \quad (23)$$

where $\dot{W}_{WP}$, $\dot{W}_{FC}$, and $\dot{W}_{AC}$ are power of pump, fuel compressor, and air compressor, respectively.

## 3. TAGUCHI DESIGN

Taguchi approach is a statistical method developed by Genichi Taguchi which is widely used in order to investigate and optimize engineering processes [25-27]. This method is utilized to study the effect of different parameters on the variance of performance characteristic that determines the appropriate operating conditions of the process by dramatically reducing the number of needed tests using orthogonal array (OA) [25, 26]. Additionally, Taguchi approach introduces an efficient and systematic procedure for specifying the optimum conditions to decrease/increase the output parameter. The steps followed in Taguchi approach are [27]:

i. Selecting the appropriate orthogonal array (OA)
ii. Running tests based on the selected OA
iii. Analyzing data and investigating the process
iv. Identifying the optimum conditions
v. Conducting the confirmation runs

Taguchi technique recommends a loss function which is converted into a signal to noise (S/N) ratio in order to compute the deviation between the experimental value and the desired value of performance characteristics. S/N ratio defines a test which proposes the best performance. S/N formulation varies with respect to the situations of the problem. Generally, there are three types of S/N used in Taguchi approach [25]. Since the aim of the present study is an investigation of power of the SOFC system, the larger-the-better S/N ratio is used in order to maximization of power [27] defined in Equation (24):

$$S/N_L = -10\ log\frac{1}{n}\left(\sum_{j=1}^{n}\frac{1}{y_j^2}\right) \quad (24)$$

where $y_i$ is the value of response obtained from the tests, $n$ is the number of trials, $i$ is the experiment number, and $j$ is trial number. The best level for each input parameter can be determined using the highest S/N values.

Another valuable analyzing tool of Taguchi approach is analysis of variance (ANOVA). The important benefit of ANOVA over S/N ratio is to statistically identify which input parameter significantly affect the outputs and how much each input parameter contributes to the outputs. The percentage of contribution of each input parameter is calculated using Equation (25):

$$Contribution\ (\%) = \frac{SS_f}{SS_T} \times 100 \quad (25)$$

where $SS_f$ is the sum of the squares for each input parameter and $SS_T$ is the total sum of the squares of all factors which are calculated using Equations (26) and (27), respectively:

$$SS_f = \sum_{j=1}^{n} n[(S/N)_{fj} - (S/N)_T]^2 \quad (26)$$

$$SS_T = \sum_{i=1}^{n}[(S/N)_i - (S/N)_T]^2 \quad (27)$$

As it was previously mentioned, the first step of Taguchi approach is the design of trials based on OA. For this purpose, firstly the considered input parameters and their levels are selected according to Table 2. Current density (j), inlet temperature of SOFC (T), and fuel utilization factor (Uf) are selected as the input parameters at five levels based on the best knowledge and experience of the authors.

According to the selected factors and their levels, the $L_{25}$ orthogonal array is proposed by default of Minitab software as shown in Table 3. Also, the electrical power as the output is presented in Table 3.

## 4. RESULTS AND DISCUSSION

### 4. 1. Validation

In order to validate the modelling of SOFC, the theoretical results of the present study were compared with the experimental results of Tao et al. [28].

**TABLE 2.** Input parameters and their levels

| Level | Input parameter | | |
|---|---|---|---|
| | j (A/m$^2$) | T (°C) | Uf |
| 1 | 5500 | 750 | 70.0% |
| 2 | 6500 | 800 | 72.5% |
| 3 | 7500 | 850 | 75.0% |
| 4 | 8500 | 900 | 77.5% |
| 5 | 9500 | 950 | 80.0% |

**TABLE 3.** $L_{25}$ orthogonal array of Taguchi approach

| Trial | j (A/m$^2$) | T (°C) | Uf | Power (kW) |
|---|---|---|---|---|
| 1 | 5500 | 700 | 75.0% | 373.3 |
| 2 | 5500 | 750 | 77.5% | 392.2 |
| 3 | 5500 | 800 | 80.0% | 396.9 |
| 4 | 5500 | 850 | 82.5% | 389.7 |
| 5 | 5500 | 900 | 85.0% | 372.4 |
| 6 | 6500 | 700 | 77.5% | 406.5 |
| 7 | 6500 | 750 | 80.0% | 431.4 |
| 8 | 6500 | 800 | 82.5% | 437.4 |
| 9 | 6500 | 850 | 85.0% | 425.2 |
| 10 | 6500 | 900 | 75.0% | 478.2 |
| 11 | 7500 | 700 | 80.0% | 425.1 |
| 12 | 7500 | 750 | 82.5% | 453.6 |
| 13 | 7500 | 800 | 85.0% | 454.7 |
| 14 | 7500 | 850 | 75.0% | 539.3 |
| 15 | 7500 | 900 | 77.5% | 526.8 |
| 16 | 8500 | 700 | 82.5% | 422.9 |
| 17 | 8500 | 750 | 85.0% | 443.4 |
| 18 | 8500 | 800 | 75.0% | 578.6 |
| 19 | 8500 | 850 | 77.5% | 578.5 |
| 20 | 8500 | 900 | 80.0% | 560.1 |
| 21 | 9500 | 700 | 85.0% | 373.7 |
| 22 | 9500 | 750 | 75.0% | 581.0 |
| 23 | 9500 | 800 | 77.5% | 603.6 |
| 24 | 9500 | 850 | 70.0% | 598.4 |
| 25 | 9500 | 900 | 82.5% | 561.2 |

The electrical power density of theoretical and experimental results versus current density is presented in Figure 2. The results indicate that there is a very good agreement between the theoretical results of the present study and experimental results of Tao et al. [28]. Therefore, the model is verified.

**4. 2. Analysis of Variance (ANOVA)** ANOVA results are presented in Table 4. Since the p-value of all input parameters are smaller than 0.05 (default error considered by Minitab software), all of them are statistically effective on the electrical power. Current density is the most significant parameter on the electrical power by 52.0% of contribution, as the results showed. It should be noted that inlet temperature of SOFC and utilization factor are the second and third parameters from effectiveness point of view. The results indicate that the contribution of inlet temperature of SOFC and utilization factor equal to 24.9 and 20.0%, respectively.

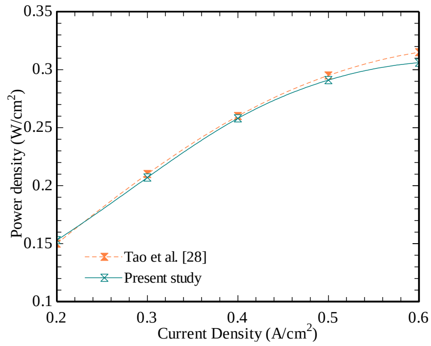


**Figure 2.** Validation of modeling of SOFC in comparison to the experimental results [28]

**TABLE 4.** ANOVA results

| Source | SS | Contribution (%) | p-value |
|---|---|---|---|
| Current density | 80426 | 52.0 | 0.000 |
| Inlet temperature of SOFC | 38562 | 24.9 | 0.000 |
| Utilization factor | 30848 | 20.0 | 0.000 |
| Error | 4833 | 3.1 | |
| Total | 154669 | 100 | |

Also, ANOVA results show that the contribution of error is 3%. This error belongs not only to the modeling but also to the un-considered parameters.

**4. 3. Effect of Parameters** The effect of current density on the electrical power is shown in Figure 3. The results indicate that the electrical power raises by increasing the current density. According to Equation (22), the electrical power has a direct relation with current density which leads to an increasing behavior of electrical power with increasing current density. It should be noted that the voltage losses raise by increasing current density. Raising voltage losses leads to reducing cell voltage. Cell voltage is in a direct relation with electrical power according to Equation (22). Therefore, it was expected that the electrical power to be reduced by increasing the current density. The effect of increasing current density overcomes the effect of decreasing the cell voltage in the studied range of current density. Hence, the electrical power enhances with increasing current density.

Figure 3 illustrates that the rate of electrical power increasing reduces by increasing current density. The reason of this phenomenon is increasing effect of voltage losses on the electrical power. Figure 4 shows the effect of inlet temperature of SOFC on the electrical power. It is evident that the electrical power enhances by increasing inlet temperature of SOFC. The rates of electrochemical reactions in fuel cell increase by raising temperature and consequently the voltage losses reduce.

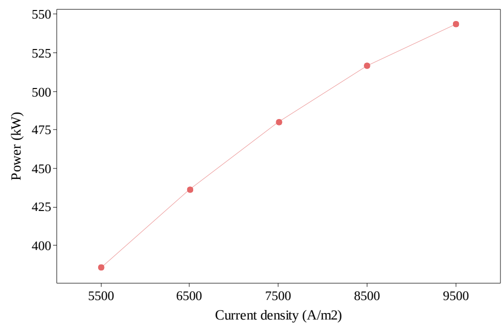


**Figure 3.** Effect of current density on the power

Decreasing voltage losses leads to increasing cell voltage. As mentioned previously, the electrical power improves by increasing cell voltage. The influence of utilization factor on the electrical power is presented in Figure 5. The electrical power reduces by increasing utilization factor, as the results shown.

**4. 4. S/N Analysis** S/N analysis is performed to optimize the output. These results are presented in Table 5. As mentioned previously, the level with highest S/N is the optimum level. Therefore, fifth level of current density, fourth level of inlet temperature of SOFC, and first level of utilization factor are the optimum condition.

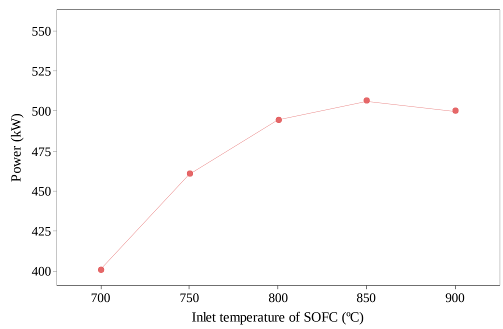


**Figure 4.** Effect of inlet temperature of SOFC on the power

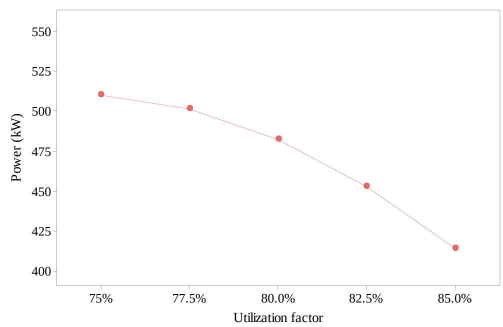


**Figure 5.** Effect of utilization factor on the power

**TABLE 5.** Results of S/N analysis

| Level | Factors | | |
|---|---|---|---|
| | Current density | Inlet temperature of SOFC | Utilization factor |
| 1 | 51.70 | 52.03 | 54.04 |
| 2 | 52.77 | 53.18 | 53.87 |
| 3 | 53.59 | 53.76 | 53.55 |
| 4 | 54.18 | 53.96 | 53.05 |
| 5 | 54.57 | 53.88 | 52.31 |
| Delta | 2.87 | 1.93 | 1.73 |
| Rank | 1 | 2 | 3 |

The electrical power at the optimum condition (i.e. current density of 9500 A/m$^2$, inlet temperature of SOFC of 850 °C, and utilization factor of 75%) equals to 644.3 kW using theoretical model. One of the valuable tools of Taguchi approach is to predict the output at the desired condition. The electrical power is obtained 615.6 kW at the optimum state using prediction tool of Taguchi approach. This value has 4.5% error in comparison with EES code.

It should be noted that the ranking of the input parameters from standpoint of significance is as following: current density, inlet temperature of SOFC, and utilization factor. It is noteworthy that the sequence of the ranking is in agreement with ANOVA results.

## 5. CONCLUSIONS

Several researches have been performed in recent years on the solid oxide fuel cells as new technologies. In the present study, investigation and optimization of an SOFC system was performed using Taguchi approach. Firstly, the modeling of SOFC is carried out and validated in comparison with the experimental data. The main corresponding conclusions can be summarized as follows:

- The current density is the most significant parameter on the electrical power followed by the inlet temperature of SOFC and the utilization factor.
- All of considered parameters are statistically effective on the electrical power.
- The electrical power enhances by increasing the current density and the inlet temperature of SOFC whiles it reduces by raising the utilization factor.
- 9500 A/m$^2$ of current density, 850 °C of inlet temperature of SOFC, and 75% of utilization factor is the optimum condition in order to achieve the highest electrical power according to the signal to noise ratio (S/N) analysis.
- The electrical power is 644.3 kW using theoretical model at the optimum state whiles this value is

615.6 kW using prediction tool of Taguchi approach. This prediction has a 4.5% error.

## 6. REFERENCES


1. Carrette, L., Friedrich, K.A. and Stimming, U., "Fuel cells–fundamentals and applications". ***Fuel Cells***, Vol. 1, No. 1, (2001), 5-39.
2. Afshari, E. and Mollayi Barzi, A., "Dynamic response analysis of the planar and tubular solid oxide fuel cells to the inlet air mass flow rate variation". ***International Journal of Engineering, Transactions B: Applications***, Vol. 28, No. 5, (2015), 794-801.
3. Shokati, N., Ranjbar, F. and Mohammadkhani, F., "Comparison of single-stage and two-stage tubular sofc-gt hybrid cycles: energy and exergy viewpoints". ***International Journal of Engineering, Transactions A: Basics***, Vol. 28, No. 4, (2015), 618-626.
4. Bove, R. and Ubertini, S. eds., "Modeling solid oxide fuel cells: methods, procedures and techniques". ***Springer Science & Business Media***, (2008).
5. Wereszczak, A., Lara-Curzio, E. and Bansal, N.P. eds., "Advances in solid oxide fuel cells II (Vol. 308)". ***John Wiley & Sons***, (2009).
6. Huang, K. and Goodenough, J.B., "Solid oxide fuel cell technology: principles, performance and operations". ***Elsevier***, (2009).
7. Ebrahimi, M. and Moradpoor, I., "Combined solid oxide fuel cell, micro-gas turbine and organic Rankine cycle for power generation (SOFC–MGT–ORC)". ***Energy Conversion and Management***, Vol. 116, (2016), 120-133.
8. Bang-Møller, C., Rokni, M. and Elmegaard, B., "Exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system". ***Energy***, Vol. 36, No. 8, (2011), 4740-4752.
9. Ozcan, H. and Dincer, I., "Performance evaluation of an SOFC based trigeneration system using various gaseous fuels from biomass gasification". ***International Journal of Hydrogen Energy***, Vol. 40, No. 24, (2015), 7798-7807.
10. Subarmono, S., Saptoadi, H., Musabbikhah, M. and Arif Wibisono, M., "Modelling and optimisation of coconut shell drying and carbonisation using multi-response taguchi method with multi-response signal-to-noise procedure". ***International Journal of Engineering, Transactions C: Aspects***, Vol. 31, No. 3, (2018), 464-472.
11. Khalkhali, A. and Daghighi, S., "Optimum design of a coir fiber biocomposite tube reinforced with nano silica and nano clay powder". ***International Journal of Engineering, Transactions C: Aspects***, Vol. 30, No. 12, (2017), 1894-1902.
12. Janani, M., Prakash, D., Harini, E. and Harish, T., "Enhancement of heat transfer over a double forward facing step with square obstacle through taguchi's optimization technique". ***International Journal of Engineering, Transactions B: Applications***, Vol. 30, No. 8, (2017), 1253-1259.
13. Bharat, K.S., Mukund, S.A. and Ramrao, T.B., "Analysis and optimization of diesel engine working on biodiesel using taguchi method". ***International Journal of Current Trends in Science and Technology***, Vol. 8, No. 1, (2018), 72-75.
14. Chen, W.H., Huang, S.R. and Lin, Y.L., "Performance analysis and optimum operation of a thermoelectric generator by Taguchi method". ***Applied Energy***, Vol. 158, (2015), 44-54.
15. Balki, M.K., Sayin, C. and Sarıkaya, M., "Optimization of the operating parameters based on Taguchi method in an SI engine used pure gasoline, ethanol and methanol". ***Fuel***, Vol. 180, (2016), 630-637.
16. Pandey, N., Murugesan, K. and Thomas, H.R., "Optimization of ground heat exchangers for space heating and cooling applications using Taguchi method and utility concept". ***Applied Energy***, Vol. 190, (2017), 421-438.
17. Chan, S.H., Ho, H.K. and Tian, Y., "Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant". ***Journal of Power Sources***, Vol. 109, No. 1, (2002), 111-120.
18. Ranjbar, F., Chitsaz, A., Mahmoudi, S.M.S., Khalilarya, S. and Rosen, M.A., "Energy and exergy assessments of a novel trigeneration system based on a solid oxide fuel cell". ***Energy Conversion and Management***, Vol. 87, (2014), 318-327.
19. Kim, J.W., Virkar, A.V., Fung, K.Z., Mehta, K. and Singhal, S.C., "Polarization effects in intermediate temperature, anode-supported solid oxide fuel cells". ***Journal of the Electrochemical Society***, Vol. 146, No. 1, (1999), 69-78.
20. Colpan, C.O., Hamdullahpur, F., Dincer, I. and Yoo, Y., "Effect of gasification agent on the performance of solid oxide fuel cell and biomass gasification systems". ***International Journal of Hydrogen Energy***, Vol. 35, No. 10, (2010), 5001-5009.
21. Campanari, S. and Iora, P., "Definition and sensitivity analysis of a finite volume SOFC model for a tubular cell geometry". ***Journal of Power Sources***, Vol. 132, No. 1, (2004), 113-126.
22. Chan, S.H., Low, C.F. and Ding, O.L., "Energy and exergy analysis of simple solid-oxide fuel-cell power systems". ***Journal of Power Sources***, Vol. 103, No. 2, (2002), 188-200.
23. Akkaya, A.V., "Electrochemical model for performance analysis of a tubular SOFC". ***International Journal of Energy Research***, Vol. 31, No. 1, (2007), 79-98.
24. Chan, S.H., Khor, K.A. and Xia, Z.T., "A complete polarization model of a solid oxide fuel cell and its sensitivity to the change of cell component thickness". ***Journal of Power Sources***, Vol. 93, No. 1, (2001), 130-140.
25. Kumar, R.S., Sureshkumar, K. and Velraj, R., "Optimization of biodiesel production from Manilkara zapota (L.) seed oil using Taguchi method". ***Fuel***, Vol. 140, (2015), 90-96.
26. Kıvak, T., "Optimization of surface roughness and flank wear using the Taguchi method in milling of Hadfield steel with PVD and CVD coated inserts". ***Measurement***, Vol. 50, (2014), 19-28.
27. Selvaraj, D.P., Chandramohan, P. and Mohanraj, M., "Optimization of surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using Taguchi method". ***Measurement***, Vol. 49, (2014), 205-215.
28. Tao, G., Armstrong, T. and Virkar, A., "Intermediate temperature solid oxide fuel cell (IT-SOFC) research and development activities at MSRI". In Nineteenth annual ACERC&ICES Conference, Utah, (2005).
29. Carrette, L., Friedrich, K.A. and Stimming, U., "Fuel cells–fundamentals and applications". ***Fuel Cells***, Vol. 1, No. 1, (2001), 5-39.
30. Afshari, E. and Mollayi Barzi, A., "Dynamic response analysis of the planar and tubular solid oxide fuel cells to the inlet air mass flow rate variation". ***International Journal of Engineering, Transactions B: Applications***, Vol. 28, No. 5, (2015), 794-801.
31. Shokati, N., Ranjbar, F. and Mohammadkhani, F., "Comparison of single-stage and two-stage tubular sofc-gt hybrid cycles: energy and exergy viewpoints". ***International Journal of Engineering, Transactions A: Basics***, Vol. 28, No. 4, (2015), 618-626.
32. Bove, R. and Ubertini, S. eds., "Modeling solid oxide fuel cells: methods, procedures and techniques". ***Springer Science & Business Media***, (2008).

33. Wereszczak, A., Lara-Curzio, E. and Bansal, N.P. eds., "Advances in solid oxide fuel cells II (Vol. 308)". ***John Wiley & Sons***, (2009).

34. Huang, K. and Goodenough, J.B., "Solid oxide fuel cell technology: principles, performance and operations". ***Elsevier***, (2009).

35. Ebrahimi, M. and Moradpoor, I., "Combined solid oxide fuel cell, micro-gas turbine and organic Rankine cycle for power generation (SOFC–MGT–ORC)". ***Energy Conversion and Management***, Vol. 116, (2016), 120-133.

36. Bang-Møller, C., Rokni, M. and Elmegaard, B., "Exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system". ***Energy***, Vol. 36, No. 8, (2011), 4740-4752.

37. Ozcan, H. and Dincer, I., "Performance evaluation of an SOFC based trigeneration system using various gaseous fuels from biomass gasification". ***International Journal of Hydrogen Energy***, Vol. 40, No. 24, (2015), 7798-7807.

38. Subarmono, S., Saptoadi, H., Musabbikhah, M. and Arif Wibisono, M., "Modelling and optimisation of coconut shell drying and carbonisation using multi-response taguchi method with multi-response signal-to-noise procedure". ***International Journal of Engineering, Transactions C: Aspects***, Vol. 31, No. 3, (2018), 464-472.

39. Khalkhali, A. and Daghighi, S., "Optimum design of a coir fiber biocomposite tube reinforced with nano silica and nano clay powder". ***International Journal of Engineering, Transactions C: Aspects***, Vol. 30, No. 12, (2017), 1894-1902.

40. Janani, M., Prakash, D., Harini, E. and Harish, T., "Enhancement of heat transfer over a double forward facing step with square obstacle through taguchi's optimization technique". ***International Journal of Engineering, Transactions B: Applications***, Vol. 30, No. 8, (2017), 1253-1259.

41. Bharat, K.S., Mukund, S.A. and Ramrao, T.B., "Analysis and optimization of diesel engine working on biodiesel using taguchi method". ***International Journal of Current Trends in Science and Technology***, Vol. 8, No. 1, (2018), 72-75.

42. Chen, W.H., Huang, S.R. and Lin, Y.L., "Performance analysis and optimum operation of a thermoelectric generator by Taguchi method". ***Applied Energy***, Vol. 158, (2015), 44-54.

43. Balki, M.K., Sayin, C. and Sarıkaya, M., "Optimization of the operating parameters based on Taguchi method in an SI engine used pure gasoline, ethanol and methanol". ***Fuel***, Vol. 180, (2016), 630-637.

44. Pandey, N., Murugesan, K. and Thomas, H.R., "Optimization of ground heat exchangers for space heating and cooling applications using Taguchi method and utility concept". ***Applied Energy***, Vol. 190, (2017), 421-438.

45. Chan, S.H., Ho, H.K. and Tian, Y., "Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant". ***Journal of Power Sources***, Vol. 109, No. 1, (2002), 111-120.

46. Ranjbar, F., Chitsaz, A., Mahmoudi, S.M.S., Khalilarya, S. and Rosen, M.A., "Energy and exergy assessments of a novel trigeneration system based on a solid oxide fuel cell". ***Energy Conversion and Management***, Vol. 87, (2014), 318-327.

47. Kim, J.W., Virkar, A.V., Fung, K.Z., Mehta, K. and Singhal, S.C., "Polarization effects in intermediate temperature, anode-supported solid oxide fuel cells". ***Journal of the Electrochemical Society***, Vol. 146, No. 1, (1999), 69-78.

48. Colpan, C.O., Hamdullahpur, F., Dincer, I. and Yoo, Y., "Effect of gasification agent on the performance of solid oxide fuel cell and biomass gasification systems". ***International Journal of Hydrogen Energy***, Vol. 35, No. 10, (2010), 5001-5009.

49. Campanari, S. and Iora, P., "Definition and sensitivity analysis of a finite volume SOFC model for a tubular cell geometry". ***Journal of Power Sources***, Vol. 132, No. 1, (2004), 113-126.

50. Chan, S.H., Low, C.F. and Ding, O.L., "Energy and exergy analysis of simple solid-oxide fuel-cell power systems". ***Journal of Power Sources***, Vol. 103, No. 2, (2002), 188-200.

51. Akkaya, A.V., "Electrochemical model for performance analysis of a tubular SOFC". ***International Journal of Energy Research***, Vol. 31, No. 1, (2007), 79-98.

52. Chan, S.H., Khor, K.A. and Xia, Z.T., "A complete polarization model of a solid oxide fuel cell and its sensitivity to the change of cell component thickness". ***Journal of Power Sources***, Vol. 93, No. 1, (2001), 130-140.

53. Kumar, R.S., Sureshkumar, K. and Velraj, R., "Optimization of biodiesel production from Manilkara zapota (L.) seed oil using Taguchi method". ***Fuel***, Vol. 140, (2015), 90-96.

54. Kıvak, T., "Optimization of surface roughness and flank wear using the Taguchi method in milling of Hadfield steel with PVD and CVD coated inserts". ***Measurement***, Vol. 50, (2014), 19-28.

55. Selvaraj, D.P., Chandramohan, P. and Mohanraj, M., "Optimization of surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using Taguchi method". ***Measurement***, Vol. 49, (2014), 205-215.

56. Tao, G., Armstrong, T. and Virkar, A., "Intermediate temperature solid oxide fuel cell (IT-SOFC) research and development activities at MSRI". In Nineteenth annual ACERC&ICES Conference, Utah, (2005).

# Thermodynamic Investigation and Optimization of a Power Generation System Based Solid Oxide Fuel Cell Using Taguchi Approach

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چکیده

پیل سوختی توسط واکنش‌های الکتروشیمیایی، انرژی شیمیایی را مستقیماً به توان الکتریکی تولید می‌نماید. پیل سوختی اکسید جامد (SOFC) یکی از پیل‌های سوختی دما بالا می‌باشد که آینده‌ی روشنی را از نقطه نظر تولید توان ارائه می‌نماید. در تحقیق حاضر، مطالعه و بهینه‌سازی یک سیستم SOFC توسط روش تاگوچی پس از صحت‌سنجی مدل ارائه شده در قیاس با نتایج تجربی، در دستور کار قرار می‌گیرد. چگالی جریان، دمای ورودی پیل سوختی اکسید جامد و ضریب مصرف سوخت به عنوان پارامترهای ورودی و توان الکتریکی به عنوان پاسخ خروجی در نظر گرفته می‌شوند. نتایج آنالیز واریانس (ANOVA) نشان می‌دهد که چگالی جریان با میزان مشارکت ۵۲٪، موثرترین پارامتر بر روی توان الکتریکی می‌باشد و پس از آن دمای ورودی پیل سوختی اکسید جامد و ضریب مصرف سوخت با میزان مشارکت‌های به ترتیب ۲۵ و ۲۰٪ در رتبه‌های بعدی قرار می‌گیرند. توان الکتریکی با افزایش چگالی جریان و دمای ورودی پیل سوختی اکسید جامد و با کاهش ضریب مصرف سوخت، بهبود می‌یابد. آنالیز نسبت سیگنال به نویز (S/N) مشخص می‌کند که چگالی جریان $9500\ A/m^2$، دمای ورودی پیل سوختی اکسید جامد $850\ °C$ و ضریب مصرف سوخت ۷۵٪ حالت بهینه برای دست‌یابی به حداکثر توان الکتریکی می‌باشد. نتایج نشان می‌دهد که توان الکتریکی در حالت بهینه 644.3 kW می‌باشد.

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