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Fuzzy logic modeling of performance proton exchange membrane fuel cell with spin method coated with carbon nanotube

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ABSTRACT

In this study, performance of proton exchange membrane (PEM) fuel cell was experimentally investigated and modeled with Rule-Based Mamdani-Type Fuzzy (RBMTF) modeling technique. Coating on the anode side of the membrane of PEM fuel cell was accomplished with the spin method by using carbon nanotube (CNT). This fuel cell performances at 20 °C, 40 °C, 60 °C were investigated experimentally and the best performance was determined and benefiting from experimental data, modeled with RBMTF method. Input parameters are; temperature (T), time (s), voltage density (V/cm^2) and current density (A/cm^2); output parameter power density (W/cm^2) were described by RBMTF if-then rules. Numerical parameters of input and output variables were fuzzificated as linguistic variables: Very Very Low (L_1), Very Low (L_2), Low (L_3), Negative Medium (L_4), Medium (L_5), Positive Medium (L_6), High (L_7), Very High (L_8) and Very Very High (L_9) linguistic classes. With the linguistic variables used, 81 rules were obtained for this system. The comparison between experimental data and RBMTF is done by using statistical methods. The coefficient of multiple determination (R^2) for power density of uncoated PEM and with CNT (20 °C) is 98.88%, power density of 20 °C, 40 °C and 60 °C temperatures is 97.12%. 80 values were obtained by RBMTF technique at 20 °C for uncoated PEM and with CNT. During discharge for 20 °C uncoated PEM for experimental power density maximum 0.021 Watt/cm^2 and uncoated PEM for fuzzy model maximum 0.0205 Watt/cm^2. The actual values and RBMTF results indicated that RBMTF can be successfully used in PEM fuel cell. Performance tests of the system were not done for intermediate values which were estimated with RMBTF. 78 values at 30 °C and 50 °C which are not obtained from experimental work for power density are predicted by fuzzy logic method.

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Nomenclature

V/cm^2	Voltage Density
A/cm^2	Current Density
W/cm^2	Power Density
s	Time

Introduction

Increase in world population, industrialization and technological advances have led to a rapid increase in energy consumption. In the fossil fuels, used to meet the energy needs, many problems have come across. These problems can be listed as; fossil fuel reserves dwindling and having the possibility to be drained away in near future and toxic gases caused by the burning of fuels resulting adverse environmental effects. Therefore, to meet the energy needs with clean and renewable energy sources has become mandatory [1]. Fuel cells are one of those energy sources. Fuel cells, in particular to be working with the most abundant hydrogen elements in nature and having only water as waste product, besides having the efficiency value that can not be underestimated all up to %70, is almost making it an ideal alternative energy source [2]. Non-greenhouse effect of carbon dioxide to produce hydrogen for the particular application has increased gradually over the last thirty years and has become more researched various aspects. Hydrogen does not cause environmental pollution from conventional energy sources and different as almost to be an endless source of energy is seen as the energy source of the future [3].

Fuel cells are the conversion technologies that are obtained by the by the electrochemical reaction between oxygen and hydrogen and electricity; can reach up to high efficiencies; clean, unharmful to the environment. Fuel cells are continuously translating fuel's chemical energy into electricity in the electrolyte system. Without using a boiler or a turbine, electric power is produced using only chemicals. Water and heat are obtained as output and minimum emissions in particular enables the fuels cells advantageous [4]. The most significant element of the proton exchange fuel cells is the polymeric membrane that has the property of proton conduction. The studies related to the development of polymeric membranes are the primary studies that are seen among the literature about fuel cells. Due to the high price and the lack of variety of the membranes used today, the studies about developing alternate membranes has been increased. The membranes used in Proton Exchange Fuel Cells must have the following qualities; proton permeability, impermeability for water, fuel (hydrogen or methanol), oxygen and other gases in air, high mechanical strength, high thermal and chemical resistance in long-term use, safe and cheap to be used in a technologically wide range [5]. Thus, improved membrane performance is very important. One of the methods that are used to determine the effects of the parameters to membrane performance is Fuzzy Logic Method.

Fuzzy set theory which formed the basis of fuzzy logic, as an alternative to classical set theory, was presented by L.A. Zadeh. In the fuzzy set theory, the transition between membership to nonmember ship is done progressively. This case provides powerful and meaningful tools for the measurement of uncertainty as well as provides the vague concept to be represented in a meaningful way that are expressed in natural language. It is now widely used in statistical or mathematical methods for uncertainty in the event examined in engineering and related assumptions about the events are made and pattern is established; however, for cases of non-random uncertainty does not suit the use of statistical or mathematical methods, and these methods are inadequate for such cases. Such non-random uncertainties are identified and modeled as fuzzy [6].

When the literature is investigated, the different studies on fuel cells are seen. Some studies which aimed at improving the membrane performance among these studies are presented below. Ata and Dincer [7–9] studied about Rule-based Mamdani-type fuzzy (RBMTF) modeling of performance proton exchange membrane fuel cell with CNT. They noted that RBMTF can be successfully used for the specification PEM performances with coating CNT. Sarıdemir ve Erşan [10] used Dowex Marathon C Type ion changing resin for membrane production that can be obtained more cheaply than traditional resin and investigated the effects of two different support materials to cell voltages, in their study. As a result, they have seen that the resin particle diameters used in membrane construction are not homogenous and the lack of resin density per unit area effects the cell efficiency and they obtained acceptable voltage values by silicon-supported membrane–electrode pairs. Devrim et al. [11] prepared composite membranes that has Nafion/TiO_2 containing different ratios of TiO_2. They studied the effect of the amount of TiO_2 used on PEM fuel cell performances. They concluded that, the performances of membranes with TiO_2 is higher than the membranes with Nafion. Dincer et al. [12] examined the performance of the PEM fuel cell membrane experimentally by coating its anode side with YSZ + SDC + NaCaNiBO and electrospin method. They stated that when PEM fuel cell membrane is coated with YSZ + SDC + NaCaNiBO in energy production tests, the working time for current density, voltage density and power density increases according to the pre-coated membrane.

Kim et al. [13] examined an electrical modeling of the fuel cell generation system. They used fuzzy logic controller to overcome inherent disadvantages such as uncontrollable large overshoot and large current ripple. They noted that fuzzy controller is very effective in output control and desired operating point operation, which in turn offers high system stability and performance. Tong et al. [14] studied about 1 kW PEM fuel cell unit and develops the models of stack voltage, cathode flow, anode flow. They proposed that the power demand of the external load can be provided by the fuel cell stack under the control of a real-time simplified variable universe fuzzy controller. Gao et al. [15] examined a fuel cell hybrid bus which is equipped with a fuel cell system and described an energy management strategy based on fuzzy logic. They proposed that fuzzy logic was developed and implemented to manage the energy flow for complex system of power train.

Benchouia et al. [16] examined 1.2 W PEM fuel cell unit and stack voltage and stack power models. They used fuzzy logic controller to control the voltage of at the presence fluctuations. They simulated PEM fuel cell with MATLAB Simulink and compared with a traditional PID controller. They stated that good control effects can be achieved by using the adaptive fuzzy control system with simulation results. Hemi et al. [17] studied about fuzzy logic power management strategy for implement in a hybrid vehicle with multiple power sources. They proposed that fuzzy logic controller can satisfy the power requirement for the unknown driving cycles and achieve the power distribution among various power source. Silva et al. [18] studied about the prediction of the output voltage reduction caused by degradation during nominal operating condition of PEM fuel cell stack. They used Adaptive Neuro-Fuzzy Inference System based methodology for prediction of time series. They reached that ANFIS model can efficiently predict the behavior of the PEM fuel cell with simulation results. Hu et al. [19] used the fuzzy logic for coolant circuit modeling PEM fuel cell. They analyzed established model and fuzzy controllers and they reached that fuzzy controller with integrator can effectively control the PEM fuel cell temperature and the inlet coolant temperature within their objective working ranges.

In this study, different from the other studies, PEM fuel cell membrane performance experimentally investigated during discharge and the fuzzy logic method is used to evaluate the performance of carbon nanotubes coated PEM fuel cell membrane. Performance parameters are; temperature, time, voltage density, the current density and power density. The study contains; the fuzzification of the input variables, the creation of 9 fuzzy sets with linguistic variables, the rule base formation and output values obtained by Rule based Mamdani type fuzzy model technique calculations and comparison of experimental results with these output values. These results were compared using multiple coefficient of determination methods, also the results that are not performed in this experimental study were estimated with the fuzzy logic model.

The main objective of this study is to provide a fuzzy logic model and to state that it is possible to evaluate the performance of carbon nanotubes coated PEM fuel cell membrane with this model.

Materials and methods

In this study, with an area of 2 × 2 cm^2 PEM fuel cell membrane has been coated with CNT by spin method. PEM fuel cell performances for the coated and uncoated membranes during discharge has been investigated experimentally for 20 °C. The membrane coating has 2.5 mg weight. Also, PEM fuel cell performances at 20 °C, 40 °C and 60 °C has been investigated experimentally during discharge. With the experimental data obtained a fuzzy logic model has been created.

Fuzzy logic aims at modeling human thinking and reasoning and at applying the model to problems according to needs. It tries to equip computers with the ability to process special data of humans and to work by making use of their experiences and insights. When human logic solves problems, it creates verbal rules such as “if <event realized> is this, the <result> is that”. Fuzzy logic tries to adapt these verbal rules and the human ability to make decisions to machines/computers. It uses verbal variables and terms together with verbal rules. Verbal rules and terms used in the human decision-making process are fuzzy rather than precise [20].

A fuzzy process consists of three parts. These units are respectively; Fuzzification Unit, rule processing unit, and defuzzifier unit and output informations. In this layout, fuzzification unit, comes into play as the first unit of the fuzzy processing system. Information entered into this unit as definitive results or feedback form is fuzzificated here by a scale change. In other words; a membership value assigned to each of these data is converted to a linguistic structure, and than they are sent to the rule processing unit. Information entering the rule processing unit are in a way combined with such rules like “if … else … and“, stored in rules-based processing unit. Logical propositions mentioned herein may be established also with the numerical values according to the nature of the problem. In the final step; results obtained using logical decision propositions according to the structure of the problem is sent to the defuzzifier unit. In the fuzzy sets relations sent to defuzzifier units, each fuzzy information is converted into real number with scale change [21].

A fuzzy model expresses a complex system in the form of fuzzy implications. Mamdani model can be built by using these implications (linguistic relationships) and observed data. The Mamdani-based fuzzy models use excessive number of rules for system modeling. Let X be input (regression) matrix and g an output vector defined as Eqs. (1) and (2).

$$X = [x_1, \ldots, x_2]^T = \begin{bmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \\ \vdots & \vdots \\ x_{n1} & x_{n2} \end{bmatrix} \tag{1}$$

$$g = [g_1, \ldots, g_n] \tag{2}$$

where upper script T denotes the transpose. In the Mamdani fuzzy model, both the antecedent and consequent are fuzzy propositions. A general form of linguistic fuzzy if-then rule is given as Eq. (3).

$$R_i : \textit{if } x \text{ is } A_i \text{ then } y \text{ is } B_i,\ i = 1,\ 2, \ldots,\ K \tag{3}$$

where Ri is the rule number, Ai and Bi are the fuzzy sets, x is the antecedent variable representing the input in the fuzzy system, and y is the consequent variable related to the output of the fuzzy system. The membership function, μa(x) is defined as the fuzzy subset a in the universe of discourse, x. The triangular membership function can be shown as Eq. (4) [22].

$$\mu_a(x) = \begin{cases} (x-a)/(b-a) & \textit{if } a \le x \le b \\ (x-c)/(b-c) & \textit{if } b \le x \le c \\ 0; & \text{otherwise} \end{cases} \tag{4}$$

The triangular fuzzy membership functions is defined by (a, b, and c), where a and c represent the minimum and maximum values, respectively, and b represents the most likely value are shown in Fig. 1.

Defuzzification is the process of taking the fuzzy outputs and converting them to a single or crisp output value. This process may be performed by any one of several defuzzification methods. Some common methods of defuzzification

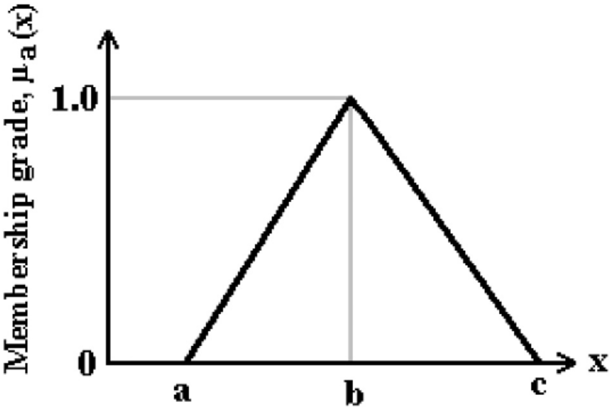

Fig. 1 – Construction of membership function.

include the max or mean-max membership principles, the center-of-gravity method (centroid-COG), and the weighted-average method. If C is the fuzzy set in question and C can be integrated, then the defuzzified value of C by this method is Eq. (5).

$$z^* = \frac{\int_a^b zC(z)dz}{\int_a^b C(z)dz} \tag{5}$$

where [a, b] is an interval containing the support of C. This kind of defuzzification determines z* point as the middle of area [23].

The aim of this study, with the aid of experimental data, performance of PEM fuel cell were modeled with RBMTF modeling technique. RBMTF was designed using MATLAB fuzzy logic toolbox in Windows 8. General structure of the four-input, one-output RBMTF model developed is given in Fig. 2. This model is constructed into RBMTF using input, time (t), voltage density (Volt/cm^2), current density (Ampere/cm^2), temperature (T) and output parameter power density (Watt/cm^2) described by RBMTF if-then rules. The fuzzy triangular membership functions for the four input variables are shown in Figs. 3a–d, respectively. Similarly; the graph showing fuzzy triangular membership functions for the output variable, is given in Fig. 4.

In this study, structure of the fuzzy model of rule-based mamdani-type fuzzy modeling of performance anode side of PEM fuel cell with spin method coated with CNT is illustrates in Fig. 5. Numerical parameters of input and output variables were fuzzificated as linguistic variables. Very very low (L_1), very low (L_2), low (L_3), negative medium (L_4), medium (L_5), positive medium (L_6), high (L_7), very high (L_8) and very very high (L_9) as shown Table 1.

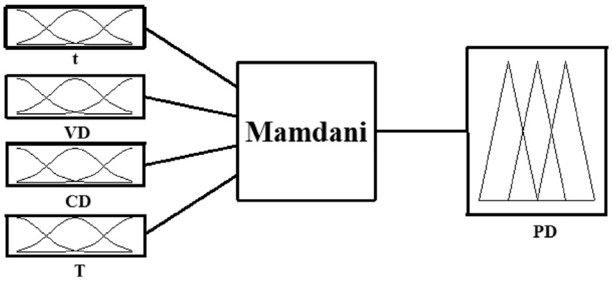

Fig. 2 – Designed RMBTF structure.

The most important factor that affects the performance of the fuzzy logic system is the number of the rules and their accuracy. With the linguistic variables used 81 rules were obtained for this system. Some of the rules of RBMTF for W/cm^2 was given in Table 2. Fuzzy membership functions in analytical form are expressed in Eqs. 6–10 for Voltage Density (VD), Current Density (CD), T, t and Power Density (PD) for this study.

$$VD_5(x) = \begin{cases} 0 & ;\ x \le 0.102 \\ (x - 0.102)/0.001375 & \textit{if}\ \ 0.102 \le x \le 0.103 \\ (0.104 - x)/0.001375 & \textit{if}\ \ 0.103 \le x \le 0.104 \\ 0 & ;\ x \ge 0.104 \end{cases} \tag{6}$$

$$CD_5(x) = \begin{cases} 0 & ;\ x \le 0.032 \\ (x - 0.032)/0.00125 & \textit{if}\ \ 0.032 \le x \le 0.033 \\ (0.034 - x)/0.00125 & \textit{if}\ \ 0.033 \le x \le 0.034 \\ 0; & ;\ x \ge 0.034 \end{cases} \tag{7}$$

$$T_5(x) = \begin{cases} 0 & ;\ x \le 33 \\ (x - 33)/4.44 & \textit{if}\ \ 33 \le x \le 37 \\ (42 - x)/4.44 & \textit{if}\ \ 37 \le x \le 42 \\ 0 & ;\ x \ge 42 \end{cases} \tag{8}$$

$$t_5(x) = \begin{cases} 0 & ;\ x \le 136 \\ (x - 136)/42.2 & \textit{if}\ \ 136 \le x \le 179 \\ (221 - x)/42.2 & \textit{if}\ \ 179 \le x \le 221 \\ 0 & ;\ x \ge 221 \end{cases} \tag{9}$$

$$PD_5(x) = \begin{cases} 0 & ;\ x \le 0.020 \\ (x - 0.020)/0.001 & \textit{if}\ \ 0.0201 \le x \le 0.0209 \\ (0.0210 - x)/0.001 & \textit{if}\ \ 0.0209 \le x \le 0.0210 \\ 0 & ;\ x \ge 0.0210 \end{cases} \tag{10}$$

Results and discussion

Two electrodes as anodes and cathodes are the major components of PEM fuel cells. These are separated from each other with the polymer electrolyte membrane. Both electrodes are covered with a thin layer of a platinum catalyst on one edge. Hydrogen as a fuel is fed from the edge of the anode of the fuel cell. It dissociates into free electrons and protons in the presence of platinum catalyst at the anode. The free electrons is used in outer loop and form an electrical current. The protons pass through the polymer electrolyte membrane moves toward the cathode, in the cathode electrons and protons combine with the oxygen from the air to form pure water and heat. The most important part of PEM fuel cells are polymeric membranes with proton conduction properties. Membrane in the fuel cells is to transmit protons from the anode to the cathode region with the highest speed. The polymer electrolyte to be used in the membrane in fuel cell must allow proton transmission as well as the absence of electronic conductivity is required to avoid short circuits. Also the membrane must allow the passage of the fuel [24].

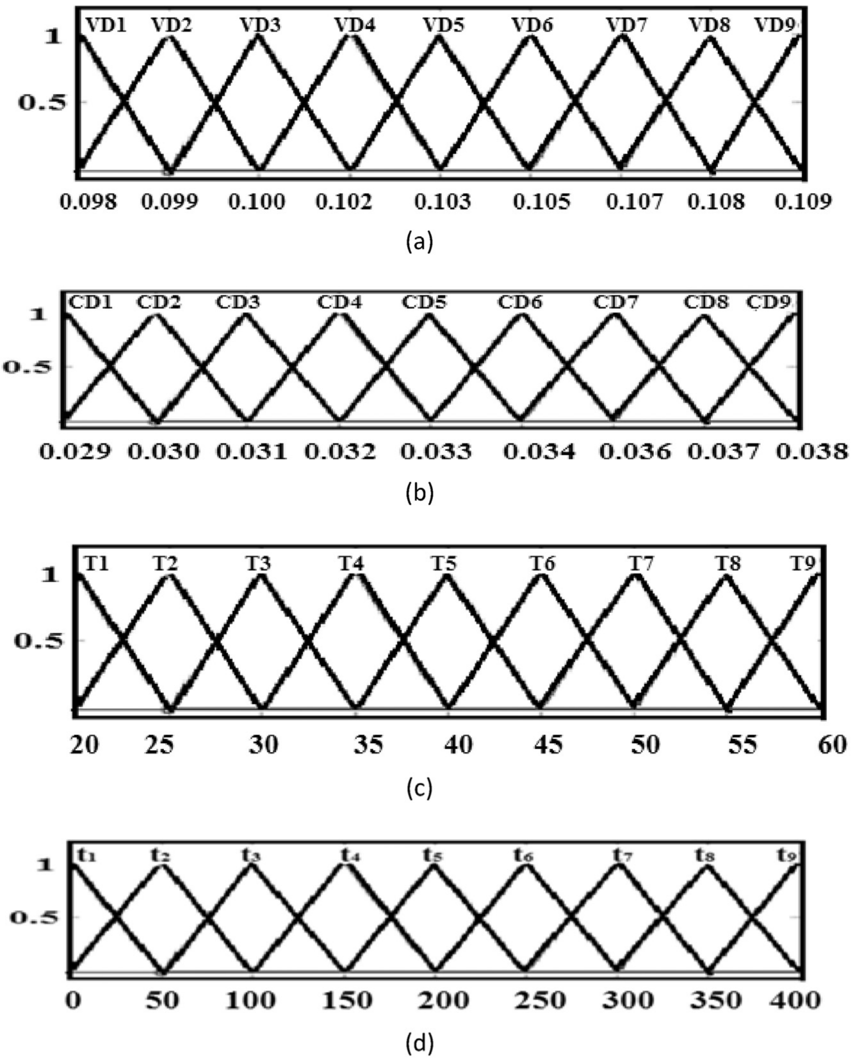

Fig. 3 – Fuzzy membership functions for four input variables. (a) VD fuzzy set graphic; (b) CD fuzzy set graphic; (c) T fuzzy set graphic; (d) t fuzzy set graphic.

The aim of this study with the aid of experimental data, PEM performances with coating carbon nanotube were modeled with RBMTF modeling technique. In the developed RBMTF system, outlet parameter power density was determined using inlet parameters t, voltage density, current density and T. Hereafter the rules, which are used to detect the behavior of the fuzzy logic controller and the relationship between system's input and output, are determined. As a result of these rules, every value obtained from the experimental study is also determined by fuzzy logic too.

Figs. 6–8 shows comparison of experimental data with RBMTF variation of time, voltage density, current density of power density values respectively for 20 °C. 80 values were obtained by RBMTF technique at 20 °C for uncoated PEM and with CNT. From a comparison of the experimental results with the results of the fuzzy logic study, one can see that the results are quite compatible (Figs. 6–8).

The results of Figs. 6–8 are summarized as follows:

- ➢ The power density values of uncoated PEM is more higher during discharge. The power density value for uncoated

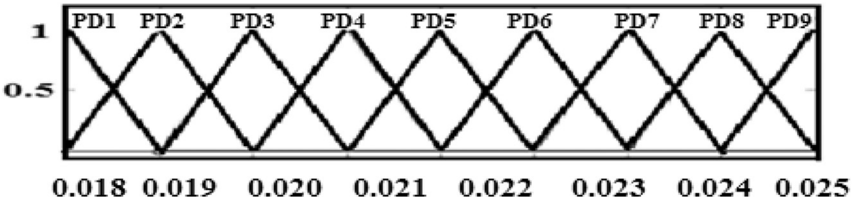

Fig. 4 – Fuzzy membership function for output variable: PD fuzzy set graphic.

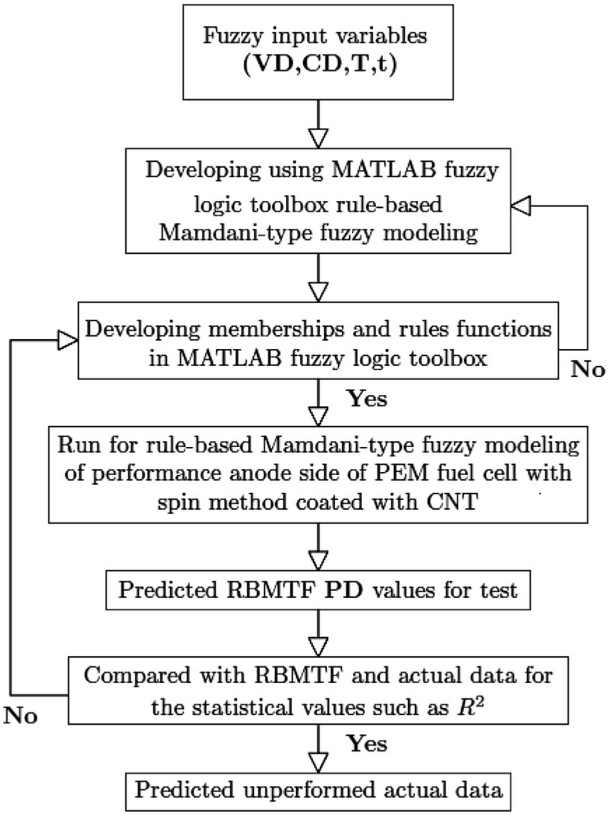

Fig. 5 – Structure of the fuzzy model of rule-based mamdani-type fuzzy modeling of performance anode side of PEM fuel cell with spin method coated with CNT.

PEM was 0.021 W/cm^2 at most but with CNT this value was 0.017 W/cm^2 at most (Fig. 6).

- The voltage density value of coating with CNT is more higher. The voltage density value uncoated PEM was 0.102 V/cm^2 at most but with CNT this value was 0.108 V/cm^2 at most (Fig. 7).
- Performance of uncaoted PEM is more higher during discharge. The current density value uncoated PEM was 0.034 V/cm^2 at most but with CNT this value was 0.025 V/cm^2 at most (Fig. 8).

Both of uncoated PEM and with CNT, The best performance occurred at 250 s. At that time for with CNT power density value was 0.017 W/cm^2 and for uncoated PEM this value reached 0.021 W/cm^2. When compared to 10 s, one can see that these value are very good performance. Because experimental system should be stable structure for great performance value (Figs. 6–8).

Fig. 9 shows comparison of experimental data with RBMTF for the variation of time with temperature of power density value (T = 20–60 °C; t = 10–390 s). 117 values were obtained by RBMTF technique. From a comparison of the experimental results with the results of RBMTF study, one can see that the results are quite compatible (Fig. 9). This figure present that; the power density values increase according to increasing temperature values by the passage of time. The minimum power density value was obtained at 20 °C as 0.0177 W/cm^2 and the maximum power density value was obtained at 60 °C as 0.0263 W/cm^2.

Fig. 10 shows comparison of experimental data with RBMTF for the variation of time and voltage density with temperature of power density value (T = 20–60 °C; Voltage Density = 0.095–0.11 V/cm^2; t = 10–390 s). 117 values were obtained by RBMTF technique. From a comparison of the experimental results with the results of RBMTF study, one can see that the results are quite compatible (Fig. 10). This figure present that; the voltage density values increase according to increasing temperature and power density values by the passage of time. The minimum voltage density value was obtained at 20 °C as 0.0982 V/cm^2 and the maximum power density value was obtained at 60 °C as 0.1098 V/cm^2.

Fig. 11 shows comparison of experimental data with RBMTF for the variation of time and current density with temperature of power density value (T = 20–40 °C; Current Density = 0.027–0.039 A/cm^2; t = 10–390 s). 78 values were obtained by RBMTF technique. From a comparison of the experimental results with the results of RBMTF study, one can see that the results are quite compatible (Fig. 11). This figure present that; the current density values increase according to increasing temperature and power density values by the passage of time. The minimum voltage density value was obtained at 20 °C as 0.0288 A/cm^2 and the maximum power density value was obtained at 40 °C as 0.0384 A/cm^2.

In this study, fuzzy logic is also used for prediction. 78 values at 30 °C and 50 °C which are not obtained from

Table 1 – Fuzzy sets of input and output variables.

Membership name	Very very low	Very low	Low	Negative medium	Medium	Positive medium	High	Very high	Very very high
	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9
Voltage Density (Volt/cm^2)	**VD_1** 0–0.099	**VD_2** 0.098–0.100	**VD_3** 0.099–0.102	**VD_4** 0.100–0.103	**VD_5** 0.102–0.104	**VD_6** 0.103–0.105	**VD_7** 0.104–0.107	**VD_8** 0.105–0.108	**VD_9** 0.107–0.109
Current Density (Ampere/cm^2)	**CD_1** 0–0.029	**CD_2** 0.028–0.030	**CD_3** 0.029–0.032	**CD_4** 0.030–0.033	**CD_5** 0.032–0.034	**CD_6** 0.033–0.035	**CD_7** 0.034–0.036	**CD_8** 0.035–0.037	**CD_9** 0.036–0.038
T (°C)	**T_1** 0–24	**T_2** 20–28	**T_3** 24–33	**T_4** 28–37	**T_5** 33–42	**T_6** 37–46	**T_7** 42–51	**T_8** 46–55	**T_9** 51–60
t (s)	**t_1** 0–52	**t_2** 10–94	**t_3** 52–136	**t_4** 94–178	**t_5** 136–221	**t_6** 179–263	**t_7** 221–305	**t_8** 263–347	**t_9** 305–390
Power Density (Watt/cm^2)	**PD_1** 0–0.018	**PD_2** 0.017–0.019	**PD_3** 0.018–0.020	**PD_4** 0.019–0.020	**PD_5** 0.020–0.021	**PD_6** 0.020–0.022	**PD_7** 0.021–0.023	**PD_8** 0.022–0.024	**PD_9** 0.023–0.0249

Table 2 – Rules of RBMTF for power density (W/cm^2).

Rule no		T		t		V/cm^2		A/cm^2		W/cm^2
1	If	T is T_1	and	t is t_1	and	V is V_2	and	A is A_2	then	W is W_1
3	If	T is T_1	and	t is t_3	and	V is V_2	and	A is A_2	then	W is W_1
5	If	T is T_1	and	t is t_5	and	V is V_1	and	A is A_3	then	W is W_2
7	If	T is T_1	and	t is t_7	and	V is V_2	and	A is A_5	then	W is W_3
9	If	T is T_1	and	t is t_9	and	V is V_1	and	A is A_5	then	W is W_3
11	If	T is T_2	and	t is t_2	and	V is V_4	and	A is A_9	then	W is W_9
13	If	T is T_2	and	t is t_4	and	V is V_3	and	A is A_8	then	W is W_6
15	If	T is T_2	and	t is t_6	and	V is V_3	and	A is A_8	then	W is W_6
17	If	T is T_2	and	t is t_8	and	V is V_2	and	A is A_8	then	W is W_5
19	If	T is T_3	and	t is t_1	and	V is V_3	and	A is A_8	then	W is W_6
21	If	T is T_3	and	t is t_3	and	V is V_3	and	A is A_9	then	W is W_8
23	If	T is T_3	and	t is t_5	and	V is V_3	and	A is A_8	then	W is W_6
25	If	T is T_3	and	t is t_7	and	V is V_3	and	A is A_8	then	W is W_6
27	If	T is T_3	and	t is t_9	and	V is V_2	and	A is A_8	then	W is W_5
29	If	T is T_4	and	t is t_2	and	V is V_4	and	A is A_9	then	W is W_9
31	If	T is T_4	and	t is t_4	and	V is V_3	and	A is A_8	then	W is W_6
33	If	T is T_4	and	t is t_6	and	V is V_3	and	A is A_8	then	W is W_6
35	If	T is T_4	and	t is t_8	and	V is V_2	and	A is A_8	then	W is W_5
37	If	T is T_5	and	t is t_1	and	V is V_5	and	A is A_8	then	W is W_8
39	If	T is T_5	and	t is t_3	and	V is V_6	and	A is A_9	then	W is W_9
41	If	T is T_5	and	t is t_5	and	V is V_5	and	A is A_8	then	W is W_8
43	If	T is T_5	and	t is t_7	and	V is V_5	and	A is A_8	then	W is W_8
45	If	T is T_5	and	t is t_9	and	V is V_4	and	A is A_9	then	W is W_7
47	If	T is T_6	and	t is t_2	and	V is V_6	and	A is A_9	then	W is W_9
49	If	T is T_6	and	t is t_4	and	V is V_6	and	A is A_8	then	W is W_8
51	If	T is T_6	and	t is t_6	and	V is V_5	and	A is A_8	then	W is W_8
53	If	T is T_6	and	t is t_8	and	V is V_5	and	A is A_8	then	W is W_8
55	If	T is T_7	and	t is t_1	and	V is V_5	and	A is A_8	then	W is W_8
57	If	T is T_7	and	t is t_3	and	V is V_6	and	A is A_9	then	W is W_9
59	If	T is T_7	and	t is t_5	and	V is V_5	and	A is A_8	then	W is W_8
61	If	T is T_7	and	t is t_7	and	V is V_5	and	A is A_8	then	W is W_8
63	If	T is T_7	and	t is t_9	and	V is V_4	and	A is A_9	then	W is W_7
65	If	T is T_8	and	t is t_2	and	V is V_6	and	A is A_9	then	W is W_9
67	If	T is T_8	and	t is t_4	and	V is V_6	and	A is A_8	then	W is W_8
69	If	T is T_8	and	t is t_6	and	V is V_5	and	A is A_8	then	W is W_8
71	If	T is T_8	and	t is t_8	and	V is V_5	and	A is A_8	then	W is W_8
73	If	T is T_9	and	t is t_1	and	V is V_6	and	A is A_5	then	W is W_5
75	If	T is T_9	and	t is t_3	and	V is V_7	and	A is A_5	then	W is W_5
77	If	T is T_9	and	t is t_5	and	V is V_7	and	A is A_5	then	W is W_5
79	If	T is T_9	and	t is t_7	and	V is V_8	and	A is A_2	then	W is W_3
81	If	T is T_9	and	t is t_9	and	V is V_9	and	A is A_1	then	W is W_1

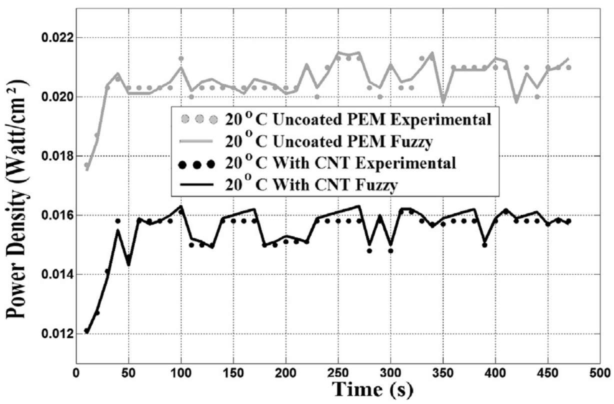

Fig. 6 – **Comparison of experimental data with RBMTF for the variation time of power density values.**

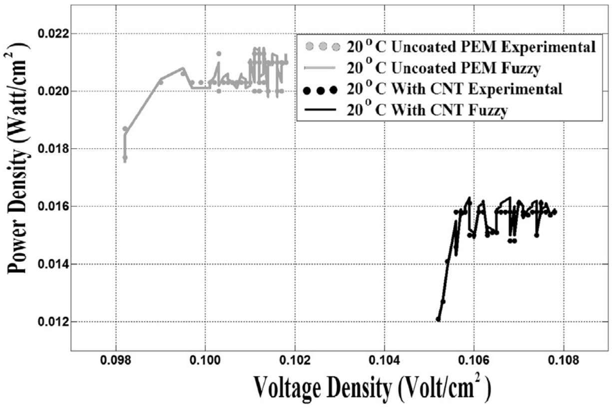

Fig. 7 – **Comparison of experimental data with RBMTF for the variation voltage density of power density values.**

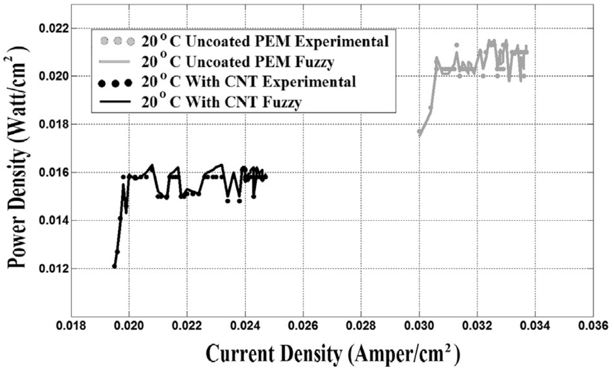

Fig. 8 – Comparison of experimental data with RBMTF for the variation current density of power density values.

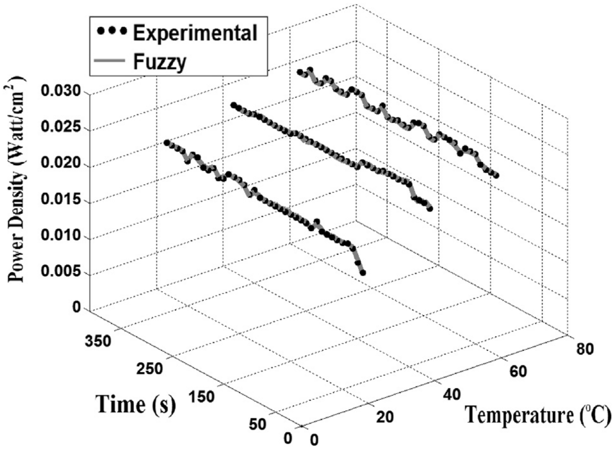

Fig. 9 – Comparison of experimental data with RBMTF for the variation of time with temperature of power density values.

experimental work for power density are predicted by fuzzy logic method. Fig. 12 shows the comparison of experimental data with fuzzy prediction the variation of time with temperature of power density value. This figure present that; the power density value predicted by RBMTF for the T = 30 °C and t = 50s is higher than the power density value from the results of the experimental work for the T = 20 °C and t = 50s, but less than the power density value from the results of the experimental work for the T = 40 °C and t = 50 s (Fig. 12).

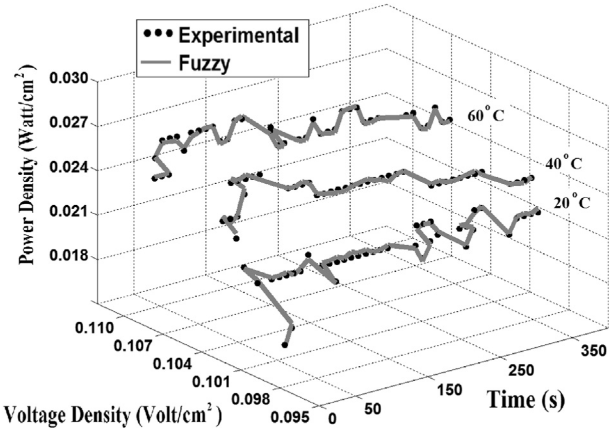

Fig. 10 – Comparison of experimental data with RBMTF for the variation of time with voltage density of power density values.

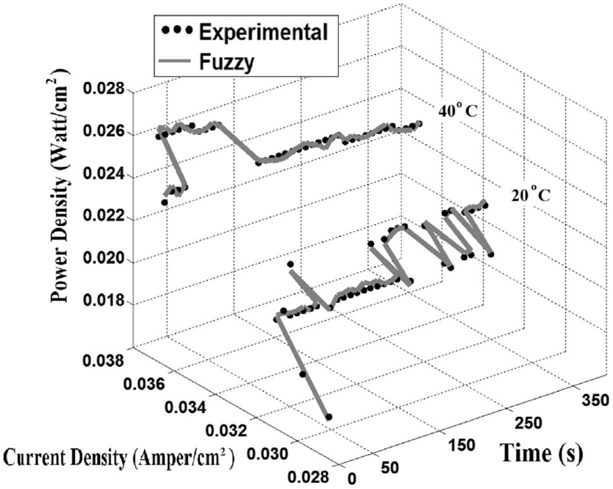

Fig. 11 – Comparison of experimental data with RBMTF for the variation of time with current density of power density values.

Some statistical methods, such as the coefficient of multiple determination (R^2) are defined as Eq. (11) [18].

$$R^2 = 1 - \frac{\sum_{m=1}^{n}\left(t_{m,m} - y_{p,m}\right)^2}{\sum_{m=1}^{n}\left(t_{m,m} - \bar{t}_{m,m}\right)^2} \tag{11}$$

where n is the number of data patterns, $y_{p,m}$ indicates the predicted, $t_{m,m}$ is the actual value of one data point m, and $t_{m,m}$ is the mean value of all actual data points.

Figs. 13 and 14 shows comparison of the actual and RBMTF results for power density. The statistical values of R^2 for power density of uncoated PEM and with CNT (20 °C) is 98.88%, power density of 20 °C, 40 °C and 60 °C temperatures is 97.12%. To give an example, when 40 °C, for actual values power density values change in range 0.017–0.021 W/cm^2, for fuzzy value these values change in range 0.0173–0.0208 W/cm^2. When 60 °C, for actual values power density values change in range 0.022–0.026 W/cm^2, for fuzzy value these values change in range 0.0224–0.0265 W/cm^2. These result show that, fuzzy logic rules appropriately selected. When Figs. 13 and 14 are observed, it is found that actual values and the values from fuzzy technique are very close to each other.

Conclusions

In this study, PEM performances with coating carbon nanotube were experimentally investigated and modeled with RBMTF technique. When during discharge for uncoated PEM fuel cell performance is 0.021 Watt/cm^2, with CNT this value decreased to 0.017 Watt/cm^2. When voltage density values for uncoated PEM 0.102 V/cm^2, with CNT this value increased to 0.107 V/cm^2. When current density values for uncoated PEM

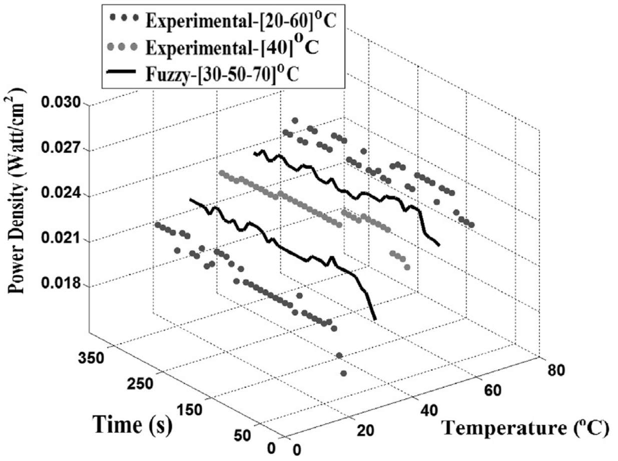

Fig. 12 – Comparison of experimental data with fuzzy predict for the variation of time with temperature of power density values.

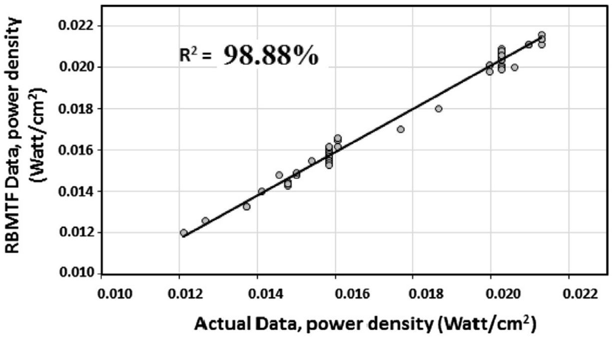

Fig. 13 – Comparison of the actual and RBMTF results for power density of uncoated PEM and with CNT.

0.033 Ampere/cm^2, with CNT this value decreased to 0.025 Ampere/cm^2. In the developed RBMTF system, outlet parameters power density was determined using inlet parameters T, t, voltage density and current density. The rules, which are used to detect the behavior of the fuzzy logic controller and the relationship between system's input and output, are determined. As a result of these rules, every value obtained from the experimental study is also determined by fuzzy logic too. The comparison between fuzzy logic and experimental data is done using statistical methods. The statistical values of R^2 for power density of uncoated PEM and with CNT (20 °C) is 98.88%, power density of 20 °C, 40 °C and 60 °C temperatures is 97.12%. The actual values and RBMTF results indicated that RBMTF can be successfully used for the specification PEM performances with coating carbon nanotube. Unperformed experiments are predicted with RBMTF.

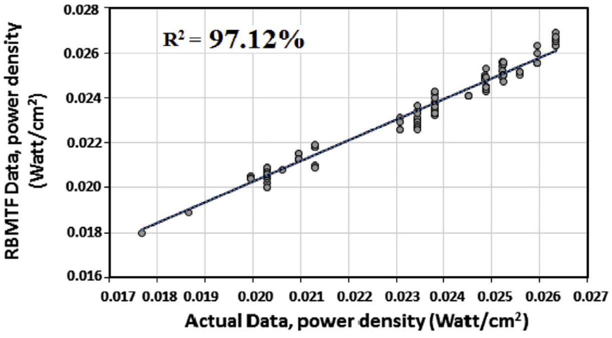

Fig. 14 – Comparison of the actual and RBMTF results for power density of 20 °C, 40 °C, 60 °C.

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REFERENCES

[1] Yılmaz B. Polimer Elektrolit Membranlı Yakıt Pilleri İçin Anot Üretimi. Yüksek Lisans Tezi. İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü; 2006.

[2] İçingür Y, Kireç L. Bir Polimer Elektrolit Membran Yakıt Pilinde Kullanılmak Üzere Gaz Akış Plakaları Tasarımı ve Denenmesi. Politeknik Derg 2011;14(1):31–7.

[3] Bayrak SM. Proton Değişim Membran Yakıt Hücresinin Sayısal Olarak İncelenmesi. Yüksek Lisans Tezi. Gazi Üniversitesi, Fen Bilimleri Enstitüsü; 2011.

[4] Mat A. Katı Oksit Yakıt Pilleri İçin İletken Pasta Geliştirilmesi. Yüksek Lisans Tezi. Niğde Üniversitesi, Fen Bilimleri Enstitüsü; 2011.

[5] Dincer K. PEM Yakıt Hücresinin Katod Tarafı Performansının Geliştirilmesi. Selçuk Üniversitesi Teknik-Online Dergi 2014;13(2):38–49.

[6] Murat YŞ, Uludağ N. Bulanık Mantık ve Lojistik Regresyon Yöntemleri ile Ulaşım Ağlarında Geçki Seçim Davranışının Modellenmesi. İMO Tek Dergi 2008;288:4363–79.

[7] Ata S. PEM Yakıt Hücresinin Membran Performansının Deneysel Olarak İncelenmesi ve Enerji Ayrışımı Olayının Bulanık Mantık Yöntemi ile Modellenmesi. Yüksek Lisans Tezi. Konya: Selçuk Üniversitesi, Fen Bilimleri Enstitüsü; 2015.

[8] Ata S, Dincer K. Rule-based Mamdani-type fuzzy modeling of performance proton exchange membrane fuel cell with carbon nanotube. In: 15th International multidisciplinary scientific GeoConference SGEM 2015, Bulgaria; 2015. p. 487–94.

[9] Ata S, Dincer K. Anot Tarafı Karbon Nanotüp İle Kaplanmış PEM Yakıt Hücresi Performansının Bulanık Mantık Yöntemiyle Modellenmesi. 2015. Ulusal Hidrojen Teknolojileri Kongresi UHTEK-2015, İstanbul.

[10] Sarıdemir S, Erşan K. Farklı İki Destek Maddesi İle Elde Edilen Membranların PEM Yakıt Pilinde Test Edilmesi. Taşıt Teknol Elektron Derg (TATED) 2010;2(3):29–35.

[11] Devrim Y, Erkan S, Baç N, Eroğlu İ. Nafion/TiO_2NanokompozitMembranların PEM Yakıt Pili Performansları Üzerine TiO_2 Miktarının Etkisi". IV. Kocaeli: Ulusal Hidrojen Enerjisi Kongresi ve Sergisi; 2009.

[12] Dincer K, Şahin O, Yayla S, Avcı A. Anot Tarafı Elektrospin Metodu ile YSZ+SDC+NaCaNiBO ile Kaplanmış PEM Yakıt Hücresinin Performansının Deneysel Olarak İncelenmesi. Selçuk Üniversitesi Teknik-Online Dergi 2014;13(1):12–24.

[13] Kim Y, Kim S. An electrical modeling and fuzzy logic control of a fuel cell generation system. IEEE Trans Energy Convers 1999;14(2).

[14] Tong SW, Qian DW, Fang JJ, Li HX. Integrated modeling and variable universe fuzzy control of a hydrogen-air fuel cell system. Int J Electrochem Sci 2013:3636–52.

[15] Gao D, Jin Z, Lu Q. Energy management strategy based on fuzzy logic for a fuel cell hybrid bus. J Power Sources 2008;185:311–7.

[16] Benchouia NE, Derghal A, Mahmah B, Madi B, Khochemane L, Aoul EH. An adaptive fuzzy logic controller (AFLC) for PEMFC fuel cell. Int J Hydrogen Energy 2015;40:13806–19.

[17] Hemi H, Ghouili J, Cheriti A. A real time fuzzy logic power management strategy for a fuel cell vehicle. Energy Convers Manag 2014;80:63–70.

[18] Silva RE, Gouriveau R, Jemei S, Hissel D, Boulon L, Agbossou K, et al. Proton exchange membrane fuel cell degradation prediction based on adaptive Neuro-Fuzzy inference systems. Int J Hydrogen Energy 2014;39:11128–44.

[19] Hu P, Cao GY, Zhu XJ, Hu M. Coolant circuit modeling and temperature fuzzy control of proton exchange membrane fuel cells. Int J Hydrogen Energy 2010;35:9110–23.

[20] Yılmaz A, Ayan K. Cancer risk analysis by fuzzy logic approach and performance status of the model. Turkish J Electr Eng Comput Sci TÜBİTAK 2013;21:897–912.

[21] Kıyak E, Kahvecioğlu A. Bulanık Mantık ve Uçuş Kontrol Probleminin Uygulanması. Hava ve Uzay Teknol Derg 2003;1(2):63–72.

[22] Önal G, Dincer K, Yayla S, Yılmaz Y, Ersoyoğlu AS. Pt/C coating for proton exchange membrane fuel cell (PEMFC) and rule-based Mamdani-type fuzzy modeling of PEMFC performance. Int J Min Metallurgy Mech Eng (IJMMME) 2015;3(3).

[23] Yılmaz Y, Dincer K, Baskaya S. Rule-based Mamdani-type fuzzy modelling of performance of Counter flow Ranque-Hilsch vortex tubes with different Geometric constructions for Aluminum. Int J Arts Sci 2011;4(20).

[24] Efendioğlu D. PEM Yakıt Hücresi Performansının Deney Tasarımı Kullanılarak Optimizasyonu. İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü; 2013. Yüksek Lisans Tezi.