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DESIGN OF MICRO DIRECT METHANOL FUEL CELL BY AXIOMATIC DESIGN

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ABSTRACT

In recent years, design of micro direct methanol fuel cells (μDMFCs) has attracted notable attentions as new product design of portable power supply. A design of a μDMFC integrates multiple areas of novel technologies into a very limited volume and some of these technologies are coupled with significant effects on μDMFC's power density, which easily leads to a bad design with low ratio of performance to material cost. Therefore, in this paper, a design of a μDMFC by applying axiomatic design is proposed. The result is a decoupled design matrix that meets the customer needs effectively and efficiently. Two first-level functional requirements (FRs), respectively for energy conversion mechanism and refueling are defined from a general set of customer needs of a Direct-Current power supply. In Constraints (Cs), voltage, power and maximal current are taken from the limitation employed in Centaurus Ltd's Micro Fuel Cell Program; and mechanical rigidity and safety requirements are also included. Design parameters (DPs), satisfying these specified FRs and Cs, are selected with minimal material cost. Through the process of mapping and zigzagging to the next level, FRs and DPs are defined in the same number and proven to be decoupled by design matrix.

Keywords: Axiomatic Design, Direct Methanol Fuel Cell (DMFC), Micro Fuel Cell, Fuel Cell Design

1 INTRODUCTION

Direct Methanol Fuel Cells (DMFCs) promise to power the future micro- and portable electronic devices, owing to its high energy density and inherent simplicity of operation with methanol as the liquid fuel.[1] In recent years, as new product design of power supply for portable application such as cell phone, laptop and etc, design of micro DMFC (μDMFCs), i.e. tiny version of DMFCs, has become significantly competitive among over one hundred corporations in the world for emerging commercialization of fuel cell. [9][10][12] Designers of μDMFCs are challenging a lot to reach overall satisfaction in electrical performance, refuel cycles, damage tolerance and safety warrantee by competitive material cost owing to complex couplings in design. An axiomatic approach has applied to the design of μDMFC to overcome this difficulty.

Axiomatic design is one of well accepted design methodologies. It consists of two axioms for general design [2~5]. The first axiom is the Independence Axiom. It states that the independence of functional requirements (FRs) must always be maintained, where FRs are defined as the minimum set of functional requirements that characterize the design goals [13]. The second axiom is the Information Axiom, and it states that among those design a;ternatives that satisfy the Independence Axiom, the design with the smallest information content is the best design. [6]

In this paper, a design of μDMFC by axiomatic design is proposed. The result has shown a decoupled and flexible design to adjust parameters to meet different customer needs in a range.

2 AXIOMATIC DESIGN

Axiomatic design is completed through iterations of mappings between the goal set by a designer and the method for attaining the goal. Design is a form of a product or process that can satisfy the functional requirements (FRs). In other words, it is an embodiment process of mapping FRs pertaining to a functional domain into design parameters (DPs) in physical domain. Mapping is a process of choosing a set of relevant design parameters, which satisfy a given functional requirement. The mapping process is illustrated in figure 1. A multitude of appropriate designs that satisfy a designer's FRs can be derived. The axioms offer design principles that can give the grounds for comparing a design with others or selecting one among many alternatives [14].

According to axiomatic design principle, the essence of the design process lies in hierarchies as illustrated in figure 1. Designers begin the design from comprehensive FRs. A design can decompose FRs into hierarchies, at the same time with the decomposition of DPs. The zigzagging between FRs and DPs is necessary because the two sets of each level are connected and mutually dependent.

The axiomatic design is a systematic method for finding satisfactory product design. A satisfactory design can be expressed as one that satisfies all the FRs and constraints. Therefore, a designer's role starts with defining those FRs properly and comprehensively. In axiomatic design, an acceptable design is to satisfy FRs through proper selection of design parameters. An FR is "the goal to achieve," and a DP is "the means to achieve the goal." [8]

Axiomatic Design classifies the design in term of the independence between FRs and also in terms of the independence amongst the DPs. A design matrix is defined to pursue the relationship between FRs and DPs as following:

FR= A DP

where FR is a vector for functional requirements, DP is a vector for design parameters and A is a design matrix.

If we have three FRs and DPs, the equation above can be shown as following:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

where X means a relation exists and O means there is no relation. The components in the design matrix can be expressed by constants or equations instead of X and O.

For a design to be acceptable, the design must satisfy the Independence Axiom, i.e. the design matrix takes the form of a diagonal matrix or a triangular matrix. The design is call uncoupled or decoupled design respectively with these two kinds of design matrix, or coupled design otherwise. A coupled design is undesirable, because when a DP is modified, there is no effective solution for undesirable change on multiple FRs. It is not always easy to find a single solution which satisfies the Independence Axiom. Usually various design solutions are investigated to satisfy the Independence Axiom. If multiple solutions are identified, the Information Axiom is utilized.

In this work, the design of µDMFC is carried out as a new product design by using only the Independence Axiom because multiple design candidates are not extracted.

3 MICRO DMFC CHARACTERISTICS

A fuel cell is an electrochemical device that converts chemical energy into electrical energy (with some heats) as long as fuels and oxidants are supplied. This principle has remained unchanged since the fuel cell was invented by William Groove, in 1839. [11]In recent years Proton Exchange Membrane Fuel Cells (PEMFCs) have become the main stream of research on fuel cells [9][10][12], because of better feasibility in natural environment e.g. easy management on its solid form membrane.[9] In a PEMFC, protons and electrons are generated by fuel and catalyst at anode. Protons rapidly pass through a solid membrane without electrical conductivity, instead of liquid electrolyte, and finally reach cathode. On the other hand, electrons reach cathode via the circuit that the fuel cell supports. In this way, at cathode, water is generated by the protons, electrons and oxidant (typically the oxygen in ambient air) with help of catalyst and meanwhile a voltage about 1 volt is released. Like batteries, fuel cells can also work in stacks, i.e. connected in serial or parallel structure, for higher voltage or current.

Hydrogen and methanol (dissolved in water) are the two typical types of fuel to generate protons at present. And methanol fuel is more feasible for portable application owing to its much higher density and safety than hydrogen gas in common environments. A DMFC is a PEMFC fueled by methanol solution and directly generates protons at anode without conversion to hydrogen to work as a hydrogen fuel cell. And its theoretical potential between the electrodes is 1.18 volt. [11] At present, the power density of a DMFC can be about 4 times of that of ion-lithium battery. Because of easier handling with its liquid form fuel compared with hydrogen, many companies are paying much attention to its miniaturized version, which is called micro direct methanol fuel cell (µDMFC), for portable application typically of less than or around 50 watt power.

In a µDMFC, as shown in Figure 2, in addition to the reaction process of a typical PEMFC, carbon dioxide is generated along with protons at anode where the typical catalyst is carbon supported platinum with ruthenium. [11] The sandwich of anode, membrane and cathode is the most sophisticated and important part of fuel cells and its thickness is usually in micrometres. It determines the maximal performance of fuel cell and much research is focused on its material selection. In this work, design of this sandwich is not included. Instead, the design is carried out potentially to fit different types of such thin film of sandwich, covering 4 other aspects of challenges: fuel cell stack structure for minimizing total volume, chemicals flow control for maximizing chemical reaction efficiency, waste disposal for repetitive refueling and fuel leakage proof for safety.

4 CUSTOMER NEEDS, FUNCTION REQUIREMENTS AND CONSTRAINTS

Considering characteristics of µDMFCs, a µDMFC is firstly needed to output direct current electricity. In this work, we take 22V in open-loop voltage and 50W in maximal power, defined by Centaurus Ltd's Micro Fuel Cell Program. And a µDMFC is needed to be refuelled many (this work takes 100) times for long term usage. It should tolerate accidental shocking, dropping and pressing of usual force as a battery can. And sealing of chemicals is also highly required, especially for methanol, because methanol is harmful if inhaled or touched by skin and may cause blindness or even death if swallowed [7].

Therefore, 2 highest level FRs to satisfy these customer needs are defined.

FR1: Maximize power density of direct current electrical energy output

This is the electrical function as a fuel cell basically should have, where chemical energy is converted into electrical energy.

FR2: Chemicals can be initialized

Here the chemicals include fuel, carbon dioxide and water. This FR enables fuel cells to get refueled for multiple cycles of usage.

And the constraints are defined as below.

C1: Total Volume is within 500cc
C2: Working temperature is 1~64 degree-C, normally 20 degree-C
C3: Un-fueled storage environment temperature = -30~90 degree-C
C4: No requirements of additional power supply or repetitive manual operation.
C5: Leakage of methanol is no more than 0.001% per day
C6: Leakage of water is no more than 0.01% per day
C7: Tolerate impact force of 50kg
C8: Open-loop voltage is 22 volt
C9: Maximal Power is 50W
C10: Life cycle is no less than 100 times of refuel

C1 is defined for portable application. C2 is defined by chemicals' boiling point, freezing point and common environment. C3 is defined for storage in transportation. C4 is defined for passive type of work mode as an isolated power supply. C5 and C6 are defined for security requirements. Especially, the affection of C6 to the design is also pointed out in the zigzagging of the design. C7 is defined for basic mechanical strength, especially to insure the fuel cell is hard to be broken and cause methanol leakage. C8, C9 and C10 are defined directly by the customer needs of electricity and refuel.

The zigzagging of design parameters is carried out satisfying these constraints. The mappings between FRs and DPs are uncoupled by default, unless specification.

5 FINDING DESIGN PARAMETERS THROUGH ZIGZAGGING

In consideration of the feature of μDMFC, the design parameters (DPs) to achieve FRs are conceived in physical region. At the highest level, DPs are selected as follows.

DP1: Energy conversion mechanism

DP2: Chemicals cartridge replacement mechanism

DP1 designs how to fulfill the whole process of energy conversion from fuel feed to electricity output. And DP2 designs how to replace chemicals cartridge so as to initialize the fuel cell for the next cycle of usage.

And the design matrix of these highest level settings is uncoupled.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

The DPs are decomposed to the next level through zigzagging process, and the FRs of the next level and DPs are defined.

5.1 ENERGY CONVERSION MECHANISM

From μDMFC's characteristics, FR1 is decomposed to 6 FRs for DP1, according to the chemical flow of the whole chemical reaction and the requirement of electricity output.

FR1,1: Feed methanol solution to anode
FR1,2: Maximize supply efficiency of ambient air with oxygen to cathode
FR1,3: Maximize efficiency of chemical reactions at anode and cathode
FR1,4: Diffuse carbon dioxide out of anode
FR1,5: Remove water out of cathode
FR1,6: Adjust electrical performance to the desired

FR1,1~FR1,5 are from necessary processes for a single μDMFC to operate with continuous chemical reation.FR1,6 is for overall performance. A single fuel cell can only generate a fixed potential, therefore stack structure and voltage conversion by electrical methods is needed for a stack of fuel cells to achieve specific performance.

Furthermore, equal number of DPs are selected accordingly for decoupled design, in some of which one more step of zigzagging is also shown below. For FR1,1~FR1,5, this work makes the fuel cell like an isolated power supply by designing a passive chemicals delivery system which uses no power supply as a starter to control chemicals flow.

DP1,1: Fuel feed mechanism

Effective contact area between anode and fuel significantly affects performance of fuel cell, therefore, to reach maximal performance by minimal fuel feed, it is required to get anode immersed by fuel as fast as possible. In this work, the anode is placed beneath the anode chamber. By gravity, fuel of minimized volume can automatically cover the anode. Considering the constraints for sealing, the DPs are selected to use a spring to push the fuel into anode chamber from the bottom of chamber. Along with the fuel filled into the chamber, reduction of the spring's elastic force and an increasing pressure from the increasing height of chamber's fuel and the compressed air in chamber will stop the fuel feed automatically. Anode chamber height is selected to be the minimum height to cover all the balance heights and it also affects the air compression rate which contributes to stop the fuel feed.

As fuel is needed to immerse anode as fast as possible, this work takes minimizing required fuel quantity to immerse anode as one of the FRs instead of maximizing fuel feed speed, because the latter is more coupled with other FRs, .e.g. fast fuel feed is hard to stop to prevent flooding carbon dioxide duct which affects the FR on carbon dioxide disposal. Besides, the forces to start and stop fuel flow are also required as FRs. As result, the decomposed FRs are as below.

FR1,1,1: Minimize the fuel required to immerse anode
FR1,1,2: Add a pressure to push fuel to anode chamber
FR1,1,3: Automatically stop fuel feed when enough fuel contained in anode chamber

The DPs are mapped to the following, as described above.

DP1,1,1: Structure of assembly that anode is beneath anode chamber
DP1,1,2: Elastic coefficient of a spring pushing a piston in cartridge to feed fuel from bottom of anode chamber
DP1,1,3: Anode chamber height

And the design is decoupled as design matrix has shown.

$$\begin{Bmatrix} FR1,1,1 \\ FR1,1,2 \\ FR1,1,3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP1,1,1 \\ DP1,1,2 \\ DP1,1,3 \end{Bmatrix}$$

Besides, the piston and fuel chamber in cartridge are of round shape owing to good feasibility to meet constraints of sealing.

DP1,2: Straight channel of ambient air ventilation at cathode

The channel for ambient air ventilation is designed to be a straight shape which minimizes the blockings of air flow.

DP1,3: Thin film sandwich of anode, membrane and cathode assembly

This part is assumed to be given as stated in introduction part.

DP1,4: Carbon dioxide disposal mechanism

Because methanol is easy to naturally diffuse with any gas above it, needless to say the air with carbon dioxide at anode chamber, considering the Constraint C8, carbon dioxide is designed to be absorbed by solid chemicals (e.g. active carbon) in cartridge, instead of direct diffusion into ambient air. These solid chemicals get updated with the cartridge as well as the fuel.

FR1,4,1: Diffuse carbon dioxide out of anode chamber
FR1,4,2: Dispose carbon dioxide out of fuel cell
DP1,4,1: Carbon dioxide outlet at the top of anode chamber
DP1,4,2: Carbon dioxide absorption chamber in cartridge

DP1,5: Water disposal mechanism

Some of water generated at cathode can be naturally diffused into ambient air. Therefore, only liquid water needs to be concerned here. Further DPs are selected to lead liquid water through channel by gravity to water chamber in the cartridge which is thus placed at the bottom of the fuel cell.

DP1,6: Fuel cell stack structure and electricity output interface

In this part, FRs and DPs are decomposed to realize the serial and parallel connection structure, just like batteries.

FR1,6,1: Stack fuel cells in serial way to reach desired open-loop voltage
FR1,6,2: Stack fuel cells in parallel way to reach desired maximum current
FR1,6,3: Connect cartridge to the whole fuel cell stack in chemicals flow
FR1,6,4: Connect positive and negative electrodes to circuits

DP1,6,1: Geometry of serial stack of fuel cells
DP1,6,2: Geometry of parallel stack of fuel cells
DP1,6,3: Geometry of stack connector of chemicals channels
DP1,6,4: Electricity output interface

Each fuel cell assembly consists of two fixed plates to form a Membrane Electrodes Assembly, fuel cells can then be easily stacked in serial, as shown in Figure-7. And parallel stack can also be realized, just like sandwiching an entire sheet of electrodes by two plates with multiple cells. For stacking between different fuel cell products, electrodes are electrically connected to the stack connector shown in Figure 5 and 6 where conductive materials are sandwiched between fixing plates with a membrane and two electrodes. By electrical conduction of stack connection, fuel cells can work with different requirements of voltages and currents.

5.2 CHEMICALS CARTRIDGE REPLACEMENT MECHANISM

As the chemicals cartridge contains fuel for input and wastes such as carbon dioxide and redundant water generated at cathode for removal, the chemical cartridge, as a replaceable part, functions to initialize the contents of these chemicals in time. This part designs how to achieve easy operations to use the cartridge.

FR2,1: Insert/withdraw chemical cartridge to/from the bottom of fuel cell
DP2,1: Installation slot for chemicals cartridge

FR2,2: Attach/detach chemicals cartridge to fuel cell and enable/disable chemicals flow automatically

DP2,2: Automatic connection valves for fuel duct and carbon dioxide duct

Based on the above zigzagging, the result of this decouple design is illustrated by Figure 3 ~ 6. And it is flexible to adjust the design parameters to meet more customer needs of fuel cells in a range, e.g. different volume and different thin film sandwiches of membrane and electrodes assembly for different power.

6 CONCLUSIONS

In this paper, it has been demonstrated about how the Axiomatic Design can be applied in a µDMFCs design, especially by its Independence Axiom. This approach reduces the design complexity by targeting a decoupled or even uncoupled design matrix between FRs and DPs from highest level of decisions. And as the result of decoupled design, FRs are easy to be satisfied by adjusting related DPs.

For future work, this work can be improved by more consideration of the Information Axiom to maximize the feasibility and flexibility to design for different specific customer needs in a range.

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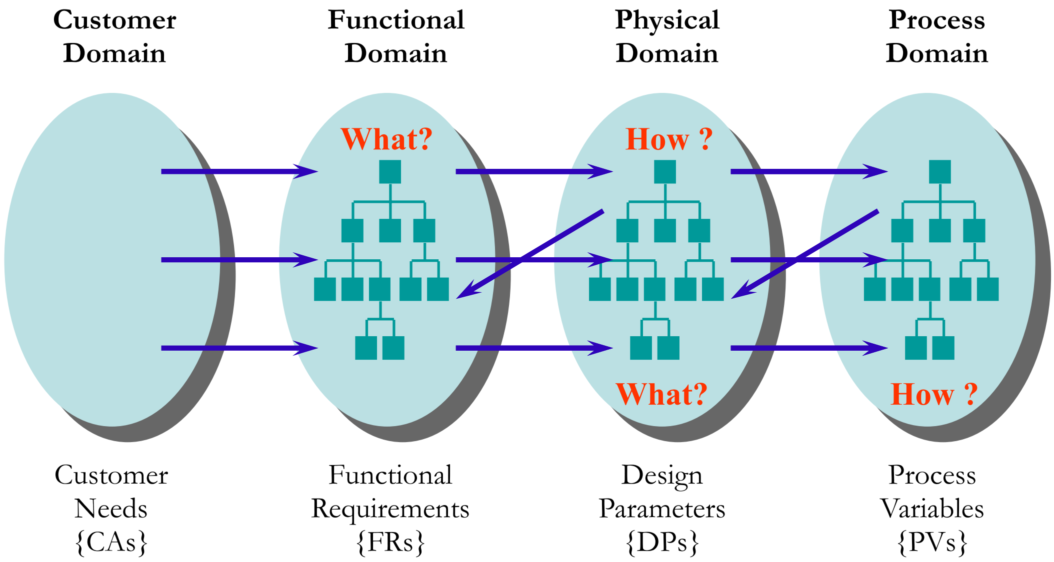

Figure-1 Axiomatic design: Mapping, hierarchies, and zigzagging (Nam P. Suh, 2002)

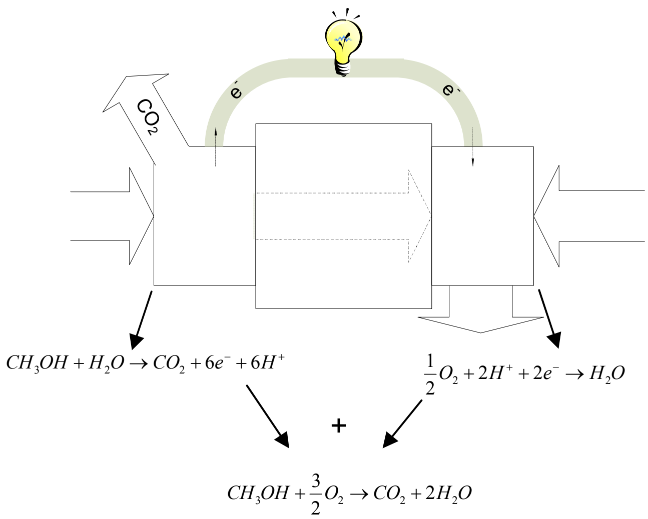

Figure-2 Direct Methanol Fuel Cell Principle

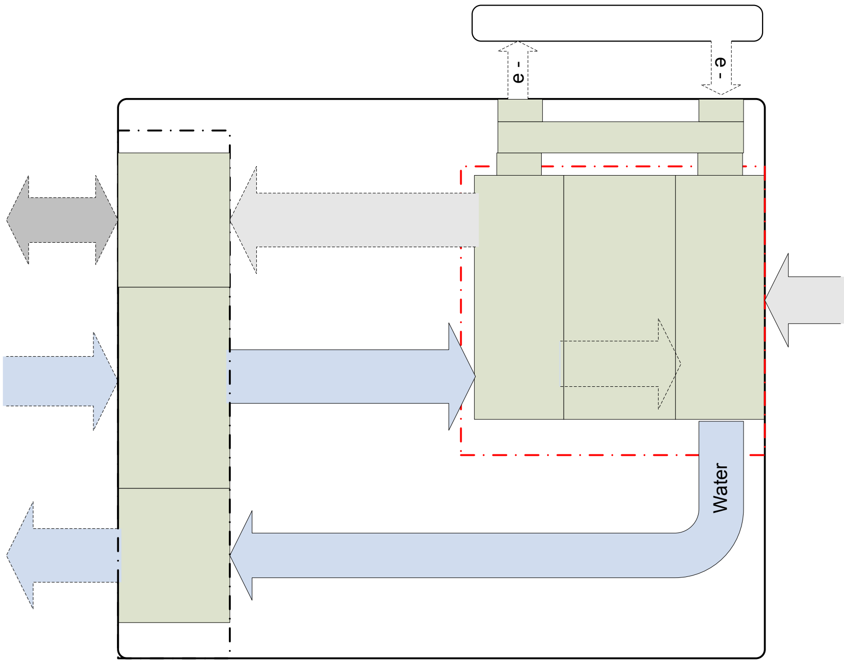

Figure-3 Scheme of µDMFC System

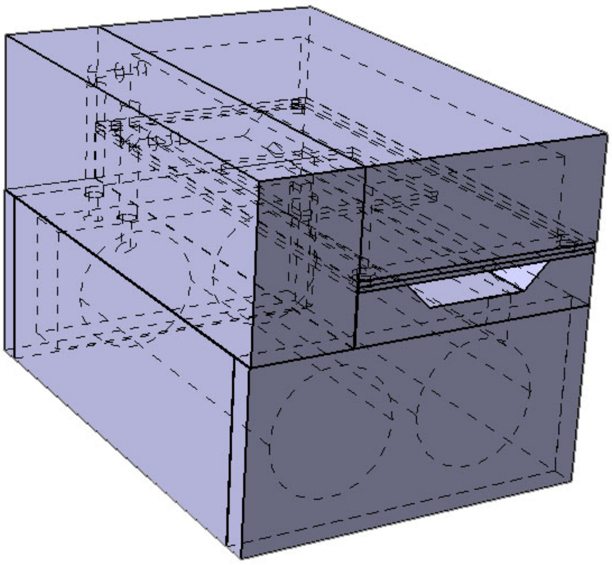

Figure-4 µDMFCs Assembly

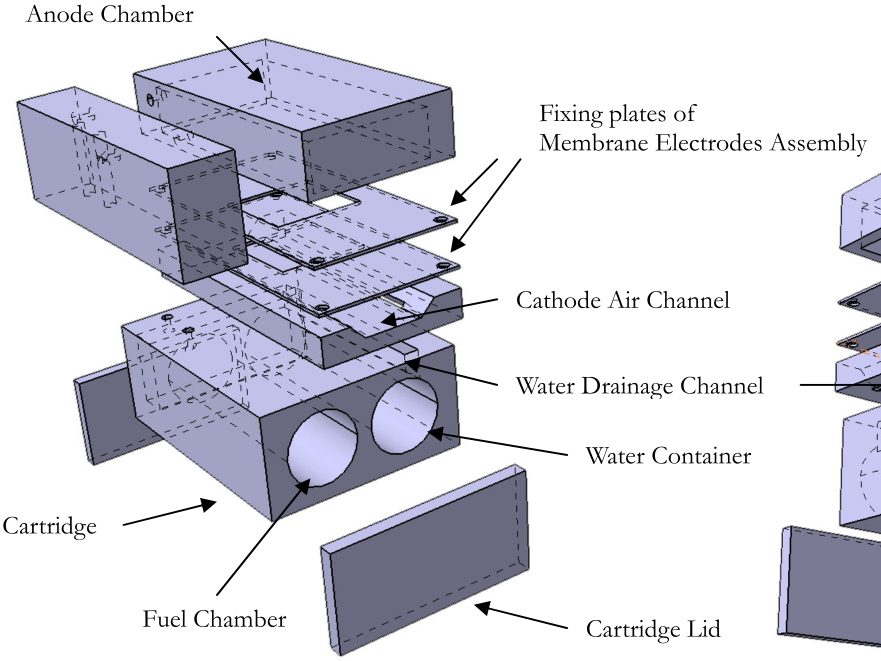

Figure-5 μDMFCs Parts (Front Perspective)

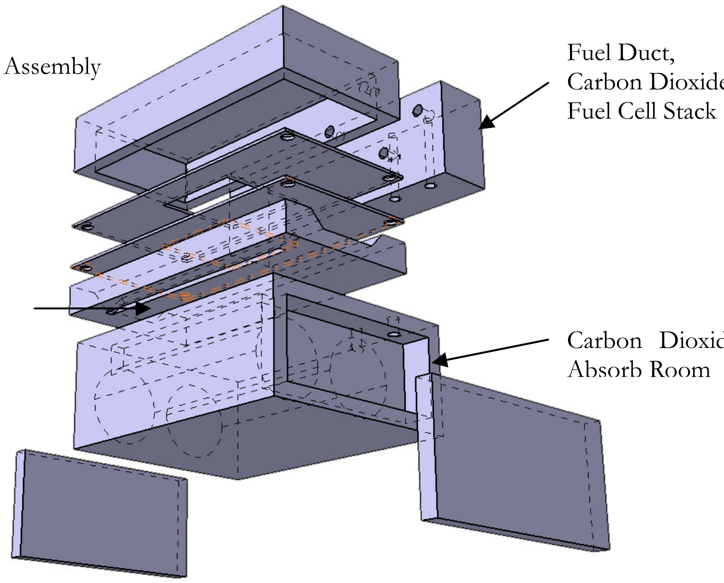

Figure-6 μDMFCs Parts (Back Perspective)

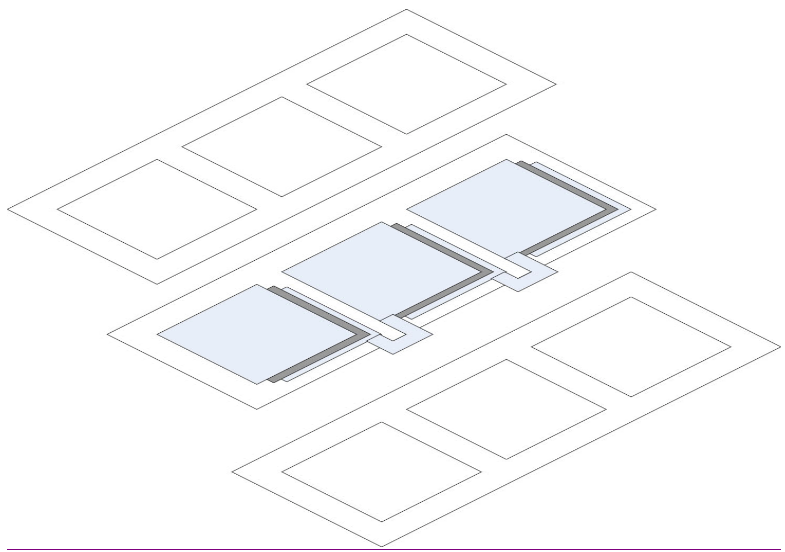

Figure-7 Fuel Cell Serial Stacking by Fixing Plates of Membrane Electrodes Assembly