Sensors and Materials, Vol. 33, No. 5 (2021) 1603–1617
MYU Tokyo

S & M 2558

Flow Control of Proton Exchange Membrane Fuel Cell with Theory of Inventive Problem Solving (TRIZ)

Chih-Ying Chuang,[1] Chun-Hsiung Lan,[2] Tian-Syung Lan,[3,4*]
Xuan-Jun Dai,[3**] and Jian-Hua Qin[3]

[1]College of Electronic Information and Electrical Engineering, Huizhou University,
46 Yanda Road, Huizhou, Guangdong 516007, China
[2]Department of Business Administration, Hsing Wu University, New Taipei City 24452, Taiwan
[3]College of Mechanical and Control Engineering, Guilin University of Technology, Guangxi 541004, China
[4]Department of Information Management, Yu Da University of Science and Technology,
Miaoli County 36143, Taiwan

(Received October 21, 2020; accepted March 9, 2021)

Keywords: proton exchange membrane fuel cell, TRIZ, game theory, COMSOL

An optimization strategy is proposed to improve the performance of a proton exchange membrane fuel cell (PEMFC) by using the theory of inventive problem solving (TRIZ) and game theory. TRIZ is widely used to provide solutions to the problems of systematic and innovative designs as it is based on the analysis of scientific and engineering aspects in patented technologies. Factors that improve and worsen the flow control of air and hydrogen are selected by TRIZ. The selected factors are assessed to establish quality optimization strategies, with game theory used to formulate the reward matrix from the negotiation between two parameters. A COMSOL simulation of quality gain and loss was performed using the measured data of inlet temperature, inlet pressure, and pressure drop, which were found to be important factors. The results showed that the outlet temperature, outlet pressure, and pressure drop were improved by 16.67, 78.8, and 11.73% by the control of the inlet temperature, inlet pressure, and flow of air and hydrogen, respectively. TRIZ with game theory was proved effective for obtaining an appropriate flow control strategy of a PEMFC, and provides an effective and easy way to design and manufacture a device when there are many factors and parameters to consider.

1. Introduction

The development of society and technologies has been increasing energy demand, which requires alternative energy sources to prevent environmental problems from burning ever-increasing amounts of fossil fuels. Hydrogen is regarded as an important alternative fuel as it is eco-friendly and has high energy density. Hydrogen is the main fuel of fuel cells that generate electricity through an electrochemical process involving hydrogen and oxygen. These fuel cells have a high energy conversion ratio with no emission of pollutants.

There are several types of fuel cells: alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs), proton exchange

---

[*] Corresponding author: e-mail: tslan888@yahoo.com.tw
[**] Corresponding author: e-mail: daixuanjun@163.com
https://doi.org/10.18494/SAM.2021.3176

ISSN 0914-4935 © MYU K.K.
https://myukk.org/

membrane fuel cells (PEMFCs), and direct methanol fuel cells (DMFCs). Among them, PEMFCs are the most widely used owing to their compactness. However, it is still necessary to enhance their efficiency through improved control of the air and hydrogen flow and lowering the operating temperature. The flow control of water and hydrogen in PEMFCs affects the inlet/outlet temperature and pressure, flow velocity, and pressure drop of air and hydrogen, which are related to humidification, drainage, and heat dissipation. Appropriate control reduces the flow resistance by improving the convection and diffusion of air and hydrogen through the electrode diffusion layers.

To establish an appropriate strategy of flow control, accurate measurement of related parameters is critical. For the measurement, various sensors are used in multichannel thermometers; electromagnetic flowmeters for air, hydrogen, and water; and electrochemical gas sensors in PEMFCs. Advanced sensing technologies allow precise and accurate measurements that provide the basic data of the required parameters for simulations of PEMFC operation, which lead to the establishment of an appropriate control strategy of flow control.

A strategy can be found with the appropriate data by the theory of inventive problem solving (TRIZ), which was first proposed by Altshuller.(1) TRIZ was created to find different characteristics of problems and general patterns for inventive solutions through the analysis of patents with scientific and technological characteristics. Studies over the last few decades have confirmed that TRIZ is efficient and reliable in creative thinking and systematic innovative designs. TRIZ enhances the quality and efficiency of innovative inventions. TRIZ is applied in improving products and processes, eliminating process restrictions, forecasting technology, and developing new products. The benefits of TRIZ include the effective use of previous inventions, the enrichment of creative technology and invention technology, the reduction of cost and improvement of product quality, and so forth. León-Rovira and Aguayo showed that the relationship between the technical parameters of quality function deployment (QFD) can be solved by a contradiction matrix in TRIZ.(2) Apte and Mann compared Taguchi's design method with TRIZ and suggested that better results are obtained by combining the two methods than by using each method separately.(3)

Engineering problems often have contradictions because a solution for a system can cause other problems that may worsen the system. Efficiency enhancement and design improvement of fuel cells also have such contradictions. TRIZ effectively solves the contradictions between two contradictory parameters with game theory. Starting from the relationship between parameters obtained by TRIZ, the optimal parameters that maximize the probability of increasing the efficiency need to be selected. This requires the application of game theory to the selection process to optimize the control of flows in a PEMFC.

In this study, we apply TRIZ with game theory to identify and analyze the problems of the flow control of air, hydrogen, and water in a PEFMC. The aim is to find an optimization strategy to improve the performance of a PEMFC by selecting the optimal parameters for flow control. The results provide a basis for the design and manufacture of flow channels in fuel cells to save time and resources when developing and manufacturing fuel cells.

2. Research Methods

2.1 Contradiction matrix

The contradiction table of TRIZ in this study is a 39 × 39 matrix with the engineering factors in a PEMFC.(4) The matrix provides a quick and simple method to find the principle of solving technical contradictions.(5) The elements (cells) of the matrix indicate corresponding innovative principles of TRIZ(6) (Table 1).

Table 1
Thirty-nine factors in TRIZ in this study.

No.	Factor	Explanation
1	Weight of moving object	The mass of an object in a gravitational field. The force that the body exerts on its support or suspension.
2	Weight of a stationary object	The mass of an object in a gravitational field. The force that the body exerts on its support or suspension, or on the surface on which it rests.
3	Length of a moving object	Any linear dimension, not necessarily the longest, is considered as a length.
4	Length of a stationary object	The same as 3.
5	Area of a moving object	A geometrical characteristic is described by the part of a plane enclosed by a line, the part of a surface occupied by an object, or the square measure of the internal or external surface of an object.
6	Area of a stationary object	The same as 5.
7	Volume of a moving object	The cubic measure of space occupied by an object. Length × width × height for a rectangular object, height × area for a cylinder, etc.
8	Volume of a stationary object	The same as 7.
9	Speed	The velocity of an object; the rate of a process or action in time.
10	Force	The force is a measure of the interaction between systems. In Newtonian physics, force = mass × acceleration. In TRIZ, the force is any interaction intended to change an object's condition.
11	Stress or pressure	The force or tension per unit area.
12	Shape	The external contours or the appearance of a system.
13	Stability of the object's composition	The wholeness or integrity of a system; the relationship among a system's constituent elements. Wear, chemical decomposition, and disassembly all decrease stability. Increasing entropy is equivalent to decreasing stability.
14	Strength	The extent to which an object can resist changes in response to a force. Resistance to breaking.
15	Duration of action by a moving object	The time that the object can act. Service life. The average time between failures is a measure of the duration of action. Also called durability.
16	Duration of action by a stationary object	The same as 15.
17	Temperature	The thermal condition of an object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate of change of temperature.
18	Illumination intensity	The light flux per unit area. Also, any other illumination characteristics of the system such as brightness, light quality, etc.
19	Use of energy by moving object	The measure of an object's capacity for doing work. In classical mechanics, energy is the product of force and distance. This includes the use of energy provided by a super-system (such as electrical energy or heat). The energy required to do a particular job.
20	Use of energy by a stationary object	The same as 19.
21	Power	The rate at which work is performed with respect to time. The rate of use of energy.

Table 1
(Continued) Thirty-nine factors in TRIZ in this study.

22	Loss of energy	The use of energy that does not contribute to the job being done. See 19. Reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category.
23	Loss of substance	Partial or complete, permanent or temporary loss of some of a system's materials, substances, parts, or subsystems.
24	Loss of information	Partial or complete, permanent or temporary loss of data or access to data in or by a system. Frequently includes sensory data such as aroma, texture, etc.
25	Loss of time	Time is the duration of an activity. Improving the loss of time means reducing the time taken for the activity. "Cycle time reduction" is a common term.
26	Quantity of substance/ matter	The number or amount of a system's materials, substances, parts, or subsystems that might be changed fully or partially, permanently or temporarily.
27	Reliability	A system's ability to perform its intended functions in predictable ways and conditions.
28	Measurement accuracy	The closeness of the measured value to the actual value of a property of a system. Reducing the error in a measurement increases the accuracy of the measurement.
29	Manufacturing precision	The extent to which the actual characteristics of the system or object match the specified or required characteristics.
30	External harm to object	Susceptibility of a system to externally generated (harmful) effects.
31	Object-generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of an object or system. These harmful effects are generated by the object or system as part of its operation.
32	Ease of manufacture	The degree of facility, comfort, or effortlessness in manufacturing or fabricating an object/system.
33	Ease of operation	Simplicity: A process is not easy if it requires a large number of people, a large number of steps in the operation, special tools, etc. "Hard" processes have low yield and "easy" processes have high yield and are easy to do correctly.
34	Ease of repair	Quality characteristics such as convenience, comfort, simplicity, and time to repair faults, failures, or defects in a system.
35	Adaptability or versatility	The extent to which a system/object positively responds to external changes. An adaptable/versatile system can be used in multiple ways under a variety of circumstances.
36	Device complexity	The number and diversity of elements and element interrelationships within a system. The user may be an element of the system, which increases the complexity. The difficulty of mastering a system is a measure of its complexity.
37	Difficulty of detecting and measuring	Measuring or monitoring systems that are complex, costly, require much time and labor to set up and use, or have complex relationships between components or components that interfere with each other all indicate "difficulty of detecting and measuring." An increased cost of measuring to a satisfactory error is also a sign of the increased difficulty of measuring.
38	Extent of automation	The extent to which a system or object performs its functions without a human interface. The lowest level of automation is the use of a manually operated tool. For intermediate levels, humans program the tool, observe its operation, and interrupt or reprogram as needed. For the highest level, the machine senses the operation needed, programs itself, and monitors its operations.
39	Productivity	The number of functions or operations performed by a system per unit time. The time for a unit function or operation. The output per unit time or the cost per unit output.

Moving objects: Objects that can easily change position in space, either on their own or as a result of external forces.
Stationary objects: Objects that do not change position in space, either on their own or as a result of external forces.

2.2 TRIZ and game theory

Liu and Chen used the innovative principles of TRIZ to improve the innovativeness of an engineering system and solve engineering problems when the contradictions in the system cannot be predicted.(5) Their method measured the number of times each innovative principle appeared and ranked them in a table according to how many times they were used. Then, they selected a principle to solve the problems. Even for unknown contradictions in a system, innovative principles could be found for a single engineering parameter.

Selecting the appropriate principle requires game theory. In a ‘game’, two or more contenders have to make interdependent decisions if they are rational. Otherwise, the result can be irrational or may even have a Platonic effect. The reward of each contender is determined by each other’s decisions. A contender tends to maximize the reward even when the other has the best strategy. As a result, the outcomes of a game may not be rational or efficient. Thus, when contenders make decisions, they consider all possible actions of the other by calculating the probability distribution. As a pay-off function, a reward is given to one contender according to the strategies of the other.

Von Neumann *et al*. developed game theory by analyzing the interaction between contenders and setting up a mathematical model.(7) Shapley discussed bargaining games,(7) and Gillies and Shapley made great contributions to the development of the core principles of game theory.(8) The prisoner’s dilemma and the Nash equilibrium are good analogies for uncooperative game theory.(9) Wu and Xia explained game theory to illustrate the main concepts of various games and categorized them into four different forms. When the contenders’ strategy and pay-off functions are completely known simultaneously, a game is ‘static’. When the strategy and functions are known sequentially but continuously, it is ‘dynamic’. The type of equilibrium of a game depends on the completeness of the information and whether the game is static or dynamic(10) (Table 2).

We assumed the selection of the quality parameters (outlet temperature, outlet pressure, pressure drop) in a PEMFC to be games having Nash equilibrium in the sub-games with the values of the parameters as contenders. The parameters were selected according to the innovative strategy by TRIZ with a single principle and sequence optimization.(5) Then, the probability of selecting the parameters was calculated in all games to select the strategy with the highest probability. The best strategy for each parameter was obtained by repeating this process.

2.3 Negotiation in game theory

Negotiation between the contenders is required for different situations in game theory to solve problems in the economy, politics, and financial analysis. Game theory based on negotiation is regarded as being precise owing to the use of a mathematical model that simplifies complex and interactive phenomena. It also helps to study the strategic behavior of contenders or decision-makers.

A negotiation game has the following characteristics.

(1) Two or more members

Bargaining involves buyers and sellers. Before transactions, buyers are unaware of the supply and sellers are unaware of the demand. From this starting point, they negotiate an appropriate price.

Table 2
Four main forms of games.

	Complete information	Incomplete information
Static	Nash equilibrium	Bayesian Nash equilibrium
Dynamic	Perfect Nash equilibrium in sub-games	Perfect Nash equilibrium or sequence equilibrium

(2) Obvious or potential benefits

Buyers and sellers have their strategies and expectations, and their goals are achieved through negotiation.

(3) Dependence on each other in competition

In a negotiation, a buyer and a seller try to obtain satisfactory results without maximizing their profit. This is because if one pursues the maximum profit, then the other will be dissatisfied. Thus, for their mutual benefit, they need to explore the possibility of compromise. As a result, the negotiation becomes interdependent.

(4) Willingness to work together

Negotiation between a buyer and a seller is to achieve a balanced benefit, which is a basic understanding of them both. Their willingness to solve problems is also essential for the negotiation; only in this way will the negotiation be successful.

In a static game, contenders pursue balanced solutions. However, contenders in a dynamic game bahave independently on the basis of their estimated probability. Therefore, perfect Nash equilibrium in sub-games is adopted to obtain greater reward in the equilibrium through changing the strategy from that in the nonequilibrium. Therefore, a simple strategy is used to simulate the process of a dynamic bargaining game with full information and mutual, conceptual, and strategic agreement. On the basis of this principle of a bargaining game, the multi-quality optimization of the flow parameters of a PEMFC was investigated.

2.4 Measurement of temperature and pressure

The parameters such as the temperature, pressure, and flow rate of a PEMFC were measured using an FCED-P200 testing platform manufactured by Asia Pacific Fuel Cell Technologies. The test platform contains devices and electrochemical sensors to measure the temperature and pressure of gases in a fuel cell, and the flow rate was calculated from the measured data and the dimensions of the fuel cell. The test platform was placed in an air-circulating box of $2500 \times 2500 \times 2500$ mm^3 (W × D × H) and operated in the temperature range of 5−40 ℃ with a gas supply of nitrogen (>99.99%), hydrogen (>99.99%), and air at a pressure of 100 psi in gauge pressure (psig).

3. Results and Discussion

3.1 Application of TRIZ and game theory to PEMFC

TRIZ is mainly applied to areas such as product and process improvement, elimination of process restrictions, technology forecasting, new product development, patent avoidance, and so forth.(11–14) As TRIZ effectively uses the accumulated knowledge in patents, it offers a creative way to reduce the time and cost of developing or inventing technologies to improve product quality and establish R&D plans. For example, TRIZ has recently contributed to integrating telemetrics into the wireless communication technology used in self-driving cars. TRIZ affords diverse variables and outcomes in the development, design, and planning of products in which there are many conflicting issues. Various analysis and deduction tools in TRIZ enable problems to be confirmed systematically and innovative solutions to be proposed.(7) Game theory also helps resolve the contradictions in economic and engineering processes. Also known as interactive decision theory, game theory provides systematic and strategic interactive analysis tools and methods that allow the best decision in complex and conflicting problems.(15)

In this study, the parameters of the flow channel may generate contradictions when improving the performance of a PEMFC. After the contradictory parameters are defined and measured as the input data, TRIZ and game theory are used to create a contradiction matrix table that corresponds to the 40 innovative rules of TRIZ (Table 3) and obtain a single-quality optimization strategy for each of the parameters. Then, the optimized strategies help to improve the performance of the PEMFC. The following sections show how the contradicting factors are defined, the contradiction matrix is created, game theory is employed, and the strategy is validated and optimized to improve the PEMFC's performance in this study.

3.2 Improving and worsening factors

First, the factors that improve or worsen the system were defined to optimize the parameters for flow control in the PEMFC; these were the outlet temperature, outlet pressure, and pressure drop. Target values of the parameters were obtained to lessen the contradictions when designing the flow control. The principles in the contradiction matrix that suggested ideas and decisions are shown in Tables 4–6.

Table 3
Forty innovative rules of TRIZ.(6)

No.	Rules	No.	Rules
1	Segmentation	21	Skipping
2	Taking out	22	Blessing in disguise
3	Local quality	23	Feedback
4	Assymmetry	24	Intermediary
5	Merging	25	Self-service
6	Universality	26	Copying
7	Nested doll	27	Cheap short-living objects
8	Anti-weight	28	Mechanics substitution
9	Preliminary anti-action	29	Pneumatics and hydraulics
10	Preliminary action	30	Flexible shells and thin films
11	Beforehand cushioning	31	Porous materials
12	Equipotentiality	32	Color changes
13	The other way round	33	Homogeneity
14	Curvature	34	Discarding and recovering
15	Dynamics	35	Parameter changes
16	Partial or excessive actions	36	Phase transitions
17	Another dimension	37	Thermal expansion
18	Mechanical vibration	38	Strong oxidants
19	Periodic action	39	Inert atmosphere
20	Continuity of useful action	40	Composite material

Table 4 shows the factors affecting the outlet temperature of the PEMFC. There are three improving factors for lowering the outlet temperature: inlet temperature, inlet pressure, and flow speed. These factors improve the performance of the PEMFC. However, at the same time, they lower the inlet temperature, which causes irregular flow speed, increases the inlet pressure, harms the proton exchange membrane, and increases the flow speed of air and hydrogen. As a result, more energy is needed and the composition of the gases for the electrochemical reaction is inferior to that at a higher temperature.

Table 5 shows the factors affecting outlet pressure in the flow control of the PEMFC. The three improving factors can worsen the performance as they lower the inlet temperature. The lower inlet temperature makes ion transportation difficult, increases the inlet pressure and the flow speed of gases, and harms the proton exchange membrane. These consequences also increase the use of energy and result in an inferior composition of gases for the electrochemical reaction to that at a higher inlet temperature.

Table 6 shows the factors affecting the outlet pressure drop. The three improving factors can worsen the performance by lowering the inlet temperature and increasing the inlet pressure and the flow speed of gases. The effects may result in difficult ion transportation, increased energy use, defects in the proton exchange membrane, and more water production in the flow channel than that at a high inlet temperature.

Table 4
Improving and worsening factors of outlet temperature in flow control of PEMFC.

Group	Improving factors	Worsening factors
1	Change of temperature → #17* temperature	higher energy demand → #22 loss of energy
		uneven distribution of local current → #31 object-generated harmful factors
2	Change of pressure → #11 stress or pressure	waste of energy → #22 loss of energy
		harm to proton exchange membrane → #31 object-generated harmful factors
3	Change of flow speed → #9 speed	higher energy demand → #22 loss of energy
		reaction gas is inferior for reaction → #31 object-generated harmful factors
		power increase → #10 force

*Numbers correspond to the factors in Table 1.

Table 5
Improving and worsening factors of outlet pressure in flow control of PEMFC.

Group	Improving factors	Worsening factors
1	Change of temperature → #17 temperature	ion transport is difficult → #31 object-generated harmful factors
2	Change of pressure→ #11 stress or pressure	higher energy demand → #22 loss of energy
		harm to proton exchange membrane → #31 object-generated harmful factors
3	Change of flow speed → #9 speed	higher energy demand → #22 loss of energy
		reaction gas is inferior for reaction → #31 object-generated harmful factors
		power increase→ #10 force

Table 6
Improving and worsening factors of outlet pressure drop in flow control of PEFMC.

Group	Improving factors	Worsening factors
1	Change of temperature → #17 temperature	higher energy demand → #22 loss of energy
		uneven distribution of local current t→ #31 object-generated harmful factors
2	Change of pressure → #11 stress or pressure	higher energy demand → #22 loss of energy
		harm to proton exchange membrane → #31 object-generated harmful factors
		harm to proton exchange membrane → #9 speed
3	Change of flow speed → #9 speed	water production in flow channel → #31 object-generated harmful factors

3.3 Contradiction matrix

On the basis of the above results, the contradictory factors of the outlet temperature, outlet pressure, and pressure drop were defined for the inlet temperature, inlet pressure, and flow speed (Tables 7–9). Each cell indicates the innovative principles for improving the flow control of the PEMFC.

Table 7
Contradiction matrix of outlet temperature in flow control of PEFMC.

		Worsening factors						
		22	31	22	31	22	31	10
Improving factors	17	21,17	22,35	21,17	22,35	21,17	22,35	35,10
		35,38	2,24	35,38	2,24	35,38	2,24	3,21
	11	2,36	2,33	2,36	2,33	2,36	2,33	36,25
		25	27,18	25	27,18	25	27,18	21
	9	14,20	2,24	14,20	2,24	14,20	2,24	13,28
		19,35	35,21	19,35	35,21	19,35	35,21	15,19

Numbers in cells correspond to the factors in Table 1.

Table 8
Contradiction matrix of outlet pressure in flow control of PEFMC.

		Worsening factors					
		22	31	22	31	9	31
Improving factors	17	21,17	22,35	21,17	22,35	2,28	22,35
		35,38	2,24	35,38	2,24	36,30	2,24
	11	2,36	2,33	2,36	2,33	6,35	2,33
		25	27,18	25	27,18	36	27,18
	9	14,20	2,24	14,20	2,24	—	2,24
		19,35	35,21	19,35	35,21	—	35,21

Table 9
Contradiction matrix of oil pressure drop in flow control of PEFMC.

		Worsening factors					
		31	22	31	22	31	10
Improving factors	17	22,35	21,17	22,35	21,17	22,35	35,10
		2,24	35,38	2,24	35,38	2,24	3,21
	11	2,33	2,36	2,33	2,36	2,33	36,25
		27,18	25	27,18	25	27,18	21
	9	2,24	14,20	2,24	14,20	2,24	13,28
		35,21	19,35	35,21	19,35	35,21	15,19

3.4 Results of game theory

On the basis of game theory, the principles with high weights are regarded as having a high probability of enhancing the performance of the PEMFC. The weight of a principle is defined as the number of appearances of the strategy in the matrix cells. The weights and ranks are shown in Tables 10−12. The control strategies for the inlet temperature, inlet pressure, and flow rate to enhance the performance of the PEMFC are listed in Tables 13−15.

Table 10
Weights and ranks of strategies for outlet temperature in flow control of PEMFC.

Weight	Probability of success	Rank	Appearances	Principles
7	High	A	More than 19 times	—
6		B	16–18	—
5	Middle	C	13–15	35: Parameter changes
4		D	10–12	2: Taking out
3		E	7–9	21: Skipping
2		F	4–6	19: Periodic action 24: Intermediary 36: Phase transitions
1	Low	G	1–3	3,10,13,14,15,17,18,20,22,25,27,28,33,38

Table 11
Weights and ranks of strategies of outlet pressure in flow control of PEMFC.

Weight	Probability of success	Rank	Appearances	Principles
7	High	A	More than 19 times	—
6		B	16–18	—
5	Middle	C	13–15	—
4		D	10–12	2: Taking out 35: Parameter changes
3		E	7–9	—
2		F	4–6	21: Skipping 24: Intermediary 36: Phase transitions
1	Low	G	1–3	6,14,17,18,19,20,22,25,27,28,30,33,38

Table 12
Weights and ranks of strategies of pressure drop in flow control of PEMFC.

Weight	Probability of success	Rank	Appearances	Principles
7	High	A	More than 19 times	—
				—
				—
6		B	16–18	—
5	Middle	C	13–15	—
4		D	10–12	2: Taking out 35: Parameter changes
3		E	7–9	21: Skipping
2		F	4–6	24: Intermediary
1	Low	G	1–3	3,10,13,14,15,17,18,20,22,25,27,28,33,38,36,19

Table 13
Weights of outlet temperature.

Factor	Selected strategy	Weight
Inlet temperature	35: Parameter changes	5
Inlet pressure	2: Taking out	4
Flow rate	35: Parameter changes	5

Table 14
Weights of outlet pressure.

Factor	Most selected strategy	Weight
Inlet temperature	35: Parameter changes	4
Inlet pressure	2: Taking out	4
Flow rate	35: Parameter changes	4

Table 15
Weights of pressure drop.

Factor	Most selected strategy	Weight
Inlet temperature	35: Parameter changes	4
Inlet pressure	2: Taking out	4
Flow rate	35: Parameter changes	5

3.5 Validation of strategies

From the contradiction matrix, the following strategies for the flow control of the PEMFC were selected.

(1) To optimize the outlet temperature of the flow channel of the PEMFC, the inlet temperature, inlet pressure, and flow rate need to increase.
(2) To optimize the outlet pressure, the inlet temperature and inlet pressure need to increase but the flow rate needs to decrease.
(3) To optimize the pressure drop, the inlet temperature needs to decrease but the inlet pressure and flow rate need to increase.

Experiments based on the innovation strategies were carried out to validate the effect of changing the inlet temperature, inlet pressure, and flow rate on the outlet temperature, outlet pressure, and pressure drop. The outlet temperature increased by 16.7% by increasing the inlet temperature from 60 to 70 °C. The outlet pressure increased by 81.5 and 10.9% by increasing the inlet pressure from 3 to 5 bar and decreasing the flow rate from 1.5 to 1 m/s, respectively. The pressure dropped by 65.0% by increasing the flow rate from 1.5 to 2 m/s. The results of the COMSOL simulation proved that the strategies selected with TRIZ and game theory produced better data than those without them (Tables 16–18).

Table 16
Optimized outlet temperature with increases in inlet temperature (A1), inlet pressure (A2), and flow rate (A3).

Experiment	Inlet temperature (°C)	Inlet pressure (bar)	Flow rate (m/s)	Outlet temperature (°C)	Temperature difference (%)
	(original values)				
	60	3	1.5	59.99957	
A1	70	3	1.5	69.99933	16.66638611
A2	60	5	1.5	59.99962	0.00008333
A3	60	3	2	59.99958	0.00001667

Table 17
Optimized outlet pressure with increases in inlet temperature (B1) and inlet pressure (B2) and decrease in flow rate (B3).

Experiment	Inlet temperature (°C)	Inlet pressure (bar)	Flow rate (m/s)	Outlet pressure (bar)	Pressure difference (%)
	(original values)				
	60	3	1.5	2.454118	
B1	70	3	1.5	2.454137	0.00077421
B2	60	5	1.5	4.454017	81.49155827
B3	60	3	1	2.722468	10.93468203

Table 18
Optimized pressure drop with decrease in inlet temperature (C1) and increases in inlet pressure (C2) and flow rate (C3).

Experiment	Inlet temperature (°C)	Inlet pressure (bar)	Flow rate (m/s)	Pressure drop (bar)	Pressure drop difference (%)
	(original values)				
	60	3	1.5	0.545882	
C1	50	3	1.5	0.545894	0.002198229
C2	60	5	1.5	0.545983	0.018502167
C3	60	3	2	0.900840	65.02467566

3.6 Optimizing strategy

A schematic diagram of optimizing the strategy in this study is shown in Fig. 1. When contender A bids 2.0, 1.8, and 1.6, contender B needs to decide which to accept. If contender B chooses 2.0, it bids back 1.0, 1.2, and 1.4 to contender A. Contender A always wants the maximum reward. If contender B is not satisfied with contender A's bid, contender A must choose less reward. In Fig. 1, contender A chooses 1.4 from contender B's bid and bids back 2.0, 1.8, and 1.6 again. Then, contender B chooses 1.8, and contender A selects 1.2. After repeating this process until the negotiation stops, contenders A and B choose 1.6 and 1.0 as the final reward, respectively. In this game, contender B is the weaker contender who concedes less benefit, while contender A is the stronger one with less loss.

Table 19 shows the simulation results of 27 different scenarios with changes (increase, unchanged, decrease) in the inlet temperature, inlet pressure, and flow rate, which are input as contenders in the bargaining game.

The scenario with the best result was obtained for the inlet temperature of 70 °C, inlet pressure of 5 bar, and flow rate of 1.6 m/s. These parameters yielded an outlet temperature of 69.99942 °C, outlet pressure of 4.39008 bar, and pressure drop of 0.609919 bar. The values were lower than those found in Tables 16–18 and superior to those used in a practical application (Table 20).

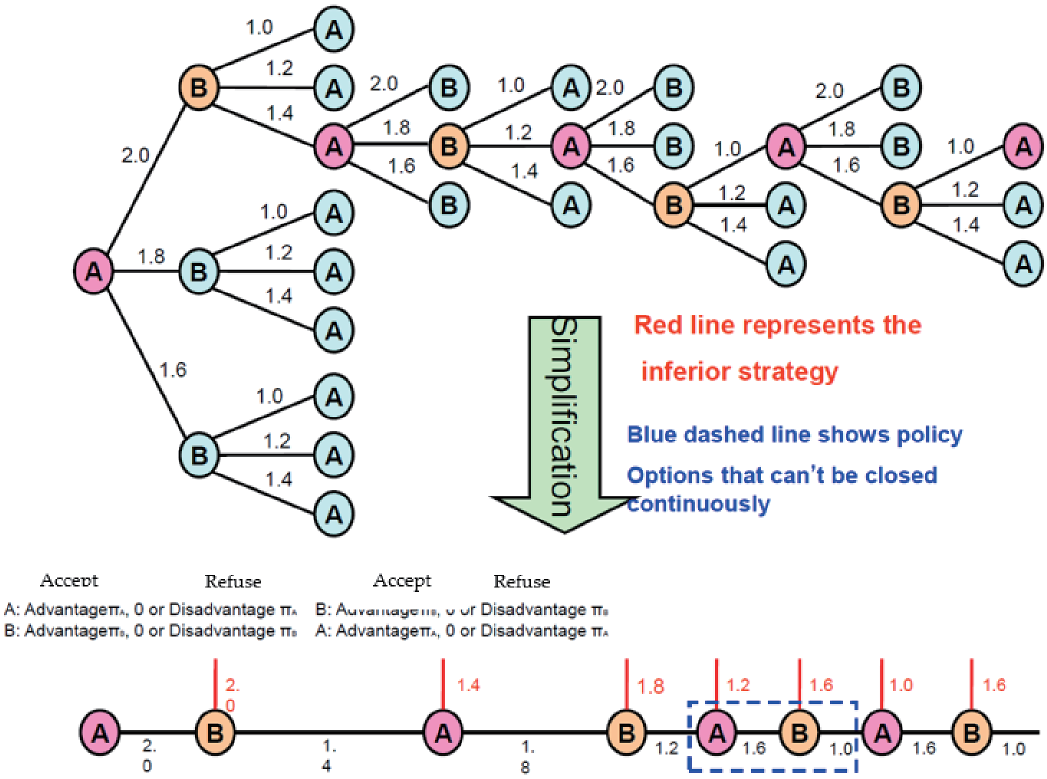

Fig. 1. (Color online) Experimental setup in this study.

Table 19
Simulation results of optimizing parameters.

Scenarios	Inlet temperature	Inlet pressure	Flow rate	Outlet temperature (°C)	Outlet pressure (bar)	Pressure drop (bar)
1	Decrease	Decrease	Decrease	48.98598	0.722437	0.277563
2	Decrease	Decrease	Unchanged	49.98657	0.454011	0.545989
3	Decrease	Decrease	Increase	49.98657	0.454011	0.900846
4	Decrease	Unchanged	Decrease	49.98762	2.722464	0.277536
5	Decrease	Unchanged	Unchanged	49.98987	2.454106	0.545894
6	Decrease	Unchanged	Increase	49.98987	2.099030	0.900970
7	Decrease	Increase	Decrease	49.99084	4.722439	0.277561
8	Decrease	Increase	Unchanged	49.99411	4.454003	0.545997
9	Decrease	Increase	Increase	49.99971	4.099110	0.900890
10	Unchanged	Decrease	Decrease	59.99118	0.722457	0.277543
11	Unchanged	Decrease	Unchanged	59.99311	0.454054	0.545946
12	Unchanged	Decrease	Increase	59.99428	0.099173	0.900827
13	Unchanged	Unchanged	Decrease	59.99375	2.722496	0.277504
14	Unchanged	Unchanged	Unchanged	59.99482	2.454117	0.545883
15	Unchanged	Unchanged	Increase	59.99558	2.099160	0.900840
16	Unchanged	Increase	Decrease	59.99626	4.722445	0.277555
17	Unchanged	Increase	Unchanged	59.99713	4.454016	0.545984
18	Unchanged	Increase	Increase	59.99802	4.099170	0.900830
19	Increase	Decrease	Decrease	69.98970	0.722474	0.277526
20	Increase	Decrease	Unchanged	69.99228	0.454136	0.545864
21	Increase	Decrease	Increase	69.99401	0.099240	0.900760
22	Increase	Unchanged	Decrease	69.99537	2.722474	0.277526
23	Increase	Unchanged	Unchanged	69.99685	2.454133	0.545867
24	Increase	Unchanged	Increase	69.99735	2.099240	0.900760
25	Increase	Increase	Decrease	69.99872	4.722481	0.277519
26	Increase	Increase	Unchanged	69.99941	4.454021	0.545979
27	Increase	Increase	Increase	69.99948	4.099230	0.900700

Table 20
Comparison of multi-quality optimal scheme and median value.

	Inlet temperature (°C)	Inlet pressure (bar)	Flow rate (m/s)	Comparison	
Parameters of this study	70	5	1.6	Outlet temperature	69.99942 (°C)
				Outlet pressure	4.390081 (bar)
				Pressure drop	0.609919 (m/s)
Median value in practical applicable range	60	3	1.5	Outlet temperature	59.99482 (°C)
				Outlet pressure	2.454117 (bar)
				Pressure drop	0.545883 (m/s)

4. Conclusions

We proposed optimizing the flow control of a PEMFC with TRIZ via the outlet temperature, outlet pressure, and pressure drop. There are contradictions in the optimization as these factors have either positive or negative effects on the performance of a PEMFC depending on their combination. Thus, game theory was applied to achieve multi-quality optimization. For the flow control of the three parameters (outlet temperature, outlet pressure, and pressure drop), the inlet temperature, inlet pressure, and flow rate were selected as the important factors. The results indicated that the outlet temperature, outlet pressure, and pressure drop increased by 16.67, 78.8, and 11.73%, respectively, upon optimization. It turned out that simulating and predicting the parameters for flow control were effective for reducing the simulation time and the amount of decision-making. This study proves that TRIZ allows a single-quality strategy and that game theory with TRIZ contributes to multi-quality optimization. The combined method provides an innovative and reliable method for establishing an appropriate strategy for developing and manufacturing devices with many factors and parameters considered. In particular, the results of this study provide a reference for designing flow control and for developing and producing PEMFCs with improved performance.

References

1 G. Altshuller: To Find an Idea, http://www.altshuller.ru/world/eng (accessed October 2020).

2 N. León-Rovira and H. Aguayo: A new Model of the Conceptual Design Process using QFD/FA/TRIZ, https://triz-journal.com/new-model-conceptual-design-process-using-qfdfatriz/ (accessed October 2020).

3 P. R. Apte and D. L. Mann: Taguchi and TRIZ: Comparisons and Opportunities, https://triz-journal.com/taguchi-triz-comparisons-opportunities/ (accessed October 2020).

4 C. Liu and J. L. Chen: A TRIZ Inventive Design Method without Contradiction Information, https://triz-journal.com/triz-inventive-design-method-without-contradiction-information/ (accessed October 2020).

5 Z. C. Liu: TRIZ Green Innovative Design Method (Green Design Newsletter, 2003) pp. 15–31. https://www.airitilibrary.com/Publication/alDetailedMesh?docid=U0026-0812200910350099/ (accessed June 2020).

6 E. Domb: https://triz-journal.com/39-features-altshullers-contradiction-matrix/ (accessed October 2020).

7 L. S. Shapley: A Value for n-Person Games, Contributions to the Theory of Games Volume II, H. W. Kuhn and A. W. Tucker Eds. (Princeton University Press, Princeton, 1953) pp. 207–318.

8 D. Gillies: Some theorems on n-person games, Ph.D. thesis (Princeton University, 1953). https://ci.nii.ac.jp/naid/10017506568/ (accessed September 2020).

9 D. M. Kreps: Game Theory and Economic Modeling, D. M. Kreps, Ed. (Clarendon Press, Oxford, 1992) pp. 91–132.

10 H. M. Wu and Z. Xia: Game Master-all-round Strategy and Application (Times Publishing, Taiwan, 2003) https://scholar.google.com.tw/scholar?cluster=9669767295693856984&hl=zh-TW&as_sdt=2005&sciodt=0,5 (accessed July 2020).

11 R. Srinivasan and A. Kraslawsk: Chem. Eng. Process. **45** (2006) 507. https://doi.org/10.1016/j.cep.2005.11.009

12 H. T. Loh, C. He, and L. Shen: World Pat. Inf. **28** (2006) 6. https://doi.org/10.1016/j.wpi.2005.07.007

13 V. Goepp, F. Kiefer, and F. Geiskopf: COMPUT. IND. **57** (2006) 189. https://doi.org/10.1016/j.compind.2005.09.001

14 G. C. Robles, S. Negny, and J. M. Le Lann: Chem. Eng. Process. **48** (2009) 239. https://doi.org/10.1016/j.cep.2008.03.016

15 D. M. Ramsey: Eur. J. Oper. Res. **188** (2008) 586. https://doi.org/10.1016/j.ejor.2007.05.031