RULE-BASED MAMDANI-TYPE FUZZY MODELING PROTON EXCHANGE MEMBRANE PERFORMANCE WITH COATING CARBON NANO TUBE

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RULE-BASED MAMDANI-TYPE FUZZY MODELING PROTON EXCHANGE MEMBRANE PERFORMANCE WITH COATING CARBON NANO TUBE

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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 PEM fuel cell was accomplished with the spin method by using carbon nanotube (CNT). In the experimental study, current and voltage density performances before and after coating have been recorded at 20 ^{O}C and then are compared to each other. It was determined the increasing of the performance of PEM fuel cell when coated with CNT. Input-output parameters 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), High (L_7), Very High (L_8) and Very Very High (L_9) linguistic classes. The comparison between experimental data and RBMTF is done by using statistical methods like absolute fraction of variance (R^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 30 ^{o}C 50 ^{o}C and 70 ^{o}C. These values were estimated with RMBTF.

Keywords: Proton Exchange Membrane (PEM) fuel cell, Carbon nano-tube (CNT), Rule-based mamdani-type fuzzy (RMBTF) modelling.

1. Introduction

Rapid technological developments and increase in the world population accelerated the consumption of the fossil-fuel-based energy sources which resulted in the increase of the harmful gases released to the environment [1]. Hydrogen is seen as one of the most promising candidates of these alternate energy resources for being the lightest, cleanest and most efficient fuel. The most important property of hydrogen energy is its direct conversion into electricity in fuel cells with higher efficiencies than conversion of fossil fuels in traditional combustion engines or to electrical energy in thermal power plants. Together with hydrogen, fuel cells have been getting a lot of attention because they directly and efficiently convert chemical energy of reactants into electrical energy [2]. A fuel cell is a device that produces electrical and thermal energy from various fuels such as hydrogen, methanol or natural gas. A fuel cell can convert the chemical energy of its fuel and oxidant into electricity without combustion or conversion through thermal energy, which, at least in theory, gives it high efficiency. If hydrogen is used as the fuel, the only reaction product is water, so there are no harmful exhaust compounds, at least not on site [3]. Within many types of fuel cells, proton exchange membrane (PEM) fuel cells are spectacular because of its compactness, light weight, high power and low cost. They have been noticed as the most promising power generating device candidates in portable electronic, automotive and distributed power generation applications in future [4]. The efficiency of energy conversion in PEM fuel cells is dependent on the catalytic activities of the catalysts used in the cathode and anode of membrane electrode assemblies (MEAs). MEAs are considered the heart of PEM fuel cells without which they cannot produce electricity [5]. Therefore enhanced membrane performance is very important. One of the methods to determine the effects of the parameters on membrane performance is fuzzy logic method.

In the existing literature, there have been many investigations about fuel cell application of fuzzy logic. Some of briefly mentioned below. Mammar et al. [6] examined dynamic model of fuel cell system for residential power generation. They realized that the fuzzy logic controller is very effective to control hydrogen flow for active power load variation. Fan et al. [7] studied about mathematical model of proton exchange membrane fuel cells and designed fuzzy logic controller. They noted that the suitable fuzzy logic control schemes can get satisfactory results in tracking a given power and guarantee that the fuel cells have constant power outputs. Gao et al. [8] 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.

In this study, rule-based Mamdani-type fuzzy (RBMTF) modeling used to evaluate performance of PEM fuel cell with coating carbon nanotube. Performance parameters are time, voltage density, current density, temperature and power density. Study includes fuzzification of input variables, representation of fuzzy set with 9 linguistic variables, formation of rule basis and a comparison between output values obtained by experiments and by calculation based on generated rules and RBMTF technique. Study also includes an inquiry of fuzzy logic model's capability on predicting PEM performance with coating carbon nanotube. Unperformed experiments are predicted with RBMTF. Main objective of the study is to present that it is possible to evaluate performance of PEM with coating carbon nanotube by generating a fuzzy logic model.

2. Developed fuzzy for determine performances proton exchange membrane with CNT

In this study, PEM fuel cell membrane which has 2x2 cm^2 area is coated with CNT spray method. PEM fuel cell performances were examined for uncoated PEM and with CNT. The coating on the membrane has 2.5 mg weight. In addition PEM fuel cell performances 20^{o}C, 40^{o}C, 60^{o}C, 80^{o}C temperature were investigated. PEM fuel cell was used in the production of hydrogen and oxygen.

The fuzzy logic approach gives machines the ability of processing special data of humans and of working by benefiting from their experiences and foresights. While bringing in this ability, it uses symbolical expressions instead of numerical expressions. The transfer of these symbolic expressions to the machines is based on a mathematical basis. This mathematical basis is the fuzzy logic sets theory and fuzzy logic is based on this. The basis of a fuzzy logic controller is this kind of verbal expression and the logical relationships between them [9].

The knowledge base of RBMTF is a collection of fuzzy IF-THEN rules. The term fuzzy logic denotes a modelling approach, where functional dependencies between the input and output variables are described by means of a set of IF-THEN rules following the reasoning wih the operators AND, OR and NOT in general linguistic usage. RBMTF is a type of fuzzy relational model where each rule is represented by an IF-THEN relationship. It is also called a linguistic model, because both the antecedent and consequent are fuzzy propositions. Output from a RBMTF is a fuzzy membership function based on rules created [10].

The aim of this study, with the aid of experimental data, performance of PEMFC were modeled with RBMTF modeling technique. RBMTF was designed using MATLAB fuzzy logic toolbox in Windows 8. This model is constructed into RBMTF using input, time (t), voltage density (Volt/cm^2), current density (Amper/cm^2), temperature (T) and output parameter power density (Watt/cm^2) 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). 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 1.

3. Result and Discussion

Fuel cells are electrochemical devices that directly convert the chemical energy of fuel into direct current electricity. Their working principle is just the reverse of water hydrolysis; in which pure hydrogen and oxygen are produced from water as a result of an applied potential difference. PEM fuel cells have a solid organic polymer membrane which plays an active role in proton transport between anode and cathode compartments. A good membrane must have, good separation between the anode and cathode compartments, thus low fuel cross-over rates, high proton conductivity to enhance the proton transfer and must be electrically insulating and good thermal and chemical stability to overcome the harsh environment of the fuel cell. Therefore enhanced membrane performance is very important. One of the methods to determine the effects of the parameters on membrane performance is fuzzy logic method [2].

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.

Table 1. 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_5	and	A is A_5	then	W is W_4
3	If	T is T_1	and	t is t_3	and	V is V_6	and	A is A_3	then	W is W_3
5	If	T is T_1	and	t is t_5	and	V is V_7	and	A is A_3	then	W is W_3
7	If	T is T_1	and	t is t_7	and	V is V_8	and	A is A_2	then	W is W_2
9	If	T is T_1	and	t is t_9	and	V is V_9	and	A is A_2	then	W is W_2
11	If	T is T_2	and	t is t_2	and	V is V_4	and	A is A_5	then	W is W_4
13	If	T is T_2	and	t is t_4	and	V is V_4	and	A is A_5	then	W is W_4
15	If	T is T_2	and	t is t_6	and	V is V_5	and	A is A_5	then	W is W_4
17	If	T is T_2	and	t is t_8	and	V is V_4	and	A is A_6	then	W is W_5
19	If	T is T_3	and	t is t_1	and	V is V_4	and	A is A_5	then	W is W_4
21	If	T is T_3	and	t is t_3	and	V is V_4	and	A is A_5	then	W is W_4
23	If	T is T_3	and	t is t_5	and	V is V_5	and	A is A_5	then	W is W_4
25	If	T is T_3	and	t is t_7	and	V is V_4	and	A is A_6	then	W is W_5
27	If	T is T_3	and	t is t_9	and	V is V_5	and	A is A_5	then	W is W_4
29	If	T is T_4	and	t is t_2	and	V is V_4	and	A is A_5	then	W is W_4
31	If	T is T_4	and	t is t_4	and	V is V_4	and	A is A_5	then	W is W_4
33	If	T is T_4	and	t is t_6	and	V is V_5	and	A is A_5	then	W is W_5
35	If	T is T_4	and	t is t_8	and	V is V_4	and	A is A_6	then	W is W_4
37	If	T is T_5	and	t is t_1	and	V is V_1	and	A is A_6	then	W is W_4
39	If	T is T_5	and	t is t_3	and	V is V_1	and	A is A_8	then	W is W_6
41	If	T is T_5	and	t is t_5	and	V is V_2	and	A is A_8	then	W is W_7
43	If	T is T_5	and	t is t_7	and	V is V_2	and	A is A_9	then	W is W_8
45	If	T is T_5	and	t is t_9	and	V is V_3	and	A is A_8	then	W is W_8
47	If	T is T_6	and	t is t_2	and	V is V_1	and	A is A_7	then	W is W_5
49	If	T is T_6	and	t is t_4	and	V is V_2	and	A is A_8	then	W is W_6
51	If	T is T_6	and	t is t_6	and	V is V_2	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_2	and	A is A_9	then	W is W_8
55	If	T is T_7	and	t is t_1	and	V is V_1	and	A is A_6	then	W is W_4
57	If	T is T_7	and	t is t_3	and	V is V_1	and	A is A_8	then	W is W_6
59	If	T is T_7	and	t is t_5	and	V is V_2	and	A is A_8	then	W is W_7
61	If	T is T_7	and	t is t_7	and	V is V_2	and	A is A_9	then	W is W_8
63	If	T is T_7	and	t is t_9	and	V is V_3	and	A is A_8	then	W is W_8
65	If	T is T_8	and	t is t_2	and	V is V_1	and	A is A_7	then	W is W_5
67	If	T is T_8	and	t is t_4	and	V is V_2	and	A is A_8	then	W is W_6
69	If	T is T_8	and	t is t_6	and	V is V_2	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_2	and	A is A_9	then	W is W_8
73	If	T is T_9	and	t is t_1	and	V is V_8	and	A is A_8	then	W is W_6
75	If	T is T_9	and	t is t_3	and	V is V_9	and	A is A_9	then	W is W_8
77	If	T is T_9	and	t is t_5	and	V is V_9	and	A is A_9	then	W is W_8
79	If	T is T_9	and	t is t_7	and	V is V_9	and	A is A_9	then	W is W_9
81	If	T is T_9	and	t is t_9	and	V is V_9	and	A is A_9	then	W is W_9

Fig. 1 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 (Fig. 1).

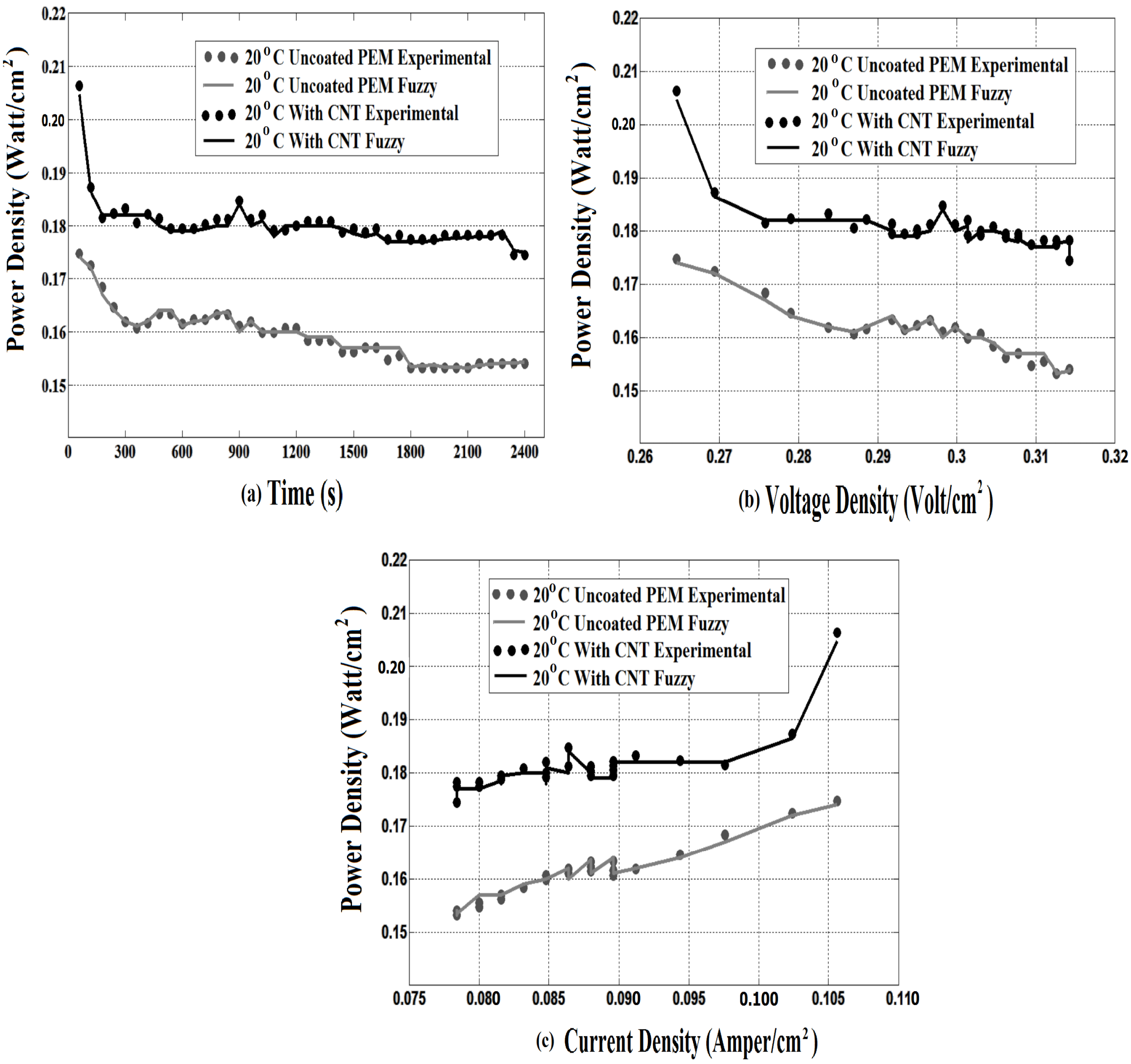


Fig. 1 (a) Comparison of experimental data with RBMTF for the variation time of power density values, (b) Comparison of experimental data with RBMTF for the variation voltage density of power density values, (c) Comparison of experimental data with RBMTF for the variation current density of power density values.

The results of Fig.1 are summarized as follows:

- The power density values of coating with CNT is more higher. The power density value for uncoated PEM was 0.1747 W/cm^2 at most but with CNT this value was 0.2064 W/cm^2 at most (Fig. 1a).

- The voltage density value of coating with CNT is more higher. The voltage density value uncoated PEM was 0.3142 Volt/cm^2 at most but with CNT this value was 0.3712 Volt/cm^2 at most (Fig. 1b).

- Performance of coating with CNT is more higher. When current density is 0.08 A/cm^2, the power density value uncoated PEM was 0.1547 W/cm^2, but with CNT this value was 0.1792 W/cm^2 (Fig. 1c).

Fig. 2a shows comparison of experimental data with RBMTF for the variation of time with temperature of power density value (T = 20-80 ^{o}C; t = 60-2400 s). 160 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. 2a). 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 ^{o}C as 0.1532 W/cm^2 and the maximum power density value was obtained at 80 ^{o}C as 0.2065 W/cm^2.

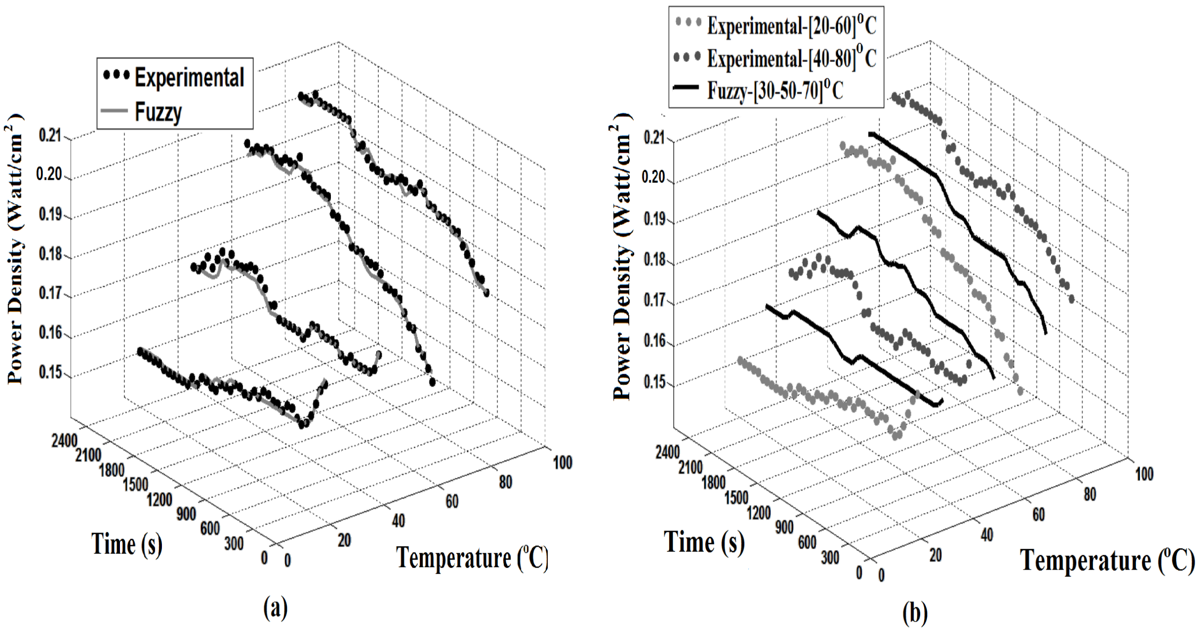


Fig. 2 (a) Comparison of experimental data with RBMTF for the variation of time with temperature of power density values, (b) Comparison of experimental data with fuzzy predict for the variation of time with temperature of power density values.

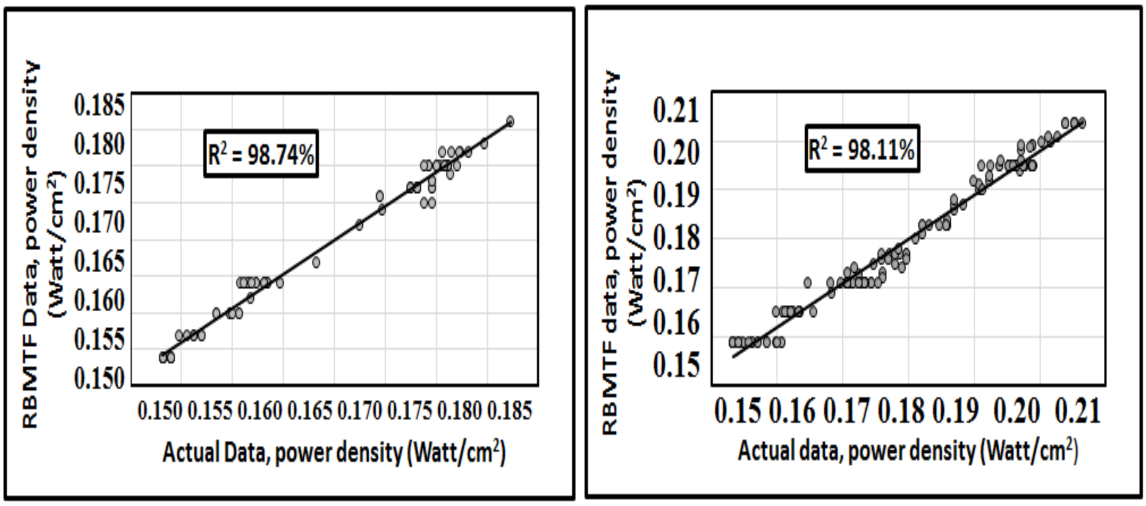
Fuzzy logic, can turn the disadvantages encountered during experimental studies (such as economical losses, loss of time, measurement errors caused by sensitivity of measurement devices, loss of sensitivity over time, harmful effect of environmental temperature on measurement devices). Fuzzy logic also have the advantage of evaluation of intermediate values that is not possible to obtained with experiments [11].

In this study, fuzzy logic is also used for prediction. 120 values at 30 ^{o}C, 50 ^{o}C and 70 ^{o}C which are not obtained from experimental work for power density are predicted by fuzzy logic method. Fig. 2b 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=1140s is higher than the power density value from the results of the experimental work for the T=20 °C and t=1140s, but less than the power density value from the results of the experimental work for the T=40 °C and t=1140 s (Fig. 2b).

The comparison between experimental data and fuzzy logic is done using statistical methods such as the coefficient of multiple determination (R^2) are defined as follows, where t is the target value, o is the output value [12].

$$R^2 = 1 - \left(\frac{\sum_j (t_j - o_j)^2}{\sum_j (o_j)^2} \right) \tag{1}$$

Fig. 3a and b 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 98.74%, power density of 20°C, 40°C, 60°C and 80°C temperatures is 98.11%. When figs. 3a and b are observed, it is found that actual values and the values from fuzzy technique are very close to each other.



(a) (b)

Fig. 3 (a) Comparison of the actual and RBMTF results for power density of uncoated PEM and with CNT, (b) Comparison of the actual and RBMTF results for power density of 20°C, 40°C, 60°C and 80°C.

4. Conclusions

In this study, PEM performances with coating carbon nanotube were experimentally investigated and modeled with RBMTF technique. In the developed RBMTF system, outlet parameters power density was determined using inlet parameters T, voltage density, current density and t. 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 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.

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