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Multi-Response Optimization of Process Parameters influencing Electro-Mechanical behavior of Composite Bipolar plates for PEM Fuel Cells

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ABSTRACT—*Proton Exchange Membrane (PEM) fuel cells are considered a promising candidate for zero emission power source required for environmentally friendly transportation applications. Bipolar plate is a multifunctional component within the PEM fuel cell stack and serves the major functions such as providing a uniform distribution of fuel gas and oxygen within the cell, for which the bipolar plates must exhibit excellent electrical conductivity (>100Scm^{-1}) and flexural strength (>25Mpa) as stated by the Department of Energy (DoE, USA). The earlier works carried out with metallic bipolar plates showed poor electrical conductivity (<100Scm^{-1}) and the results obtained by using graphite based bipolar plates showed poor flexural strength (<25Mpa). So the problem of imbalance between these properties is still persisting.. The literature review has not concentrated on optimizing both the properties simultaneously. The focus of this work is to optimize both the properties using the Desirability Function Approach (DFA). Here, the epoxy/activated carbon (50-50 by wt) composite bipolar plate is fabricated using the compression moulding machine. A box behnken experimental design was adopted for the experiment with varying the factors such as Pressure, Temperature and Time. The optimal parameter setting was 130°C, 20 Bar, 30 Minutes for which the values of Flexural strength and Electrical conductivity are 54.1318Mpa and 110.497Scm^{-1} respectively.*

Keywords— Bipolar plates, Multi-response Optimization, Desirability Function

1. INTRODUCTION

Fuel cells are nothing more than a “gaseous voltaic battery” according to the Welsh judge, inventor, physicist, and father of the fuel cell, ‘Sir William Grove’. Fuel cells are an alternative energy technology that generates electric energy through the reaction between hydrogen (a hydrogen-rich fuel source) and oxygen. These devices are particularly interesting due to high efficiencies relative to traditional combustion engines and low emissions, producing only heat and water as waste products. The development of new composite materials with increased performance and cost-effectiveness is a critical part of emerging fuel cell research. This spotlight focuses on materials for Proton Exchange Membrane (PEM) fuel cells, also referred to as Polymeric Electrolyte Membrane fuel cells, which operate at relatively low temperatures (~ 80 °C). A proton exchange membrane fuel cell transforms the chemical energy liberated during the electrochemical reaction of hydrogen and oxygen to electrical energy, as opposed to the direct combustion of hydrogen and oxygen gases to produce thermal energy. Bipolar plate is a vital component of the polymer electrolyte membrane fuel cell (PEMFC), which distributes reactants uniformly over the active area, separate reactants in the stack, dissipate heat of the reaction, collect and transmit electrical current between adjacent cells. Therefore, the bipolar plate must have high electrical conductivity, low hydrogen permeability, and high thermal conductivity. Moreover, the bipolar plates must have good mechanical strength so as to provide structural support to the membrane electrode assembly. For effective functioning of bipolar plates, the USA Department of Energy have established some target values for few properties.

Table 1: Technical Requirements of Bipolar Plates(DoE, USA)

PROPERTIES	TARGETED VALUES
WEIGHT	< $0.4 KgkW^{-1}$
FLEXURAL STRENGTH	**>25 MPa**
FLEXIBILITY	3-5% Deflection at mid span
ELECTRICAL CONDUCTIVITY	**>100 Scm^{-1}**
THERMAL CONDUCTIVITY	>10 $W(mK)^{-1}$
GAS PERMEABILITY	$2*10^{-6} cm^3 cm^{-2} s^{-1}$ (at 80 degree 3 atm)
COROSSION RESISTANCE	<1 Acm^{-2}

Various materials are available for the fabrication of bipolar plates. The metallic bipolar plates have the advantage of excellent mechanical properties like tensile strength, flexural strength. The drawback is that the metals get corroded in its continuous functioning. The graphite based bipolar plates have good electrical conductivity but they posses poor mechanical properties. Hence the composite bipolar plates are gaining importance in this regards. Hence there is imbalance in the properties of mechanical and electrical still pertaining. Hence the objective of this work is to determine the optimal parameter setting which optimizes the two responses (Flexural strength and Electrical Conductivity) simultaneously. Section II explains the materials used for the work. Section III explains the concept of design of experiment and the desirability function approach. Section IV explains the results and discussion on the work carried out. Section V gives the conclusion and the possibilities of future work in this study.

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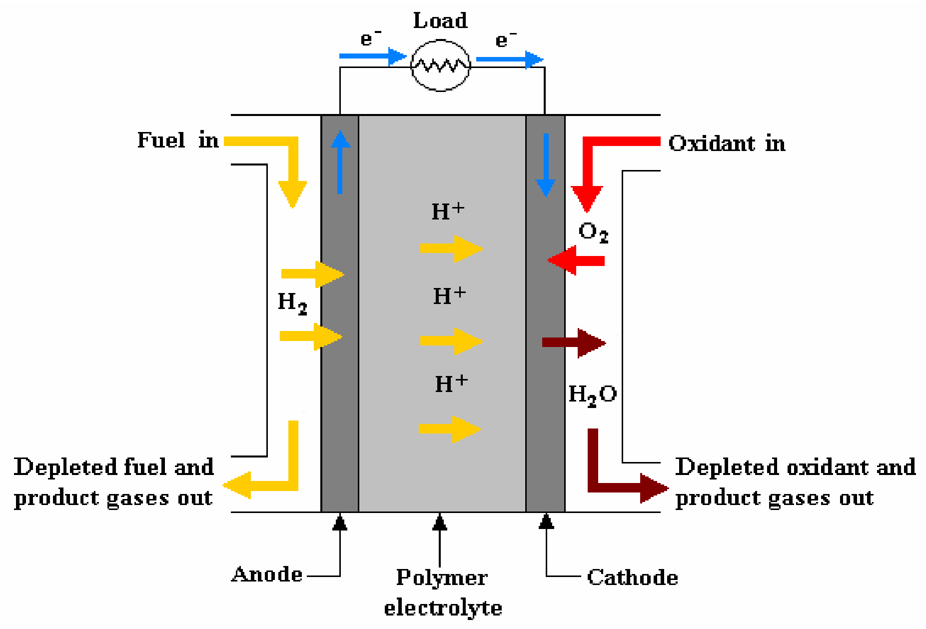

Figure 1. PEM Fuel Cell Schematic.

2. MATERIALS

Epoxy resin and Activated carbon was chosen as the materials in this study for the fabrication of the composite bipolar plate. Epoxy resin being a thermosetting plastic has excellent properties than thermo plastics. It has excellent strength and good internal structure. Activated carbon is used as the conductive filler so as to improve the electrical conductivity. The activated carbon is in the powder form that is mixed with the epoxy resin with a suitable hardener. Activated carbon, also called activated charcoal, activated coal, or carbo activates, is a form of carbon processed to have small, low-volume pores that increase the surface area available for adsorption or chemical reactions. Due to its high degree of microporosity, just one gram of activated carbon has a surface area in excess of 500 m^2, as determined by gas adsorption. An activation level sufficient for useful application may be attained solely from high surface area; however, further chemical treatment often enhances adsorption properties. It is also used in fuel cells applications for the improvement of electrical conductivity.

2.1. Preparation of Epoxy/Activated Carbon Composite

Epoxy resin and Activated carbon (50 and 50 by wt) are taken in a beaker. Hardener is added to the resin and mixed gradually. Continued with the stirring action, the conductive filler is added gradually. Stirring is done until the filler is completely added. The mixture is now transferred to the mould. The mould is kept in the hot air oven for 1 hr at a temperature of 100°C. Then the mould is transferred to the compression moulding machine and the respective setting is run on the moulding machine. Here in this study we are going to determine an optimal parameter setting of the compression moulding machine so as to optimize two responses simultaneously.

Figure 2: Epoxy/Activated Carbon Composite Bipolar Plates

3. DESIGN OF EXPERIMENTS

The design of experiments is a technique in which a set up of experiments is executed in a random order and obtaining different response values by the changing the levels of the factors within the range we have defined. This technique was developed initially for improvising the yield of the crop in agricultural field by Fischer. Similarly here in this work, we are concentrating on determining the optimal parameter setting for the compression moulding machine in which the composite is fabricated. The various levels for the three factors in this study are as given below

Table 2: Factors and Levels of the Experiment

TEMPERATURE(°C) (A)	PRESSURE(BAR) (B)	TIME(MINUTES) (C)
100	15	10
115	20	20
130	25	30

3.1. Desirability Function Approach

Derringer and Suich (1980) describe a multiple response method called desirability. It is an attractive method for industry for optimization of multiple quality characteristic problems. The method makes use of an objective function, D(X), called the desirability function and transforms an estimated response into a scale free value (di) called desirability. The desirable ranges are fromzero to one (least to most desirable, respectively). The factor settings with maximum total desirability are considered to be the optimal parameter conditions. The simultaneous objective function is a geometric mean of all transformed responses:

$$D_0 = \left(d_1^{w1}.d_2^{w2}.......d_n^{Wn}\right)^{1/\Sigma wi} \qquad 0 \leq D_o \leq 1$$

Desirability is an objective function that ranges from zero outside of the limits to one at the goal. The numerical optimization finds a point that maximizes the desirability function. Adjusting the weight or importance may alter the characteristics of a goal. For several responses, all goals get combined into one desirability function. For simultaneous optimization, each response must have a low and high value assigned to each goal. The "Goal" field for responses must be one of five choices: "none", "maximum", "minimum", "target", or "in range". Factors will always be included in the optimization at their design range by default, or as a maximum, minimum of target goal. The meanings of the goal parameters are:

• Maximum:
◦ di = 0 if response < low value
◦ 0≤di ≤1 as response varies from low to high
◦ di = 1 if response > high value
• Minimum:
◦ di = 1 if response < low value
◦ 1≤di ≤1 as response varies from low to high
◦ di = 0 if response > high value
• Target:
◦ di = 0 if response < low value
◦ 0≤di ≤1 as response varies from low to target
◦ 1≥di ≥0 as response varies from target to high
◦ di = 0 if response > high value
• Range:
◦ di = 0 if response < low value
◦ di = 1 as response varies from low to high
◦ di = if response > high value

Here in this case higher the better condition will be used for the problem defined. A box-behnken design was adopted for this study because the results can be obtained by conducting limited number of experiments which ultimately saves the time and cost. This is one of the methods of RSM which overcomes the problem of conducting experiments in a trial and error basis.

3.2. Grey Relational Analysis

Multi-performance characteristic theory using the grey relational analysis was used for optimizing parameters when only partial information is known. In the grey relational method, experimental information is classified as white, black, or grey. White information is known information and black information is unknown information. Grey information indicates an incomplete and uncertain data sequence. Therefore, grey relational grade clearly expresses the relationship between experimental results and predicted values for multi-performance characteristics. Data pre-processing is required since the range and the unit in one data sequence may differ from the others. Data processing is necessary when the sequence scatter range is too large or when the process directions of the target in the sequence are different. Data processing is a process of transferring original sequence to a comparable sequence. For this experimental research data is normalized between zero and one. Depending on characteristics of data sequence various methodologies of data pre-processing are available. In this study the response to be optimized is Flexural Strength and Electrical Conductivity. Both the responses are optimized based on Higher the Better criteria.

For Higher the Better condition,

$$y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}}$$

Individual Grey Relational Grade is calculated using the formula

$$\gamma_{ij} = \frac{\Delta_{\min} + \tau\Delta_{\max}}{\Delta_{0i}(j) + \tau\Delta_{\max}}$$

$$\Delta_{\min} = \min{}_i \min{}_j \Delta_{0i}(j) \qquad \Delta_{\max} = \max{}_i \max{}_j \Delta_{0i}(j)$$

$$\Delta_{0i}(j) = \left| y_0(j - y_i(j)) \right| \qquad \tau \in [0,1]$$

4. RESULTS AND DISCUSSION

The experiment design consists of 17 runs(Treatment Combinations) with each of the factors varied at three different levels. The response values like flexural strength and electrical conductivity are measured for each of the treatment combination. The flexural strength is measured using UTM machine and for electrical conductivity first the resistance is measured from which the resistivity is calculated and finally the reciprocal of electrical resistivity gives the conductivity values. The following table shows the experimental setup as follows:

Table 3: Experimental Setup using DFA

Temperature(°C)	Pressure(Bar)	Time (Minutes)	Flexural Strength (Mpa)	Electrical Conductivity (Scm^{-1})	d1	d2	Do
130	25	20	33.4387	97.125	0.388	0.2411	0.3058
100	25	20	31.3939	93.144	0.3275	0.0556	0.1349
115	20	20	44.4593	101.46	0.714	0.4431	0.5624
115	25	30	50.7894	104.99	0.9012	0.6076	0.7399
115	20	20	36.7122	101.06	0.4848	0.4244	0.4535
130	20	10	41.2219	108.38	0.6182	0.7655	0.6879
100	20	10	38.1217	103.842	0.5265	0.5541	0.5401
115	20	20	35.9425	100.964	0.462	0.42	0.4404
130	15	20	36.4950	102.459	0.4784	0.4896	0.4839
115	25	10	20.3228	91.9503	0	0	0
115	15	30	42.6252	113.411	0.6597	1	0.8122
115	15	10	36.3087	92.644	0.4729	0.0323	0.1235
100	20	30	40.2593	96.828	0.5897	0.2272	0.366
130	20	30	54.1318	110.497	1	0.8642	0.9296
115	20	20	38.5372	98.241	0.5388	0.2931	0.3973
115	20	20	36.8338	100.436	0.4884	0.3954	0.4394
100	15	20	37.1273	105.218	0.4971	0.6182	0.5543

The higher overall desirability value yields the optimal parameter setting which optimizes both the responses simultaneously. It is evident that the overall desirability value is high for increasing Temperature(130°C) and Time(30mins) and the Pressure(20bar) kept at the middle level. Equal weightage was given to the responses to compute the overall desirability value.

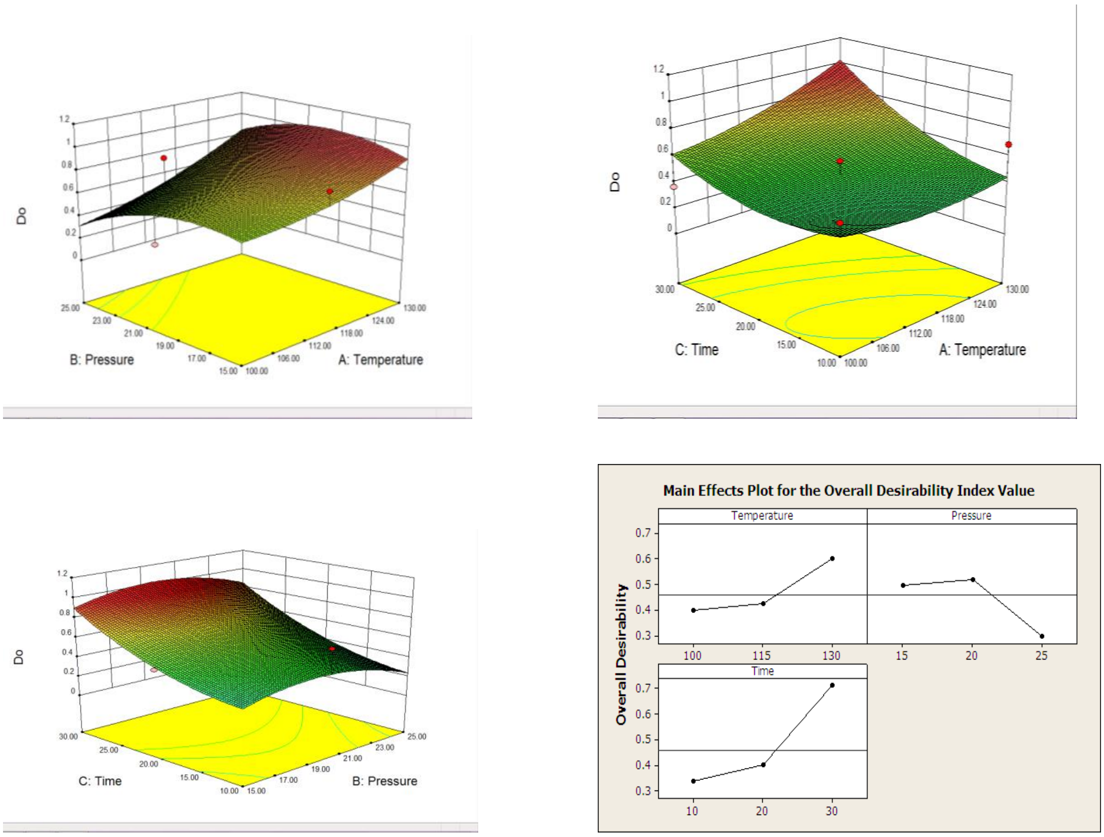

Figure 4: 3D surface plot and Main effects plot

From the above 3D plots and main effects plots shown it is evident that the overall desirability value is high for the following parameter setting:

Temperature =130°C Pressure =20Bar Time =30Minutes

The response values for the above parameter setting are achieved as follows:

Flexural Strength = 54.1318MPa Electrical Conductivity =110.497 Scm^{-1}

The results obtained for flexural strength and electrical conductivity are found to meet the target values defined by the Department of Energy(USA)

Table 4: Experimental Setup using Grey Relational Analysis

Temperature(°C)	Pressure(Bar)	Time (Minutes)	Flexural Strength (Mpa)	Electrical Conductivity (Scm^{-1})	GRG for Flexural Strength	GRG for Electrical Conductivity	Overall Grey Relational Grade
130	25	20	33.4387	97.125	0.44964	0.397172	0.423406
100	25	20	31.3939	93.144	0.426439	0.346164	0.386302
115	20	20	44.4593	101.46	0.636132	0.473082	0.554607
115	25	30	50.7894	104.99	0.835003	0.560287	0.697645
115	20	20	36.7122	101.06	0.492514	0.464857	0.478685
130	20	10	41.2219	108.38	0.567022	0.680735	0.623879
100	20	10	38.1217	103.842	0.513611	0.528597	0.521104
115	20	20	35.9425	100.964	0.481696	0.462963	0.472329
130	15	20	36.4950	102.459	0.489428	0.494854	0.492141
115	25	10	20.3228	91.9503	0.333333	0.333333	0.333333
115	15	30	42.6252	113.411	0.595026	1	0.797513
115	15	10	36.3087	92.644	0.486808	0.340669	0.413738
100	20	30	40.2593	96.828	0.549269	0.392835	0.471052
130	20	30	54.1318	110.497	1	0.786411	0.893205
115	20	20	38.5372	98.241	0.520183	0.414285	0.467234
115	20	20	36.8338	100.436	0.494267	0.452653	0.47346
100	15	20	37.1273	105.218	0.498554	0.567022	0.532788

The higher overall grey relational grade yields the optimal parameter setting which optimizes both the responses simultaneously. It is evident that the overall grey relational grade value is high for increasing Temperature(130°C) and Time(30mins) and the Pressure(20bar) kept at the middle level. Equal weightage was given to the responses to compute the overall grey relational grade.

5. CONCLUSION AND FUTURE SOPE OF WORK

The effective functioning of the bipolar plates determines the effective functioning of the fuel cells. The flexural strength and electrical conductivity is been the major concern for the bipolar plates in all the works carried out previously. But there is an imbalance in the properties of the flexural strength and electrical conductivity. So in this work, a multi-response optimization technique was adopted for the problem to simultaneously optimize both the responses. Experimental work shows that the fabricated bipolar plates meet the requirements of the Department of Energy. The test results obtained for flexural strength and electrical conductivity are 54.1318MPa and 110.497Scm^{-1}. The optimal parameter setting (with overall desirability value = 0.9296), (with overall grey relational grade = 0.8932) is found to be Temperature =130°C, Pressure =20Bar and Time =30Minutes. The results were also validated using the 3D graph plots and Main effects plot drawn using Design Expert and Minitab software.

There are various other factors influencing the properties of bipolar plates. A still more complicated design with more factors can be considered to get still more accurate results. Moreover, in this work we have focused only on flexural strength and electrical conductivity. We can also analyze the factors which influence the particular property we are interested in and the same concept of design of experiments can be applied to get the results as above.

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