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TOPSIS multiple-criteria decision support analysis for material selection of metallic bipolar plates for polymer electrolyte fuel cell

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Abstract

Several kinds of metallic bipolar plates for PEMFCs are currently being developed in order to meet the demands of cost reduction, stack volume, lower weight and enhanced power density. This work shows an application of the Technique of ranking Preferences by Similarity to the Ideal Solution (TOPSIS) Multiple Attribute Decision Making (MADM) method for solving the material selection problem of metallic bipolar plates for polymer electrolyte fuel cell (PEFC), which often involves multiple and conflicting objectives. The proposed methodological tool can aid the material designer in the modeling and selection of suitable materials according to a set of predefined criteria. After introducing the theoretical background, a case study is presented for the material selection of a bipolar plate in a PEFC. A list of all possible choices, from the best to the worst materials, is obtained by taking into account all the material selection criteria, including the cost of production. A user-defined code in *Mathematica* has been developed to facilitate the implementation of the method. It was shown that the optimum value of each criterion is independent of other criteria values (i.e., no interaction is allowed). The proposed approach may be applied to other problems of material selection of fuel cell components.

Keywords: Polymer electrolyte fuel cell (PEFC); Bipolar plate; TOPSIS; Modeling; Material selection; Cost; Production

1. Introduction

The development of polymer electrolyte fuel cell (PEFC) technology is at its critical stages. Several problems limit the performance of PEFC products: (1) poor electrochemical reactivity of oxygen at low temperatures at the start of the cathode catalyst (Pt and Pt alloys), (2) poor alcohol, acetyl or reformed hydrogen oxidation at the state of the art anode catalyst (Pt alloys), (3) the critical choice of membranes for PEFC applications and (4) the cost of graphite bipolar plates for mass production. These important issues are related to the design and fabrication of materials. Consequently, a wide range of materials – including membrane materials – are under development with two main objectives: cost reduction and high performance.

In a recent review, a comprehensive study was performed [1] to provide a design analysis of an effective PEMFC for electrical vehicle applications. The aim of the work was to facilitate material and process selections of fuel cell components taking into account a large number of design and manufacturing alternatives. In another work [2], the description of results obtained on different flow field designs for PMFC bipolar plates was reviewed. It was shown that different flow field designs have pros and cons associated with them which, in turn, make them suitable for different applications. It was concluded that the improvements in the design of bipolar plates can help achieve the set goals of cost and performance for the commercialization of PEM fuel cells. In a very recent review [3], a design analysis of the bipolar plate for PEM fuel cell applications was shown. The desired properties of the bipolar plate for such applications were also presented. Other works related to materials and to the disadvantages of materials and of design configuration of bipolar plates and PEMFC have also been presented elsewhere [4–7].

Traditionally, when choosing a new material whose characteristics are known, or replacing an existing one with another having better performing components, experts usually apply trial and error methods or use previous experimentation experience.

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Nomenclature

a	length of bipolar plate
a_f	the length of crack in ultimate fracture
b	width of bipolar plate
C_i	the relative closeness of ith candidate material to the ideal solutions
E	elastic modulus of bipolar plate
$\dot{E}$	standard equilibrium potential
$E_a(j)$	anodic cell potential
$E_c(j)$	cathodic cell potential
E_j	the entropy value for jth attribute
$E(j)$	equilibrium potential
$\Delta E(j)$	actual cell potential
f_i	ith objective
F	static load
J	the set of decision attributes
$J(j)$	current density function
k	constant of the entropy equation
K	set of benefit criteria
K'	set of cost criteria
K_t	the fracture toughness of bipolar plate
m	total mass of bipolar plates in a fuel cell stack
M	total mass of fuel cell stack
M_i	ith candidate material in the decision matrix
$\bar{n}$	number of ranking levels
n_{ij}	an element of the normalized decision matrix
P	power density of fuel cell stack
P_{ij}	an element of the decision matrix in the normalized mode for entropy method
Q	the heat content of the bipolar plate
r_{ij}	an element of the decision matrix
r_j^*	the best value of jth attribute
r_j^-	the worst value r_j^- of jth attribute
$R_e(j)$	ohmic resistance
S	stiffness of bipolar plate
S_i^+	distance of design to the ideal solution for the ith candidate material
S_i^-	distance of design from the negative ideal solution for the ith candidate
t	thickness of bipolar plate
T_i	temperature
U	elastic energy stored in the bipolar plate
V	weighted normalized decision matrix
V_{ij}	an element of the weighted normalized decision matrix
V_j^+	ideal solution for jth attribute
V_j^-	negative ideal solution for jth attribute
w_j'	the weight coefficient of jth attribute
w_j	balanced weight coefficient of jth attribute
X	the vector of optimization variables
X_j	jth attribute in the decision matrix
y_m	maximum possible deflection of bipolar plate
α	expansion coefficient of bipolar plate
σ_t	thermal stress
ε_t	thermal strain
$\eta_a(j)$	anodic over potential
$\eta_c(j)$	cathodic over potential
κ	thermal conductivity of the bipolar plate
λ_j	the priority of jth attribute comparing with others
μ	thermal diffusivity
ν	Poisson ratio
Ω	the constrained space
ρ	density of bipolar plate
σ_f	tensile strength of bipolar plate
Ψ	the set of objective functions
ξ	time of steady state

This shortcoming can be dealt with by adopting a Multiple Attribute Decision Making model. In this work, it is shown that the material selection procedure of fuel cell components can be done using Multiple Attribute Decision Making models, which often requires complex hierarchical comparisons among candidate materials based on a number of design criteria. The reason for choosing the MADM approach is briefly outlined as follows.

There are two general approaches which can be used to solve multi-objective optimization (also referred to as Multi-Criteria Decision Making, or MCDM) problems. They are: Multiple Objective Decision Making (MODM) and Multiple Attribute Decision Making approaches [8,9]. The MODM approach can be expressed in general form as [9]:

$$\text{MODM} \begin{cases} \text{optimize } \psi(X) = \{f_1(X) \dots f_i(X) \dots f_k(X)\} \\ \text{subject to } X \in \Omega \end{cases} \quad (1\text{-}1)$$

The objectives are sometimes in conflict with one another, meaning an optimal solution of one objective does not meet the optimal solution of another. The material designer should then make a compromise between the objectives to come up with the best solution. This gives rise to an infinite number of compromised solutions, usually called Pareto-optimum solutions [10]. These types of models employ decision variables that are determined in a continuous domain with either an infinite or a large number of choices. The best decision is then made so as to satisfy the material designer's preference information as well as the problem constraints and objectives [10–15].

The MADM approach, on the other hand, can be used in selection problems where decisions involve a finite number of alternatives and a set of performance attributes [9]. The decision variables can be quantitative or qualitative. The key difference in MADM models, as compared to MODM models, is that they include discreet variables with a number of pre-specified alternatives and, more importantly, they do not require an explicit relation between input and output variables [9]. Most of the MADM models are defined by a decision matrix. In turn, the decision matrix has three main parts, namely (a)

alternatives A_i ($i = 1, \ldots, m$), (b) criteria g_j ($j = 1, \ldots, n$), (c) relative importance of criteria (or weights) ω_i and (d) a decision matrix with r_{ij} elements. In the decision matrix, all the elements must be normalized so that their comparison becomes relevant.

For material selection purposes, and from a metallurgical point of view, there are currently no exact relations available describing the electrochemical behavior of fuel cell materials as a function of all micro- and macro-structural characteristics. Therefore, between MADM and MODM, it is the MADM approach that can be adapted, until now, to the material selection problem. The solution (i.e., the suitable candidate material) is then found, based on a comparison of a set of alternatives with respect to all criteria and their possible trade-offs and interactions [9].

In the literature of decision science, a variety of MADM methods are available in deterministic, stochastic and fuzzy domains. In this work, the Technique of ranking Preferences by Similarity to the Ideal Solution (TOPSIS) [8–17] in a deterministic domain is used. It is believed that the method has good potential for solving the material selection problem of fuel cell components like bipolar plates.

2. Theoretical considerations on the TOPSIS method

2.1. General considerations

The following characteristics of the TOPSIS method make it an appropriate approach which has good potential for solving material selection problem:

- An unlimited range of material properties and performance attributes can be included.
- In the context of material selection, the effect of each attribute cannot be considered alone and must always be seen as a trade-off with respect to other attributes. Any change in, for instance, thermal, mechanical, electrical and electrochemical performance indices can change the decision priorities for other parameters. In light of this, the TOPSIS model seems a suitable method for multi-criteria material selection problems as it allows explicit trade-offs and interactions among attributes. More precisely, changes in one attribute can be compensated for in a direct or opposite manner by other attributes.
- The output can be a preferential ranking of the alternatives (candidate materials) with a numerical value that provides a better understanding of differences and similarities between alternatives, whereas other MADM techniques (such as the ELECTRE methods [18–20]) only determine the rank of each material.
- Pair-wise comparisons, required by methods such as the Analytical Hierarchy Process (AHP) [21,22], are avoided. This is particularly useful when dealing with a large number of alternatives and criteria; the methods are completely suitable for linking with computer databases dealing with material selection.
- It can include a set of weighting coefficients for different attributes.
- It is relatively simple and fast, with a systematic procedure.

2.2. Characteristics of the TOPSIS method

Yoon and Hwang [16,17] introduced the TOPSIS method based on the idea that the best alternative should have the shortest distance from an ideal solution. They assumed that if each attribute takes a monotonically increasing or decreasing variation, then it is easy to define an ideal solution. Such a solution is composed of all the best attribute values achievable, while the worst solution is composed of all the worst attribute values achievable [17]. The goal is then to propose a solution which has the shortest distance from the ideal solution in the Euclidean space (from a geometrical point of view) [8–17]. However, it has been argued that such a solution may need to simultaneously have the farthest distance from a negative ideal solution (also called nadir solution) [10,23]. Sometimes, the selected solution (here candidate material) which has the minimum Euclidean distance from the ideal solution may also have a short distance from the negative ideal solution as compared to other alternatives [10–15]. An example of this situation is presented graphically in Refs. [16,17]. The TOPSIS method, by considering both the above distances, tries to choose solutions that are simultaneously close to the ideal solution and far from the nadir solution. In a modified version of the ordinary TOPSIS method, the 'city block distance' [16,24], rather than the Euclidean distance, is used so that any candidate material which has the shortest distance to the ideal solution is guaranteed to have the farthest distance from the negative ideal solution [10–15].

The TOPSIS solution method consists of the following steps:

(a) Normalize the decision matrix. The normalization of the decision matrix is done using the following transformation:

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}; \quad j = 1, 2, \ldots, n; \quad i = 1, 2, \ldots, m \tag{2-2-1}$$

(b) Multiply the columns of the normalized decision matrix by the associated weights. The weighted and normalized decision matrix is obtained as:

$$V_{ij} = n_{ij} w'_j; \quad j = 1, 2, \ldots, n; \quad i = 1, 2, \ldots, m \tag{2-2-2}$$

where w'_j represents the weight of the jth attribute.

(c) Determine the ideal and nadir ideal solutions. The ideal and the nadir value sets are determined, respectively, as follows:

$$\{V_1^+, V_2^+, \ldots, V_n^+\} = \{(\max_i V_{ij} | j \in K), (\min_i V_{ij} | j \in K') | i = 1, 2, \ldots, m\} \tag{2-2-3}$$

$$\{V_1^-, V_2^-, \ldots, V_n^-\} = \{(\min_i V_{ij} | j \in K), (\max_i V_{ij} | j \in K') | i = 1, 2, \ldots, m\} \tag{2-2-4}$$

where K is the index set of benefit criteria and K' is the index set of cost criteria.

(d) Measure distances from the ideal and nadir solutions. The two Euclidean distances for each alternative are, respectively, calculated as:

$$S_i^+ = \left\{ \sum_{j=1}^{n} (V_{ij} - V_j^+)^2 \right\}^{0.5}; \quad j = 1, 2, \ldots, n; \quad i = 1, 2, \ldots, m \tag{2-2-5}$$

$$S_i^- = \left\{ \sum_{j=1}^{n} (V_{ij} - V_j^-)^2 \right\}^{0.5}; \quad j = 1, 2, \ldots, n; \quad i = 1, 2, \ldots, m \tag{2-2-6}$$

Remark: In the so-called 'block TOPSIS' method, the two distances are obtained as:

$$S_i^+ = \sum_{j=1}^{n} |V_{ij} - V_j^+| \quad \text{and} \quad S_i^- = \sum_{j=1}^{n} |V_{ij} - V_j^-|.$$

(e) Calculate the relative closeness to the ideal solution. The relative closeness to the ideal solution can be defined as:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-}; \quad i = 1, 2, \ldots, m; \quad 0 \le C_i \le 1 \tag{2-2-7}$$

The higher the closeness means the better the rank.

The methods for assessing the relative importance of criteria must be well defined.

For solving MADM problems, it is generally necessary to know the relative importance of each criterion. It is usually given as a set of weights, which are normalized, and which add up to one. The importance coefficients in the MADM methods refer to intrinsic "weight". Some works deserve mention because they include information concerning the methods that have been developed for assessing the weights in a MADM problem: these are Refs. [25–33]. The entropy method [34–37] is the method used for assessing the weight in a given problem because, with this method, the decision matrix for a set of candidate materials contains a certain amount of information. In other words, the entropy method works based on a predefined decision matrix. Since there is, in material selection problems, direct access to the values of the decision matrix, the entropy method is the appropriate method. Entropy, in information theory, is a criterion for the amount of uncertainty, represented by a discreet probability distribution, in which there is agreement that a broad distribution represents more uncertainty than does a sharply packed one [34,37]. The entropy idea is particularly useful for investigating contrasts between sets of data. This method consists of the following procedure:

(1) Normalizing the decision matrix

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \quad j = 1, 2, \ldots, J; \quad i = 1, 2, \ldots, I \tag{2-2-8}$$

(2) Calculating the entropy with data for each criterion, the entropy of the set of normalized outcomes of the jth criterion is given by

$$E_j = -k \sum_{i=1}^{m} [p_{ij} \ln(p_{ij})] \quad j = 1, 2, \ldots, J; \quad i = 1, 2, \ldots, I \tag{2-2-9}$$

Using the entropy method, it is possible to combine the material designer's priorities with that of the sensitivity analysis. Final weights defined are a combination of two sets of weights. The first is the set of objective weights that are derived directly from the nature of the design problem using the entropy method, and with no regard to the design performers will. The second is the set of subjective weights that are defined by the material designer's preferences to modify the previous weights and find the total weights. When the material designer finds no reason to give preference to one criterion over another, the principle of insufficient reason [38] suggests that each one should be equally preferred.

$$w'_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, \quad \forall j \tag{2-2-10}$$

where $d_j = 1 - E_j$ is the degree of diversity of the information involved in the outcomes of the jth criterion. The value j is: $j = 1, 2, \ldots, J$.

Otherwise, if the material designer wants to add the subjective weight according to the experience, particular constraint of design and so on, the weight factor is revised as:

$$w_j = \frac{\lambda_j w'_j}{\sum_{j=1}^{n} \lambda_j w'_j}, \quad \forall j \tag{2-2-11}$$

In this paper, the revised Simos method (see Ref. [26]) has been used to define the subjective weights in a given problem by the following algorithm:

(i) The non-normalized subjective weights $\lambda(1), \ldots, \lambda(r), \ldots, \lambda(\bar{n})$ associated with each class of equally placed criteria, arranged in order of increasing importance. The criterion or group of criteria identified as being least important is assigned the score of 1, i.e., $\lambda(1) = 1$.

(ii) The normalized subjective weight: λ_j is designated the normalized weight of criterion X_i such that:

$$\sum_{i=1}^{n} \lambda_j = 100 \tag{2-2-12}$$

It is concluded that the introduced combined weighting scheme is important for material selection problems. It can take into account both the nature of conflicts among criteria and

the practicality of the decisions. This opportunity reflects the advantage of more controllable design selections. The entropy approach can be used as a good tool in criteria evaluation. This possibility makes the entropy method very flexible and efficient for material design.

2.3. Case study

This section focuses on the material selection of the bipolar plate in polymer electrolyte fuel cells. In a cell stack, bipolar plates provide the following [39]: (i) rigidity for the MEA, (ii) distribution and separation of the fuel and oxidant, (iii) electron flow through the stack and (iv) good electrical contact with micro-diffuser. The following characteristics are required for bipolar plates: (i) high electrical conductivity and thermal compatibility with other components, (ii) high corrosion resistance, (iii) high mechanical strength, (iv) low gas permeation, (v) low mass and volume for FC stack, (vi) easy manufacture in low-cost/high volume by automation and (vii) low material cost. State-of-the-art stacks contain bipolar plates made of machined or molded graphite. Bipolar plate materials usually operate under the static load and carry out heat efficiency close to PEMFC temperature.

The heat and electrical conduction through a loaded bipolar plate requires the use of a flat plate which is located between the cells, in a fuel cell stack. Desired plate thickness depends on heat transfer, the electrical current transported, and the geometry and dimensions of the flow field channel which will be formed on it. This plate has to resist against thermal distortion during the operation of the fuel cell stack.

Due to its good chemical stability and high conductivity, graphite is the most typical material being used as a bipolar plate PEMFC cells and stacks applications. It is, however, limited by its difficulty to machine the gas flow field channels that provide gas distribution for the streams, adding a considerable cost. To increase structure strength and minimize gas permeation, graphite plates are usually thick [39]; this allows for gas channels on both sides. To ensure high rigidity of the system and collect the current from the bipolar plates, copper end plates are added to the structure. This can be very heavy but the weight can be decreased if metal bipolar plates are used, because they can be thinner and can act simultaneously as both bipolar and end plates. For example, for a 60-cell stack, the mass distribution of the 33 kW PEFC stack is, respectively [40], (i) 40 kg with graphite plates, representing 88% of the stack weight and (ii) 24 kg with coated aluminum plates, or 81% of the stack weight. Even though machined or molded graphite is the reference material for bipolar plate applications in PEFCs, it has a high cost (particular machined graphite) and a high mass and volume (more than 75% of stack mass and volume); other materials, therefore, must be considered. Potential materials which are currently studied are stainless steels, titanium, aluminum coated with gold, electro-less nickel on aluminum, composite materials, plastics-coated metals and other coated metals, etc. [41–65]. The main challenge for bipolar issues is to develop light and low-cost materials which can act as bipolar and end plates in PEFCs. Research on light metal alloys and composite materials could be interesting approaches for suitable bipolar plate's development. Metallic bipolar plates have a lower cost than graphite plates. They also exhibit a high mechanical strength to withstand clamping forces, and high chemical stability; they can also be easily cooled with water; they have fair gas permeability, and are easily machined to form flow channels, which makes them quite suitable for mass production. However, they form a passive oxide layer in air and this oxide layer increases interfacial resistance between the fuel cell components. With aluminum and titanium bipolar plates, in order to achieve an acceptable lifespan under the environmental conditions of the fuel cell, the coating is necessary as it prevents contamination of the membrane which should be an electrical insulator [49].

3. Modeling, simulation, results and discussion

3.1. Modeling and simulation

An analytical solution is considered for examining and evaluating the criteria and their related performance indexes in the studied case. During PEMFC operation, hydrogen is oxidized at the anode (according to the following equation) to produce protons (H^+) which are transported through the polymer electrolyte membrane to the cathode:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{3-1-1}$$

At the cathode, the supplied oxygen reacts with the protons according to:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{3-1-2}$$

These electrochemical reactions are characterized by the thermodynamic equilibrium potential described by the Nernst equation:

$$E(j) = E^0 + \frac{RT}{2F} \ln\left(\frac{P_{H_2}^2 P_{O_2}}{P_{H_2O}^2}\right) \tag{3-1-3}$$

Electrical energy comes from a PEMFC only when a current is drawn, but the actual cell potential $\Delta E(j)$ is decreased from its ideal potential because of irreversible losses.

$$\Delta E(j) = E_c(j) - E_a(j) = E(j) - (|\eta_a(j)| + |\eta_c(j)| + R_e(j)) \tag{3-1-4}$$

The bipolar plates are used as current collectors and also to connect the cells in series for a stack which provides us a system with a certain power. The measure of power per unit mass for a fuel cell stack, including n similar cells, is called specific power

$$P = \frac{n[E(j) - (|\eta_a(j)| + |\eta_c(j)| + R_e(j))]J(j)}{M} \tag{3-1-5}$$

where M is the total mass of the fuel cell stack. The total mass of the other parts of cell stack, e.g., membranes, cathodes and anodes compared to the mass of the bipolar plates in a specified fuel cell stack is negligible, and replacing the mass m of a bipolar

plate instead of total mass M of the fuel cell stack in Eq. (3-1-5) can be considered as a good approximation.

As a result, a light and highly conductive bipolar plate which characteristics may satisfy the mechanical, thermal, corrosive and electrochemical criteria for PEMFC operating conditions might be the appropriate materials to consider if we want to get a high specific power density of the stack.

In many engineering applications, three-dimensional problems may be idealized as two-dimensional – or plane – problems. The effects of normal transverse strain are often neglected in kinematics compared to the effects of in-plane strains due to the thinness of the plate. Also, the plate is assumed to be in an approximate state of plane stress (if one of the dimensions is small in comparison with other dimensions, then the stress in the direction of the small dimension is negligible). In deriving the equilibrium equations, statically equivalent forces and moments acting on the reference surface of the plate can be defined by integrating stress through the thickness. In this way, the 3D plate behavior may be described using a 2D approximation. Therefore, the Roark relationships [66] used for a thin bipolar plate, in this paper, could be accurate and present a good approximation of a 3D model.

A light bipolar plate with specified thickness t, length a and width b, should meet the constraint on its stiffness, S, meaning that it should not deflect under a static load F during the operation time of the fuel cell. This constraint requires that the stiffness of the bipolar plate be high enough to tolerate the maximum possible deflection of an applied load. To determine the stiffness, the bipolar plate is modeled as a simply supported plate subject to a uniform load applied over the entire in-plane area of the bipolar plate.

$$S = \frac{F}{y_m} \geq \chi \frac{Et^3}{b^4} \tag{3-1-6}$$

η can be obtained from the following relation [66]:

$$\chi = -0.00505\left[\left(\frac{a}{b}\right)^5\right] + 0.0068\left[\left(\frac{a}{b}\right)^4\right] - 0.0306\left[\left(\frac{a}{b}\right)^3\right] + 0.0371\left[\left(\frac{a}{b}\right)^2\right] + 0.0835\left[\left(\frac{a}{b}\right)\right] - 0.0519 \tag{3-7}$$

Decreasing the geometry parameters of the bipolar plate reduces the mass of the fuel cell stack, but it is noted that the stiffness constraint should be met. Introducing the Eqs. (3-1-6) and (3-1-7) into mass relation ($m = \rho V$) leads to the following relation:

$$m \geq \left(\frac{\rho}{E^{1/3}}\right)\left(\frac{Sb^7}{\chi}\right)^{1/3} a \tag{3-1-8}$$

Obviously, the best material for a light, stiff bipolar plate is that with large values of $E^{1/3}/\rho$ index.

In the strength-limited design, the objective function is still to minimize the mass but the constraint is now that of strength. Therefore, the bipolar plate has to be designed in such a way that it will not fail under a given load. This means that it should stand up to the maximum bending stress of a uniform load applied over the entire area of plate. The maximum stress in a simply supported plate due to a uniform load is defined as:

$$\sigma_F \geq \beta \frac{Fb^2}{t^2} \tag{3-1-9}$$

where β follows

$$\beta = -0.00907\left[\left(\frac{a}{b}\right)^5\right] + 0.0097\left[\left(\frac{a}{b}\right)^4\right] - 0.0137\left[\left(\frac{a}{b}\right)^3\right] + (-0.1883)\left[\left(\frac{a}{b}\right)^2\right] + 0.8678\left[\left(\frac{a}{b}\right)\right] - 0.3874 \tag{3-1-10}$$

Again, introducing the Eqs. (3-9) and (3-10) into mass relation ($m = \rho V$) will result in the following equation:

$$m \geq \left(\frac{\rho}{\sigma_F^{1/2}}\right)(F\beta)^{1/2} ab^2 \tag{3-1-11}$$

The mass is minimized by selecting materials with the large values of the index $\sigma_F^{1/2}/\rho$.

When the fuel cell starts operating, the temperature of the bipolar plate suddenly changes by ΔT, thermal strains $\varepsilon_t = 1/2E\alpha(T_i - T_o)$ happen and the temperature gradient through the thickness of the plate will be linear. The maximum thermal stress in the given bipolar plate is defined as follows [66]:

$$\sigma_t = \frac{1}{2}E\alpha\left[T_i + T_o - 2T_o + \frac{1-\nu}{3+\nu}(T_i - T_o)\right] \tag{3-1-12}$$

If this stress exceeds the tensile stress of the bipolar plate, a fracture results. The safe temperature interval ΔT is therefore maximized by choosing a material with a large value of $\sigma_t/E\alpha$. Also, the plate distortion due to temperature changes is proportional to the thermal strain gradient and is defined by using Fourier's Law in the steady state condition:

$$\frac{d\varepsilon_t}{dx} = \frac{\alpha\, dT}{dx} = \left(\frac{\alpha}{\kappa}\right) Q \tag{3-1-13}$$

For a given geometry and heat flow, the distortion is reduced by selecting material with large values of the index (α/K). The heat content of the bipolar plate per unit area, when heated through a temperature interval of ΔT, gives the objective function

$$Q = \frac{\sqrt{2\xi}\Delta T\kappa}{\mu^{1/2}} \tag{3-1-14}$$

The heat capacity of the bipolar plate is minimized by choosing material with a high value of $\kappa/\mu^{1/2}$.

When the hydrogen embrittlement happens in the bipolar plate, it defects elastically until it fractures. The elastic energy per unit stored in the bipolar plate is the integral over the volume of

$$U = \int_0^{\sigma_{F=CKt/\sqrt{\pi a_f}}} \sigma\, d\varepsilon = \frac{C^2}{2\pi a_f}\left(\frac{K_t^2}{E}\right) \tag{3-1-15}$$

For a given initial flaw size, energy is maximized by choosing materials with large values of K_t^2/E.

The high resistance to corrosion in high acid environments is another essential requirement for a bipolar plate; one can consider the amount of corrosion in sulphuric acid (lower is desirable) as the corrosion resistance performance index.

Since high electrical conductivity is desirable in order to enhance the specific power density of the stack according to the Eq. (3-1-5), one can make the amount of electrical resistivity of the bipolar plate (lower is desirable) the electrical criterion.

Cost criteria are divided into two main parts: (1) the first one is proportional to the density of the bipolar plate according to Eqs. (3-1-1) and (3-1-2) and (2) the price of the base material, which is specified by the fraction recycled and the price of the material (higher and lower values are desirable for both, respectively). The fraction recycled is a measure of the proportion of a bipolar plate in use in products which can economically be recycled.

The other criterion is the gas compatibility of the bipolar plate, which is proportional to hydrogen permeability. A small number for this index denotes desirability for separation of the anode and cathode components.

Obviously, the ideal material cannot be found due to the conflicting trade-offs between selection criteria. For modeling a given problem, at the initial stage, one should determine all the material properties related to the given functional requirements. To narrow down the number of candidate materials from the range of options, minimum constraints on materials should be imposed. Ashby and Cambridge University have developed the Cambridge Engineering Selector (CES) software-database and reported results [41–65] for finding the proper candidate materials and related properties. With the chosen materials, we can also generate a decision matrix. This information has been presented in Tables 1 and 2 and Fig. 1 which indicate the decision matrix and the direction of the performance of the criteria. For the methods discussed, the elements of the decision matrix for each criterion are taken as inputs. A *Mathematica* program developed for this reason enables one to obtain the entropy-weighted coefficients and the output of the TOPSIS method.

It should be pointed out that the material indices considered above in Table 2 are assumed to be independent measures of the corresponding each parameter of performance. The goal is to optimize each index, regardless of the values of individual material properties defined in that index. Furthermore, the initial optimum value of each criterion is independent of other criteria values (i.e., no interaction is allowed). However, when these criteria are used with the TOPSIS method which cannot treat the material properties as individual criteria, the ranking results obtained in this work might not be very sensitive to the inclusions of indices. In order to check the sensitivity of the results to the inclusion of indices, one may solve the same decision problem by considering the material properties as individual criteria and using other methods (like ELECTRE IV) rather than the TOPSIS method. We are actively investigating this aspect because it may

Table 1
List of candidate materials for the bipolar plates

Material number	Material name
1	316 Austenitic stainless steel
2	310 Austenitic stainless steel
3	317L Austenitic stainless steel
4	316L Austenitic stainless steel
5	Aluminium (gold plated)
6	AISI 446 Ferritic stainless steel
7	AISI 436 Ferritic stainless steel
8	AISI 444 Ferritic stainless steel
9	AISI434 Ferritic stainless steel
10	304 Austenitic stainless steel
11	Titanium (coated with nitride)
12	A560 (50Cr–Ni)

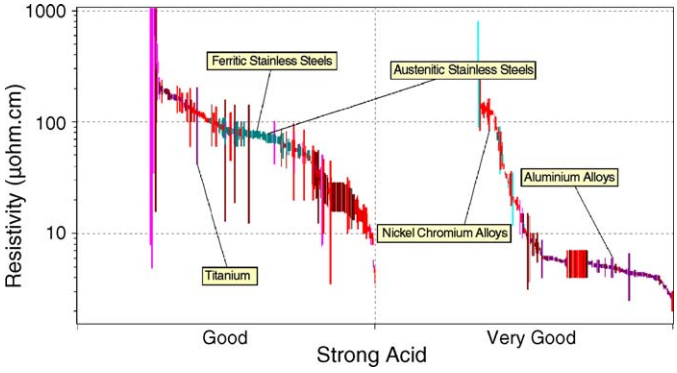

Fig. 1. Result of CES simulation for material selection of a bipolar plate.

Table 2
Decision matrix for material selection of the bipolar plate in PEFC

Performance index ID	Material ID	1	2	3	4	5	6	7	8	9	10	11	12
1	$E^{1/3}/\rho$	0.729	0.840	0.867	0.768	2.474	0.822	0.891	0.821	0.950	1.018	1.824	0.952
2	$\sigma_f^{1/2}/\rho$	2.812	2.781	3.214	2.714	5.814	3.240	3.141	3.10	3.351	3.735	5.792	3.342
3	$\sigma_f/E\alpha$	0.147	0.094	0.133	0.111	0.036	0.246	0.2	0.198	0.159	0.092	0.142	0.200
4	α/κ	19.02	29.31	24.10	24.43	158.8	13.12	15.70	15.63	20.97	40.26	40.67	16.64
5	$\kappa/\mu^{1/2}$	270.9	251	244.4	269.6	629.4	295.4	305.8	292.0	267.3	232.0	203.9	237.3
6	K_t^2/E	253.5	44.15	174	322.0	4.224	76.60	28.95	51.49	42.52	12.42	4.385	50.56
7	Resistivity μohm cm	71	80	74	69	3.9	65	55	57	62	77	60.3	40
8	Cost (CAN$/kg)	5.089	10.83	7.142	5.184	50	4.954	5.69	5.53	5.76	5.99	34.56	10.37
9	Corrosion rate (in/year)	0.081	0.081	0.23	0.081	2	0.105	0.105	0.105	0.105	0.081	0.061	0.005
10	Recycle fraction	0.7	0.7	0.7	0.7	0.9	0.75	0.75	0.75	0.75	0.7	0.65	0.3
11	Hydrogen permeability	5.1	5.4	5.3	2.2	160	0.69	0.69	0.69	0.69	5.4	0.32	4.2

Table 3
Weighted coefficients of the performance indexes without and with the criterion of cost

Performance index	Without the criterion of cost		With the criterion of cost	
	Designer weighted coefficients	Entropy-weighted coefficients	Designer weighted coefficients	Entropy-weighted coefficients
$E^{1/3}/\rho$	11.4	0.0226781	9.2	0.0190989
$\sigma_f^{1/2}/\rho$	11.4	0.00946816	9.2	0.00797387
$\sigma_f/E\alpha$	5.7	0.0103501	6.1	0.0115589
α/κ	5.7	0.048621	6.1	0.0542999
$\kappa/\mu^{1/2}$	11.4	0.0135546	9.2	0.0114154
K_t^2/E	14.3	0.17835	10.8	0.140567
Resistivity (μohm cm)	17.2	0.0317112	12.4	0.0238576
Price of material	–	–	13.9	0.13997
Corrosion rate (in/year)	14.3	0.351417	10.8	0.276969
Recycle fraction	–	–	4.6	0.00235528
Hydrogen permeability	8.6	0.333849	7.7	0.311934

Table 4
Final score of candidates for the bipolar plate in PEFC

Material	With the criterion of cost				Without the criterion of cost			
	Ordinary TOPSIS		Block TOPSIS		Ordinary TOPSIS		Block TOPSIS	
	Closeness to ideal solution	Rank	Closeness to ideal solution	Rank	Closeness to ideal solution	Rank	Closeness to ideal solution	Rank
1	0.937	2	0.787	2	0.931	2	0.795	2
2	0.823	8	0.705	9	0.808	8	0.708	10
3	0.875	3	0.736	4	0.862	3	0.736	5
4	0.962	1	0.811	1	0.959	1	0.825	1
5	0.028	12	0.028	12	0.030	12	0.308	12
6	0.844	4	0.744	3	0.828	4	0.737	4
7	0.821	9	0.728	8	0.802	9	0.719	8
8	0.833	5	0.734	5	0.814	6	0.727	6
9	0.827	7	0.729	7	0.809	7	0.721	7
10	0.810	10	0.704	10	0.791	11	0.695	11
11	0.878	11	0.660	11	0.792	10	0.715	9
12	0.832	6	0.732	6	0.818	5	0.740	3

help to make systematic comparison between ranking results obtained from models which are sensitive to the inclusion of indices and those which may consider the material properties as individual criteria. Such an approach will help to evaluate the performance of each of the Multiple-Criteria Decision Making models in material selection for polymer electrolyte fuel cell applications.

3.2. Results and discussion on the material choice

Table 3 summarizes the weighted coefficients of different performance indexes obtained using the entropy method, with or without considering the criterion of cost (price of material and recycled fraction). For the first case, the strength performance index has a very low value compared to other attributes. For the second case, the criterion of the recycled fraction has a low value similar to the strength performance index. One sees that for the attributes with a low range, which possess no critical points due to a uniform rate of increase, the entropy-weighted coefficients are negligible. It can be concluded that those attributes whose weighted coefficients are of low value have no major effect on the final decision compared to the effect of hydrogen embrittlement, hydrogen permeability and corrosion resistance.

The results of Ordinary and Block TOPSIS methods are given in Table 4 and Figs. 2 and 3.

When one considers the decision matrix without the criterion of cost and its related attributes (Table 4 and Fig. 2), the materials 1 and 2 [41–53,54–65] and 12 [41,58] are considered as the first three choices using Ordinary TOPSIS and Block

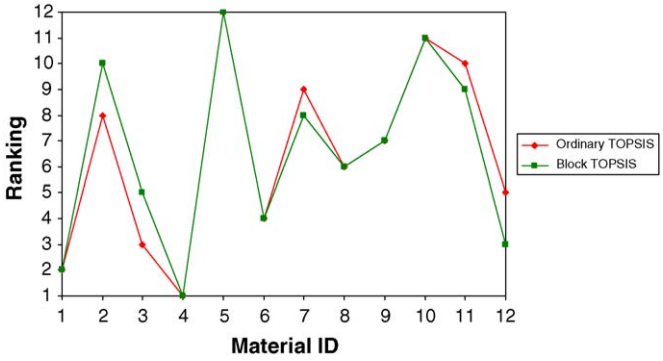

Fig. 2. Ranks of candidate materials without the criterion of cost.

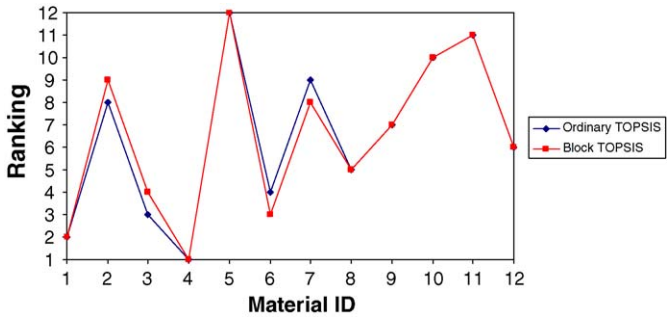

Fig. 3. Ranks of candidate materials with the criterion of cost.

TOPSIS methods. The first three choices are reasonable, since these materials have one of the best electrochemical, mechanical and corrosion resistance compared to other candidates in the decision matrix. As can be seen, these materials (when the price of base material and recycling are not factors) can be used for selecting a material with high performance requirements, such as in aerospace applications.

It is worth noting that material 5 [49] shows a TOPSIS score value that is significantly worse than other candidate materials. The reason is clear: the most important criteria values, which are highlighted by the entropy method for the other candidate materials, dominate those for material 5. Accordingly, one may decide to repeat the solution by eliminating this candidate material (which clearly is the worst material solution and has no power to compete with other candidate materials) in order to add to the accuracy of the final decision, particularly when the methods are linked to a material database.

Materials 3 and 12 have the same ranking in Ordinary TOPSIS and Block TOPSIS. For comparison purposes, the score of each material is determined by the TOPSIS methods and it can provide a clear idea to the designer. It is observed that the results obtained by the above methods are significantly different if the score of the candidate materials are very close to each other. As seen in Table 4, the TOPSIS methods are able to show distinctions and similarities in candidate materials.

When considering the criterion of cost (Table 4 and Fig. 3), the ranking of candidate materials changes significantly, particularly for materials 12 and 6 [63,64], when compared to the first case. For mass production of these components, the criterion of cost (price of material and recycling fraction) plays an essential role and, as seen, 316-types materials are preferred in all cases; they are therefore the most appropriate.

Although it is sufficient to use each of the Ordinary and Block TOPSIS methods in a stand-alone fashion, they may also be used as complements. Three hundred and sixteen types and AISI 446 have an almost stable ranking, with and without the criterion of cost, in all methods. As such, material 4 can be considered the best choice because of the minimum distance to the ideal solution and longest distance to the negative ideal solution, as determined by Ordinary TOPSIS and Block TOPSIS, respectively. In that case, the selected candidate material is optimal. In an approach which involves replacing the material 4 already in use with a newer one, material 6 is the most appropriate. This confirms the obtained results about the applicability of material 6 in Refs. [63,64] compared to material 4. In addition, the materials which are selected as the best choices by the TOPSIS methods are in agreement with the Cambridge Engineering Selector (CES) databases as well as with reported results [41–65] which contain information about the applicability of these materials for the bipolar plate in PEFC.

4. Concluding remarks

Using MADM models in material selection problems can be considered an efficient and suitable tool. The decision matrix is introduced for selecting the appropriate materials for the bipolar plate in a polymer electrolyte fuel cell based on design criteria and possible candidate materials. The weighted coefficients are obtained for every attribute by making use of the entropy method. The decision matrix and weighted coefficients are taken as the input for Ordinary TOPSIS and Block TOPSIS. These models list candidate materials from the best to the worst, taking into account all material selection criteria including cost. Methods that determine both the score and the rank of each candidate material may be preferred over methods that provide only the rank of materials. The score option can provide better insight to the designer and it takes into account both the differences and similarities of the candidate materials. In order to enhance the accuracy of the final decision, using the Ordinary and Block TOPSIS methods together can be considered an efficient tool. The results show good agreement with available data in CES databases.

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