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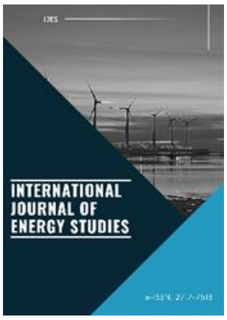

Research Article
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Simulation study of bio-inspired leaf flow field designs for direct methanol fuel cell

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Highlights

- Bio-inspired leaf flow fields investigated for DMFC bipolar plate.
- Bio-inspired flow fields are designed to match leaf sizes.
- Flow and pressure analysis of bio-inspired Mulberry, Loquat and Fig leaf designs suitable for fuel cell.

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ABSTRACT

The flow field design in the bipolar plate, which is a DMFC structure, is extremely important in the mass transfer in the fuel cell and the electrochemical reactions occurring in the cell. One of the main purposes of DMFC is to improve the flow plate in order to provide less pressure drop in all channels. Therefore, different leaf types have been investigated to improve the flow distribution performance of DMFC. Populus, Large-surface Bamboo, Palm, Philodendron, Lotus, Mulberry, Loquat and Fig leaves with similar properties were sized using the COMSOL Multiphysics program and designed by examining their environmental and physical properties. Flow and pressure distributions in accordance with the flow field design similar to leaf dimensions in two dimensions were investigated. The biological and physical properties of each bio-inspired leaf design are described and its compliance with the DMFC is explained. Finally, flow images are presented with a comparison of flow areas. When these studies in the literature are examined; while applying the bio-inspired approach, it was seen that the shape similarity approach was adopted. However, by specifying the leaf, the flow field was not created exactly in the size of the leaf. Although there is a research on the flow design in the PEM fuel cell, it has not been used at the same rate for the DMFC. Considering that it is suitable for the DMFC system with the flow channel designs in the bipolar plate in question, it is expected that the performances that will increase the flow transmission to optimum levels will also increase when used.

Keywords: Direct methanol fuel cell, Bio-inspired flow fields, Flow field design and modeling, Numerical analysis

1. INTRODUCTION

Direct methanol fuel cell (DMFC), one of the most promising alternative sources of energy technologies, has an important place in fuel cell (FC) technologies due to its high energy density, ease of fuel storage, and easy application to electronic devices. The importance of this zero emission power source has increased in recent years due to environmental problems. Although DMFCs have unique characteristics as suitable power supplies for portable applications due to the low operating temperatures of liquid methanol, they have features that need improvement such as methanol passage through the polymer membrane, slow electrochemical kinetics in methanol oxidation, liquid water accumulation at the cathode, and the flow management of the reactant input methanol+water mixture at the anode. For these reasons, it is thought that the systems in which water is best transported and distributed in nature are a subject that should be investigated more for DMFC [1, 2, 3]. The flow field models that are widely researched are serpentine, multi-serpentine, parallel, pin, spiral, and network-type flow fields. Scientific studies have been conducted to provide increases in the DMFC performance of each design. These are experimental, analytical or numerical studies on different important parameters such as heat management, water transmission and humidity control in general [4-7]. In these designs, the serpentine flow field provides improved mass transfer and reactant distribution along the flow channels. Thus, it has a more stable and improved performance [8, 9]. These superior properties can mainly reduce the efficiency due to the dispersion of the reactant, sensitive to large pressure drops across the inlet and outlet, although this is actually due to the pressure difference. The high pressure difference can also lead to high mechanical stresses on the Membrane-Electrode Assembly (MEA), resulting in a decrease in the durability of the MEA and sealing components. In addition, it has several disadvantages, such as a significant pressure drop due to localized overflow at the channel bends and at the inlet and outlet [10].

Nature-inspired leaf vein models have significant potential to efficiently and homogeneously transport alternative fluids to develop a viable flow field design considering all innovative flow field designs [11]. An analogy is made between natural structures and fuel cell flow field designs in terms of both function and structure. Many researchers are of the opinion that bio-inspired flow fields have enormous potential to disperse reactants efficiently and improve the performance of FC. There are some studies conducted to investigate the effects of bio-inspired field flow field designs on fuel cell performance. Arbabi et al. [12] used a two-dimensional numerical model to evaluate the performance of a new flow field, inspired by plant leaves. The overall pressure drop and homogeneous pressure and velocity distributions across the flow channels have been confirmed to be much more homogeneous in the new channel design, thus demonstrating its potential for higher-performance designs.

T. Chen et al. [13] conducted several researches on bio-inspired designs by investigating leaf canal structure. It has been reported that the narrowing of the cross-section along the channel with the increase in the number of channel branching in bio-inspired designs increases the cell performance in these flow model designs, as in fuel cells with conventional flow fields. Numerical simulations were also conducted to investigate the effect of channel number and location and to find that water removal is improved with more channels.

P. M. Belchor et al. [14] determined that adding branches of appropriate size to conventional flow areas where the pressure loss is low along the in-channel, flow length may not make a significant contribution to reducing the pressure loss. They also stated that the addition of branching to the channels can create more effective reactant distribution on the active surface.

V.B. Oliveira et al. [15] investigated the effects of the one-dimensional model of DMFC on the flow distributions due to heat and mass. In this calculation, a one-dimensional design was created by using electrochemical equations. Researchers have been carried out on the methanol transition in the cathode and anode layers, the battery’s temperature profile, and how the water distribution can be created in equilibrium. They emphasized that the amounts in the water + methanol transition of the designs can be determined before the experiment.

The uniformity of the reactant distribution and the performance of the water drainage depending on the flow area were investigated by J.Dong et al. [16]. Based on the bio-inspiration principle and Murray's law, a new type of flow field is presented and its effect on performance is examined by numerical simulation. In order to better performance compare with parallel flow fields, it has been stated that the inputs (O_2, H_2 and H_2O) are more evenly distributed. As a result, the new flow-field plate structure not only improves the uniformity of the reaction gas distribution, but also reduces the pressure drop in the flow channels. The maximum output power of the fuel cell with the new structure under the same conditions and on a geometric scale has been increased by 114% compared to the parallel flow area.

In the computational fluid dynamics (CFD) modeling study, four different tree leaf configurations were considered by Damian-Ascencio et al.[17]. It has been determined that the number of bifurcations and the number of slopes of leaf channels can be considered as parameters and these parameters can help in model formation. A study of mass transfer in new designs related to entropy formation was also conducted using CFD simulation results. They concluded that intra-channel water management is achieved by increasing the number of channels in terms of higher current density and lower entropy generation.

Two new bio-inspired flow domains have been created by studying the leaf channel structures of Ginkgo and Dicotyledonous plants by Kang et al.[18]. When the performance of the models was examined, they compared with traditional serpentine and parallel flow fields. In the research conducted, the highest performance of Ginkgo leaf vein design has been achieved in the research. It has shown 7% of lower performance than the serpentine compared to the power density. In order to ensure the circulation of the reactant in the channel, the pumping energy required by it is required up to 3% compared to the serpentine flow area. From best to worst designs according to water discharge performance were stated serpentine flow design, Ginkgo plant leaf vein design, parallel flow design, and Dicotyledon plant design, respectively.

L.Xia et al. [19] designed an improved bionic flow field (LVFF) according to the characteristics of the leaf vascular network structure. A detailed performance study of proton exchange membrane fuel cell (PEMFC) with LVFF was carried out with three-dimensional (3-D) design CFD by optimizing the flow area structure and the number of branch channels on one side of the main channel. Compared to the traditional flow field of LVFF, a lower pressure drop, smoother reaction gas distribution and higher power output are achieved. According to the results of experimental studies, it has been stated that LVFF has a power output of 5.894% more than the power output of the conventional serpentine flow field (CSFF) design. In addition, the distribution of the reaction gas and the new bionic flow field structure, where the current density provides a more uniform distribution, the performance improvement of the PEMFC has been reported as an area that needs to be investigated and developed more in the future.

Inefficient distribution of reactants in the active flow layer of a fuel cell is one of the most important performance parameters that also affects water and heat management. Especially in parallel flow designs with long flow path length and multiple fixed straight channels, it is known that the unbalanced distribution of reactants along the active surface is more pronounced and leads to a loss of performance. In order to solve this problem, Wang et al. [20] suggested that a more homogeneous reactant distribution can be obtained with less pressure loss, including two new flow areas. They reported that the pressure loss with the new designs is much less than in a traditional serpentine flow field. Although it has been reported that a good performance gain has been achieved from these designs, fluctuations in the flow rate of reactants and blockages due to water accumulation due to this condition have made liquid water management of design performance important.

In recent years, bio-inspired geometries have been found to be an alternative to traditional flow fields, as the research conducted within the scope of this study has been examined. There have been many researches on flow design in PEM fuel cells in the literature. Flow field designs commonly used in research are presented in Figure 1. which visuals of flow fields in the form of parallel, serpentine, intertwined, pin, spiral and radial designs. Especially in bio-inspired structures, the structures in the circulatory system of plant leaves have been intensively studied. Within the scope of the study, it is to be able to deliver the appropriate amount of methanol + water mixture to the targeted reaction sites with bio-inspired leaf flow channel designs. Thus, the natural structure of the leaf was used and appropriate reactant distribution was ensured. Depending on these results, it was determined that the vein structure dimensions and branching structures of the plant leaves were not similar. The biological and physical properties of leaf models containing bio-inspired structures for DMFC were investigated and methods have been developed for using the leaf flow field DMFC. By determining the appropriate leaf shapes, the designs were first modeled in three-dimensional, and then the flow velocities and pressure distributions were analyzed using the COMSOL Multiphysics simulation model. In addition, the applicability of bio-inspired leaf designs in the DMFC flow field was demonstrated by comparing different leaf motifs in nature. As a result, it was thought that the distribution of the optimum amount of reactant to the reaction sites could be naturally increased in cell performances.

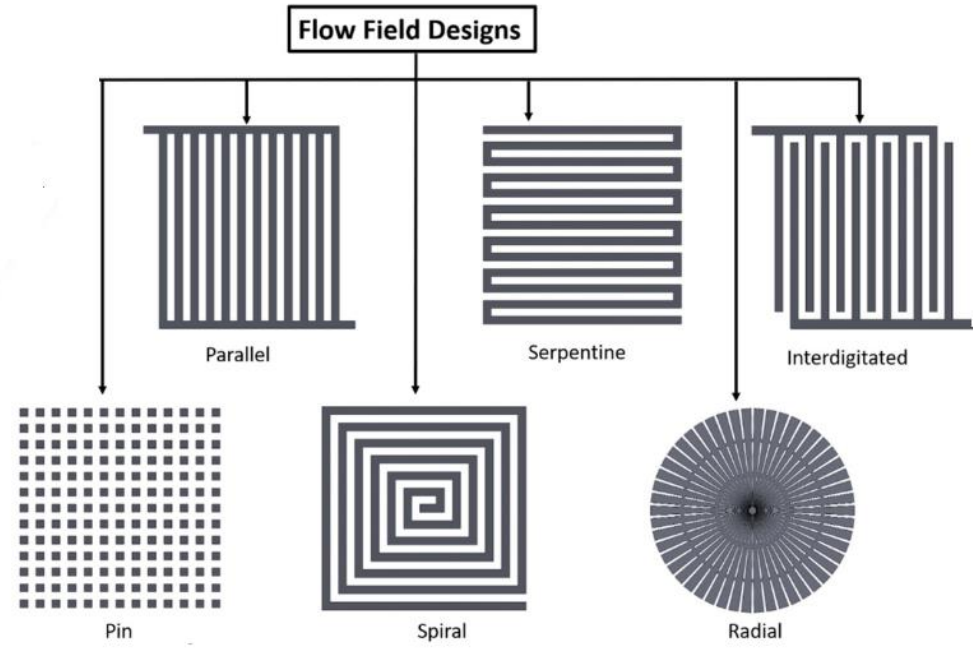


Figure 1. The most popular flow field designs used in FC [21].

2. SIMULATION

2.1. Equations

The general structure of DMFC consists of anode cell surface, anode current distributor, membrane electrode group, cathode current distributor, and cathode cell surface. DMFC is a fairly simple structured system that allows the direct use of methanol without the need for any separator. DMFC is similar to PEMFC in working principle. The reactions expected to occur in a fuel cell are as follows, respectively: An electrochemical reaction occurs on the anode of the methanol + water mixed solution fed directly into the system with the water formed on the cathode, and the resulting product forms protons, electrons and carbon dioxide. The protons formed are separated from the other output products and pass through the polymer electrolyte membrane, react with oxygen from the air in the external environment fed on the cathode, resulting in the formation of water, and the reaction is completed and the fuel cell is started.

As a result of all these reactions, voltage is generated in the external circuit and electricity production takes place. The reactions that take place are as follows;

Anode Reaction: $\mathrm{CH_3OH_{(aqueous)} + H_2O_{(liquid)} \rightarrow CO_{2(gas)} + 6H^+_{(aqueous)} + 6e^-}$

Cathode Reaction: $\mathrm{3/2\, O_{2(gas)} + 6H^+_{(aqueous)} + 6e^- \rightarrow 3H_2O_{(liquid)}}$

Total Reaction: $\mathrm{CH_3OH_{(aqueous)}} + 3/2\, O_{2(gas)} \rightarrow \mathrm{CO_{2(gas)} + 2H_2O_{(liquid)}}$

The following assumptions were made in the electrochemical analysis used in this study:

- In the flow region, laminar flow will be analyzed as fully developed and incompressible.
- The flow at the anode and cathode layers will be considered homogeneous and will be under continuous regime conditions
- Methanol can be spread to the anode side and air to the membrane area of the cathode side

Conservation of mass: A general mass conservation equation is written as valid in all component structures, including flow channels, plate surfaces, anode and cathode catalysts, and membranes:

$$m = \frac{\partial(\varepsilon p)}{\partial t} + \nabla(\partial u) \tag{1}$$

Because of the production and consumption of substances, different terms are used for anode and cathode layers. When the anode is in the catalyst layer, the amount of methanol consumption consists of the terms of total methanol passage across the membrane, water consumption, water passage on the membrane active surface, and the mass source from the produced carbon dioxide. If the cathode is in the catalyst layer, the amount of water coming from the anode to the cathode surface, the amount of oxygen consumption at the cathode, the carbon dioxide produced by the oxidation of methanol passing through the mass source terms are used.The momentum equation is given below:

$$\nabla_p + \nabla_\tau + S_u = \frac{1}{\varepsilon}\left[\left(\frac{\partial(pu)}{\partial t} + (puu)\right)\frac{1}{\varepsilon}\nabla\right] \tag{2}$$

In Equation 2, the velocity of the fluid in the backplate and catalyst layer is defined by Darcy's law. Since the transport speed is negligible in a membrane with a nano-sized pore structure, the velocity of the fluid is considered zero.

The physics interfaces which are "Secondary Current Distribution", "Transport of Concentrated Species" and "Darcy's Law" form the basis of FC simulation. One of the general definitions, physics module of “Secondary Current Distribution” is used to determine electrochemical kinetics as a sub-title of “Electrochemistry” physics model. Ohm's law is used to analyze the electrode potential (ϕ_s) in the gas diffusion layers and catalyst layers, and the electrolyte potential (ϕ_l) in the catalyst layers and membrane. The boundary conditions are set as ϕ_s=0 at the anode and ϕ_l

cell voltage at the cathode layer. The remainder of the outer boundaries are electrically insulated. According to Ohm's law, the current density for the electrolyte and the electrode is shown in Equation 3 and Equaiton 4, respectively. Here $\sigma_l$and σ_s are denoted as conductivity (S/m), ϕ_l and ϕ_s= are denoted as potential (V).

$$I_l = -\sigma_l \nabla \phi_l \tag{3}$$

$$I_s = -\sigma_s \nabla \phi_s \tag{4}$$

The charge conservation equation is shown in Equation 5 and Equation 6, respectively for the electrolyte and the electrode. Q_l and Q_s denote the source term for the electrolyte and electrode. Since the electrolyte is assumed to be neutral in the solvent program, it is assumed that the electrical charge does not change in the gas diffusion layer and the membrane. Therefore, the source terms are taken as zero.

$$\nabla \cdot i_l = Q_l \tag{5}$$

$$\nabla \cdot i_s = Q_s \tag{6}$$

The Butler-Volmer equation is used to calculate the anode and cathode electrode kinetics. The current density is calculated with this inequality as shown in Equation 7 where loc states the local current density (mA/cm^2), i_0 is the change current density (mA/cm^2), α_a and α_c are anodic and cathodic charge transfer coefficients, respectively, F is Faraday constant, R is ideal gas constant (J/mol·K), T temperature (K), and η is used to express the activation overvoltage.

$$I_{loc} = i_0 \left[exp\left(\frac{\alpha_a F_\eta}{RT}\right) - exp\left(\frac{\alpha_c F_\eta}{RT}\right)\right] \tag{7}$$

The activation overvoltage (η) is specified in Equation 8, which is associated with the electrode (ϕ_s) and electrolyte (ϕ_l) potentials. Where, E_{eq} is defined as the equilibrium potential (V).

$$\eta = \phi_s - \phi_l - E_{eq} \tag{8}$$

In the anode diffusion layer, the convection momentum of the methanol water solution comes from the liquid pressure difference and can be described by Darcy's law where, k represents the absolute permeability of the porous medium.

$$\nabla \cdot \left[p\left(-\frac{k}{\eta}\nabla p\right)\right] = Q_{darcy} \tag{9}$$

Maxwell-Stefan law was used to model the diffusion solving process in the program. The mass fractions are defined for the input from the boundary parameters of the Maxwell-Stefan equation. It has been resolved by accepting that there is no flow outside its borders. Equation 10 shows the Maxwell-Stefan equation.

$$\nabla \cdot j_i = \rho(u \cdot \nabla)\omega_i = R_i \tag{10}$$

2.2. Development of Leaf Model and Mesh Creation

Three different Populus, Large-surface Bamboo, Palm, Philodendron, Lotus, Mulberry, Loquat and Fig bio-inspired leaf designs were first transparent flow veins in the Adobe Illustrator software program and then made more prominent channels in the Vector Magic software program on a real scale for each of them. The main channel and the side channels connected to this channel were created by arranging them in a solid model program. The channel dimensions input and output length were arranged according to the flow area design and the input and output section lengths were adjusted without changing the leaf size. Finally, numerical analysis was performed in the COMSOL Multiphysics package program. All stages, from the real leaf to two-dimensional model, are shown in Figure 2. The real leaf is shown in Figure 2.a. Work has been done by using real leaf in Figure 2.b. The channels were made transparent by taking a circular section suitable for the flow area from the center of the leaf in Figure 2.c. By creating a two-dimensional model in the analysis program, the mesh process was performed and shown in the channel structure in Figure 2.d. In the flow area, all exit points from the lower main channel were determined and the flow rate for the air was visualized.

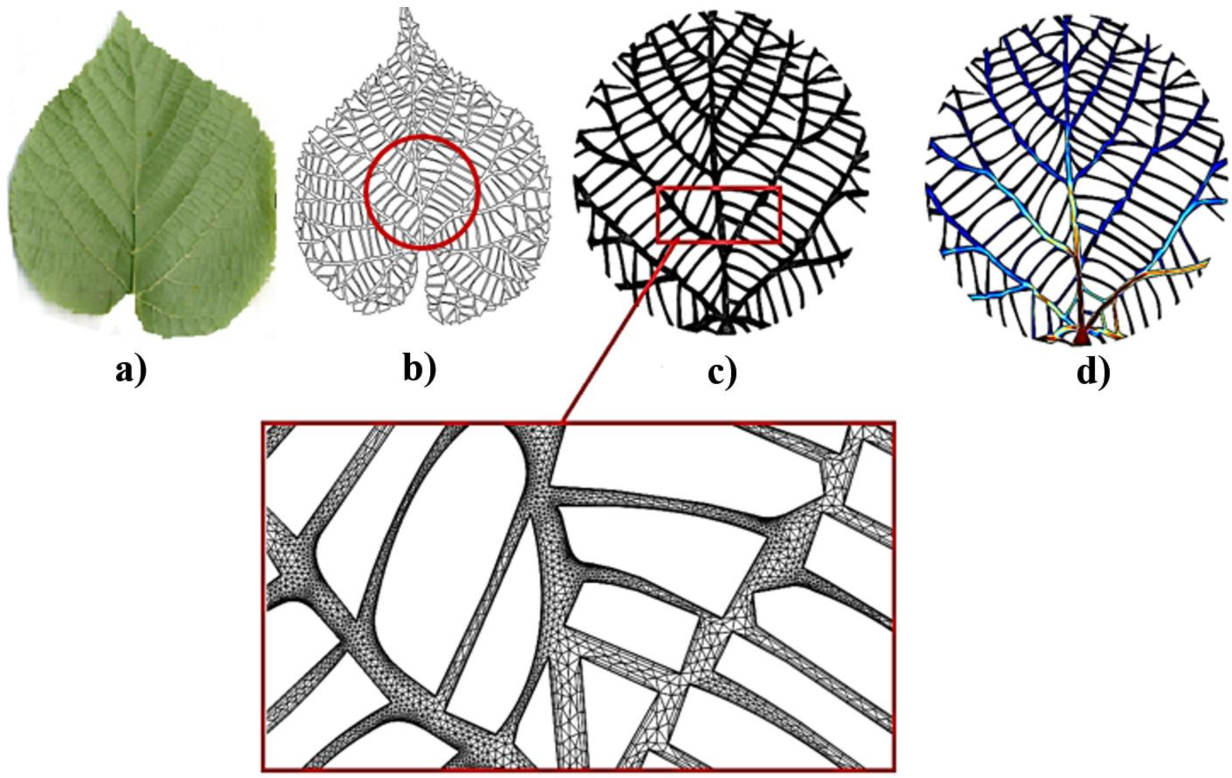


Figure 2. The stages of a real leaf shape from design to flow analysis

2.3. Structure of the Model

A two-dimensional model was created in order to observe the events taking place in the DMFC bio-inspired leaf designs in its entire structure. To determine the DMFC operating parameters, the flow velocity and pressure distribution were visualized by using the equations applied to the two-dimensional model in the COSMOL Multiphysics program. Bio-inspired leaf flow field designs were designed to be tested by using single cell dimensions in an open source computer-aided design (CAD) program. Afterwards, the input, output and channel boundaries were determined in the COMSOL Multiphysics program, and the models were created with an extra fine mesh structure. For the models used in the program, simulations were carried out with the most appropriate solver in MUMPS geometrical analysis [22].

2.4. Flow Field Design and Bipolar Plate Size Parameters

Bio-inspired Mulberry, Loquat, and Fig leaf designs were created for DMFC, and the production processes of the designs were investigated by making flow pressure distribution analyses. In recent years, the flow field on bipolar plate (BP) materials has mainly consisted of graphite materials, metals and composites. Graphite bipolar plates prevent the use of composite materials due to their high processing cost and poor workability, and their high costs. Metallic bipolar plates, on the other hand, have a long service life and relatively low cost [23]. With the appropriate material selection and surface coating, the corrosion resistance of metallic bipolar plates can be increased [24]. Therefore, metallic bipolar plates have the potential to develop in DMFCs. The size and design features of each of the bio-inspired leaf designs are presented in Table 1.

Table 1. Design dimensions of bio-inspired leaf designs in the form of cells

Parameter	**Type of Bio-inspired leaf**		
	Mulberry leaf design	**Loquat leaf design**	**Fig leaf design**
Cell dimensions	10 cm x 10cm	10 cm x10 cm	10 cm x 10 cm
Active area	20 cm^2	20 cm^2	20 cm^2
BP thickness	2 mm	2 mm	2 mm
Channel depth	1 mm	1 mm	1 mm
Support layer size	10 cm x 10 cm	10 cm x 10 cm	10 cm x 10 cm
Support layer thickness	1 cm	1 cm	1 cm
Connector sizes for input and output	2.35 mm diameter	2.35 mm diameter	2.35 mm diameter
Current collection connection dimensions	2 cm x 2 cm	2 cm x 2 cm	2 cm x 2 cm
Cell fixing hole	4 pieces 2.15 mm in diameter	4 pieces 2.15 mm in diameter	4 pieces 2.15 mm in diameter

Bio-inspired leaf flow field designs are designed in two parts. It is formed as a single plate that provides both the flow field and the current collection task.

3. RESULTS AND DISCUSSION

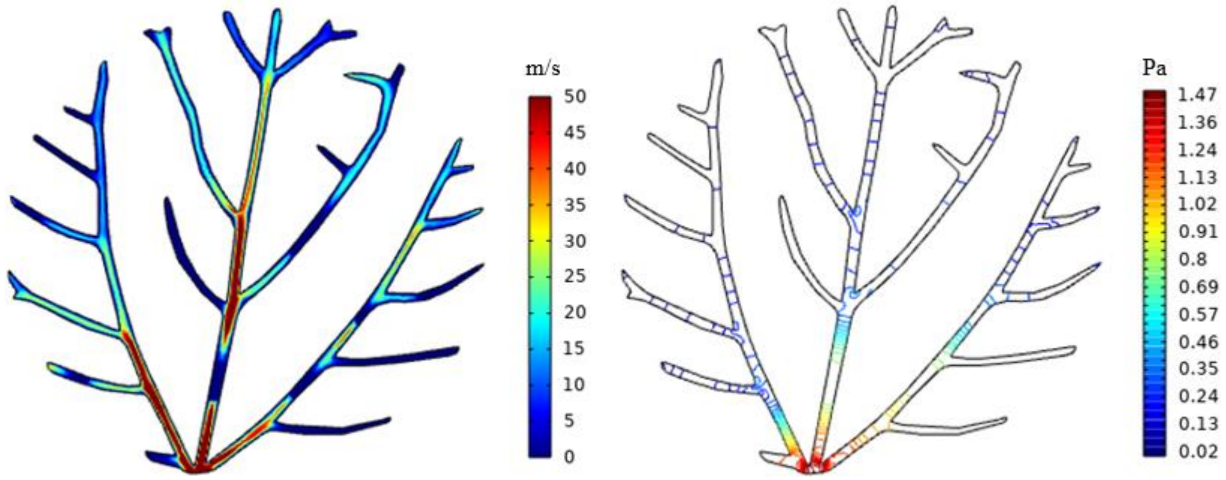
In this study, the use of bio-inspired Mulberry, Loquat, and Fig leaf designs in the flow field plays a critical role in the fuel cell flow management and therefore in its performance. It is aimed to improve the flow in the active area with flow channel designs, taking into account the physical condition of the leaves as well as their biological and physical structure. These leaf designs are categorized as the preferable ones. Since their channels and scales are more suitable for the DMFC's flow field. To consolidate this statement, Mulberry, Loquat, and Fig leaf designs were compared with less preferable leaves which are Populus, large-surface Bamboo, Palm, Philodendron, and Lotus plants. Totally eight different leaf designs were analyzed individually by scaling on-to-one into the COMSOL according to management of flow rate and pressure. Proper amount of reactants were delivered to the reactions sites of each leaf designs. Resulting products, such as water, were examined by colored scale of the flow rate and pressure distributions. This is important to understand for the potential of the reducing of the congestion by removing resulting products from the reaction site. This examining is useful in terms of the water balance in the canals and intra-system heat management. Thus, the efficiency of the cell is increased due to the natural structure of the leaf according to these analyses. Besides of the analyses, characteristics of each plant leaves were also given to understand water management in their natural-habitat.

3.1. Research and Analysis Results of Different Leaf Characteristics

The physical states of different leaves, whose preliminary research was carried out in this field, were examined by taking into account their biological and physical structures. In general, leaves growing in different regions and their climate characteristics have been investigated. Flow and pressure analyze of channels at common leaf sizes are presented. In each flow field design, a thin network of two-dimensional leaves flowed from the entrance of the main channel at a speed of 50 m/s. All other end sections of the channels are designated as outlets. Pressure changes were investigated for the same regions. Finally, leaf design and its use in the DMFC flow field are examined.

3.1.1. Populus plant leaf characteristics and analysis results

Populus Plant has a woody structure belonging to the Willow family (Salicaceae). Its most important feature is that its growing period is short. It can be easily grown in moist places with high water content. Populus trees whose average height varies between 10 and 20 meters, have wide and widespread branches depending on the climate region. When the structure of the leaves is examined, their upper parts are generally green and their lower parts are light gray. In general, Populus leaves are triangular in shape. The edges of the leaves are rough and the surface is smooth. In addition, since the surface area of the Populus leaf is narrow and the water content is high, only the main vein lines are distinct [25].



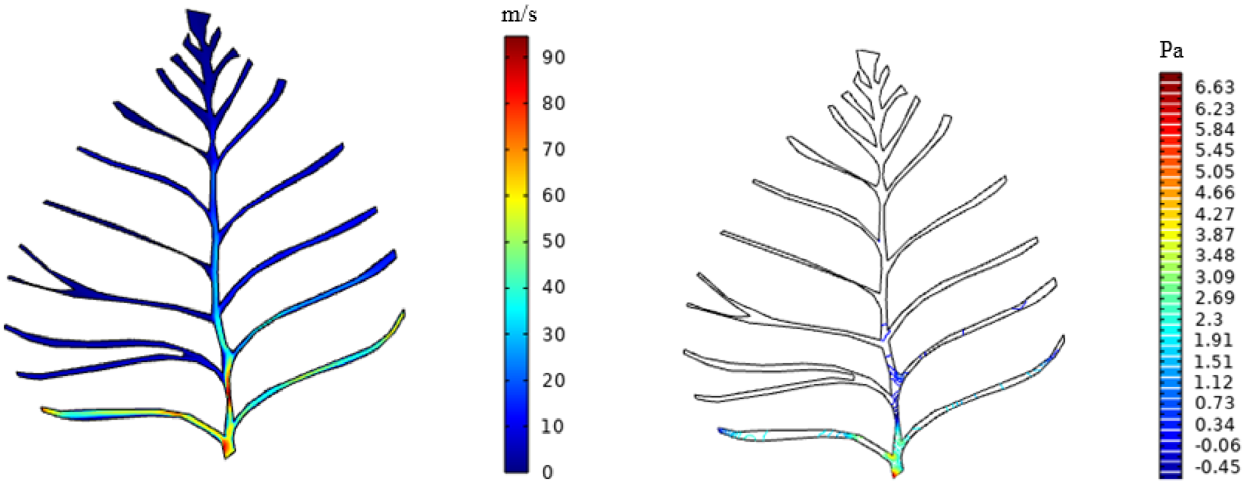
a) **b)**

Figure 3. Populus leaf a) Reactant distribution in its veins depending on the flow rate b) Pressure distribution

It was studied on a real Populus leaf. The number of leaves resolved with fine mesh is calculated as 9855. In Figure 3.a, Two-dimensional Populus plant flow rate was applied to the main vein entrance as 50 m/s. ın Figure 3.b pressure change is shown. Since the leaf is small in size and the vein structure is not obvious, it is not sized appropriately for the design. The pressure difference is the highest 1470 x 10^2 Pa

3.1.2. Large-surface bamboo plant leaf characteristics and analysis results

Bamboo is a woody perennial plant that can always maintain its vitality and green color. There are more than 200 species of evergreen bamboo, which is one of the oldest and first species of the herbaceous plant family [26]. But the one with long, thin leaves are more common. The content of the bamboo plant body has a hollow structure and the water content of the stem leaves is high. It is the fastest growing forest plant in the world, starting from the germination period. It can grow up to an average of 90 cm per day. They vary considerably in size as they begin to grow. When some leaves are fully developed, they usually have a very thin transparent structure [27]. Thus, the leaf veins are also very thin and sparse. It is the broad-leaved type studied in design.



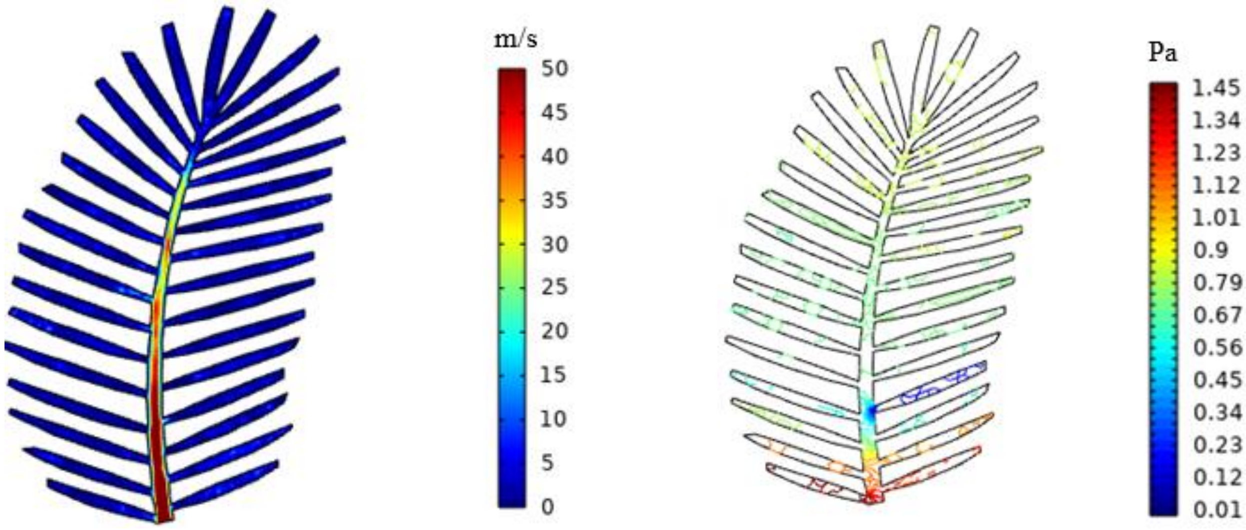
a) **b)**

Figure 4. Large-surface Bamboo leaf a) Reactant distribution in its veins depending on the flow rate b) Pressure distribution

Broad bamboo leaf has been investigated. The number of leaves resolved with the fine mesh was calculated as 6783. In Figure 4.a, flow speed of 50 m/s was applied to a two-dimensional bamboo leaf at the entrance of the main vein. The end parts are accepted as exits. In Figure 4.b, the pressure change shown is given. Although the size of the leaf is large, its vein structures are thin. Since the vascular structure is thin, the flow is fast and the pressure difference increases. The pressure difference is the highest 6630 x 10^2 Pa

3.1.3. Palm plant leaf characteristics and analysis results

Palm plant is the general name given to tree species in the palm family. They can grow in tropical regions of almost all continents. The palm plant is rich in oil content and has a wide variety of uses among tree species and there are 12 different types. The plant is very tall in the range of 25-35 meters in height. The varieties have a structure suitable for growing in very moist soils. Its leaves are long and thin and placed parallel to the main branch. The inner parts of the main tissues of the leaves have a large structure that allows the passage of lots of air, water and nutrients [28].



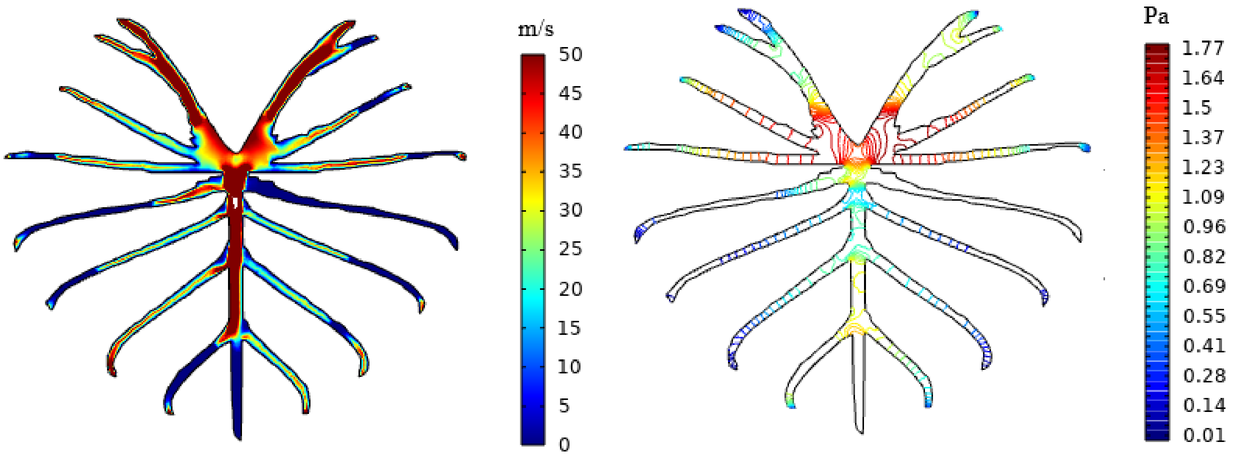
a) **b)**

Figure 5. Palm Plant Leaf a) Reactant distribution in its veins depending on the flow rate b) Pressure distribution

Figure 5.a shows the analyzing of two-dimensional palm plant leaf flow rate. Before the analysis was created, it was resolved by assigning fine mesh. As a result of the analysis, the number of meshes was calculated as 7299. In Figure 5.b, reactive air was given at a speed of 50 m/s from the inlet main section of the main duct, and all exit points of the other end sections of the wing were determined. Pressure distribution is observed in the entire leaf flow area design from inlet to outlet. In general, although there was intense pressure in the inlet region, it decreased along the main channel. The pressure difference is the highest 1450 x 10^2 Pa.

3.1.4. Philodendron plant leaf characteristics and analysis results

It is a species of the Arum family and grows in very humid and very wet areas. It is a herbaceous plant species. Philodendron plant is commonly known as a kind of fern [29]. This plant species has a broad shield-like surface with its leaf feature. It accumulates a high amount of humus in the leaves which it feeds from its roots. Previous studies on this plant habitat have not been common, and no studies have been conducted on exact measurements of physical and leaf sizes [30]. Very little is known about the anatomical structure and design of the leaves. Based on the habitat characteristics and physical appearance of Araceae leaves, which are described among its species, it is known that the surface area is very large and the water content of the leaf is high. This species has a leaf structure that can grow up to 1-2 m in length and width. Inspired by the canal structure and distribution among broad-leaved plant species.



a) **b)**

Figure 6. Philodendron plant leaf a) Reactant distribution in its veins depending on flow rate b) Pressure distribution

In Figure 6.a, two-dimensional Philodendron leaf flow rate was analyzed. Before the analysis was created, it was similarly dissolved with fine mesh. As a result of the analysis, the number of meshes was calculated as 47375. In Figure 6.b, reactive air central zone inlet flowed at a speed of 50 m/s. The ends of the channels connected to the central region are designated as exits. Pressure distribution is observed in the entire leaf flow area design from inlet to outlet. In general, the flow rates and pressure in the inlet region are determined intensely. The highest pressure difference is is obtained as 1770 x 10^2 Pa.

3.1.5. Lotus (Nelumbo) plant leaf characteristics and analysis results

It is a species called Lotus (Nelumbo nucifera) that can grow up to about 30 cm in diameter and grows in a semi-wetland habitat. Some of the leaves grow on the surface of the water to adapt to the aquatic environment of the lotus plant, which has remarkable water-repellent properties [31]. Lotus leaf has super hydrophobicity and surface structure self-cleaning of plant surfaces. When the structure of the leaf is examined, it shows an extraordinary waterproof feature especially on the upper side, it is more robust than the lower surface and shows better resistance against mechanical conditions. The reasons for these superior properties can be attributed to the geometric shape and chemical composition of the microstructures [32]. Plant surfaces are very large and provide water and nutrients through channels, and they also cover a very large surface area.

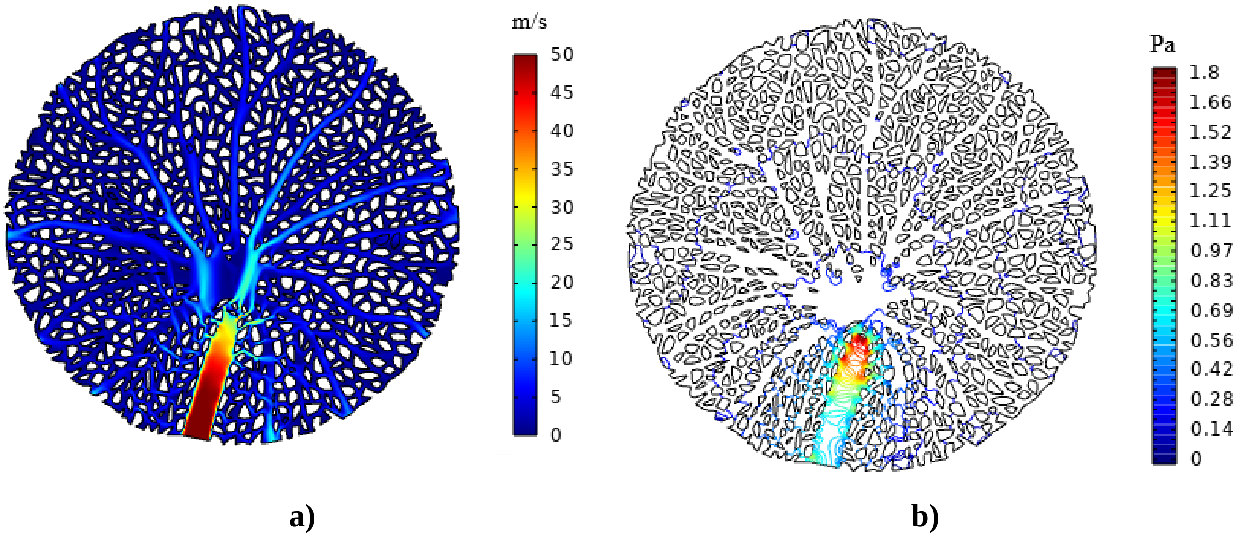


Figure 7. Lotus (Nelumbo) plant leaf a) Reactant distribution in its veins depending on flow rate b) Pressure distribution

Figure 7.a shows the Lotus (Nelumbo) plant leaf and its flow rate was analyzed. Before creating the analysis, it was solved with fine mesh applied to other leaves. As a result of the analysis, the number of meshes was calculated as 76596. Reactive air was supplied to the central region of the leaf at a speed of 50 m/s to the main channel entrance in Figure 7.b. All end sections of the connection channels radiating from the central region to the periphery are designated as exits. It decreased from the center, where there is intense flow from the entrance, to the extreme parts. Also, this situation is similar for pressure distribution. In general, the pressure is very intense in the entrance area. It has decreased greatly in a wide area. The pressure difference is the highest 1800 x 10^3 Pa.

In general, the physical structure of different leaf shapes has been investigated. The leaves are generally chosen in large sizes, so the channels are aimed to be clear. Research on plants growing in more humid and watery areas has concluded that the leaf channels are not very thin and not evident. When the leaves are examined, the water storage capacity of the Populus leaf is high, the main channels are obvious, but the connection channels are not. This makes its design difficult. On the large-surface Bamboo leaf, the central flow channels are very thin and their connections are disconnected. Additionally, the number of channels in the active area is very small. Palm leaf flow channels are distinct and regular. However, its elongated shape is not suitable for circular designs. Philodendron leaves are wide and main channels are evident. But the main channel is in the central region of the leaf. This prevents the flow fields from being crossed at the inlet and outlet in DMFC designs. The lotus leaf has a wide structure and many channels, which is suitable for the design. However, there is no production method that can create very thin channels in production. It also increases the cost of the flow area plate greatly. In addition to all these leaf designs, Mulberry, Loquat, and Fig leaves are preferred to be both wide and prominent and numerous in the active area of the channel. The fact that the leaves do not grow in too humid areas increases the capacity of the leaves to hold and transmit more nutrients and water. Additionally, three different leaf designs were compared by performing detailed flow pressure analyses.

3.2. Mesh Design, Characteristics and Analysis Results of Preferred Plant Leaves

Populus, Large-surface Bamboo, Palm, Philodendron, and Lotus (Nelumbo) plant leaves have unique shapes to inspire to design flow channel of the DMFCs for flow management. However, some of these leaves have bigger to integrate directly into the DMFCs and some of them have very tight channels to disallow the flow the fuel inside through them. Because of all these deficiencies, Mulberry, Loquat and Fig plant leaves are more preferable to integrate into the DMFCs as a flow channel. Hence, the characteristics and analysis results are given for these three leaves in this part in detail. Also, mesh designs are given to understand better how these channels are more suitable to preferred to inspire to use in the DMFCs.

3.2.1. Mulberry plant leaves mesh design, characteristics, and analysis results

Mulberry is known as a perennial tree belonging to the Moraceae family. It can be grown in different regions, including temperate, subtropical and tropical [33]. The general air temperature of the growing regions of the Mulberry plant can naturally develop between 5–35 °C. Growing the habitats in naturally moist environments has excessive water demand, especially during the growing phase. This allows the mulberry leaves to be large in size, and their width and length are in the range of about 3-12 cm. It is thought that the main and lateral channels of the leaf of the mulberry plant are more prominent, and it has the ability to carry more substances depending on the inner diameter of the channel [34].

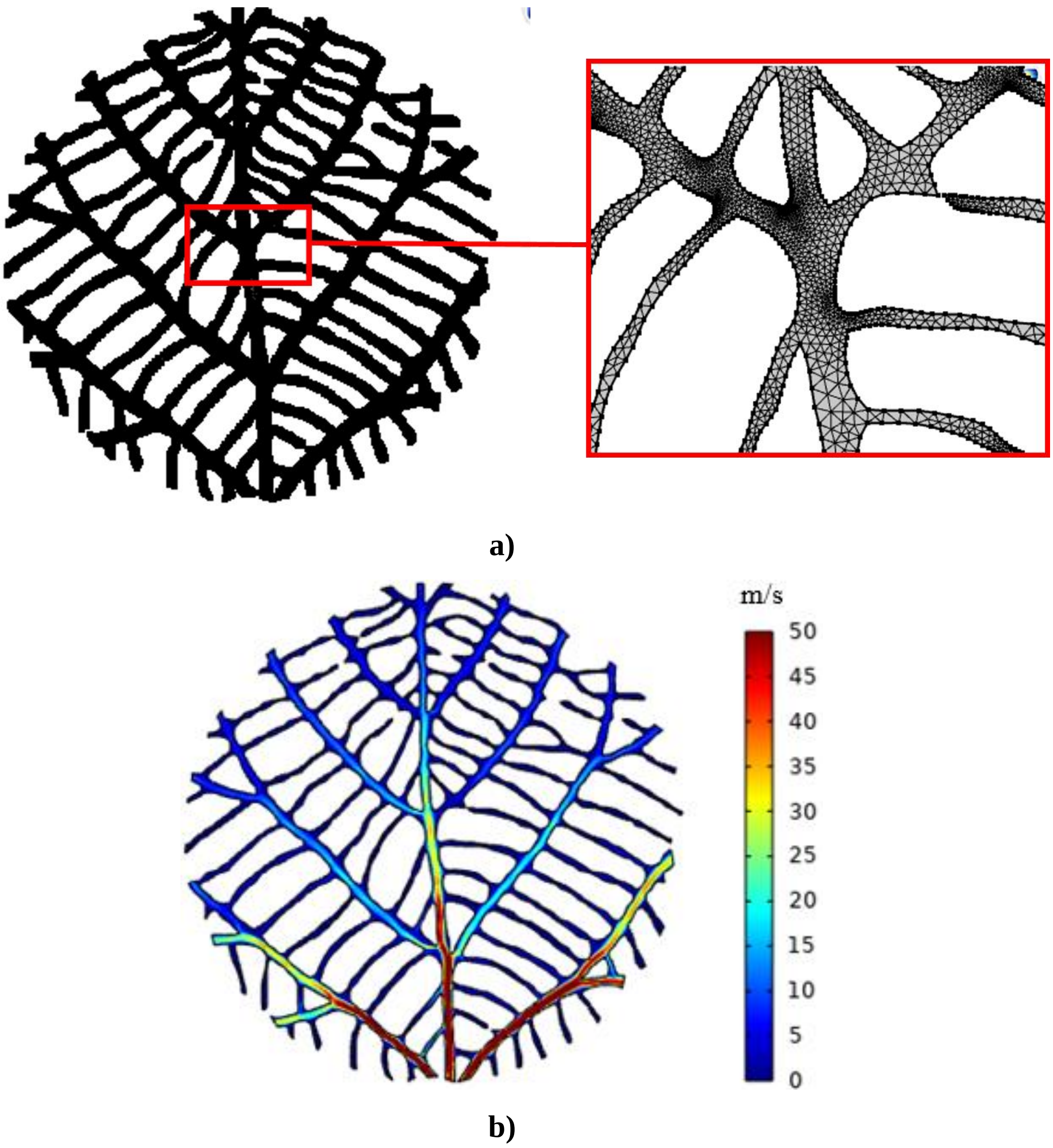


Figure 8. a) Mesh version of the bio-inspired mulberry leaf design b) Reactant distribution depending on the flow rate in the active area

In Figure 8.a, two-dimensional mulberry plant leaf is made suitable for flow rate and pressure analysis by taking fine mesh. As a result of the analysis, the mesh number was calculated as 39979. In Figure 8.b, Reactant air was supplied at 50 m/s from three different inlet sections of the main duct, and all other end points of the leaf were determined as outlets.

3.2.2. Loquat leaf characteristics mesh design, characteristics, and analysis results

It is a species of Loquat (Rosaceae) family. A medium-sized woody tree species, mostly apical leaves are elliptical-narrow long. Leaf is 12 to 30 cm long and 3 to 10 cm wide. The leaves on the lower part of the branches then take an oval shape according to the developmental stage. Although it needs water in the first years of its growing period, it has the ability to hold enough water in its body in the later stages. With this feature, it can easily develop in hot and humid climates [35].

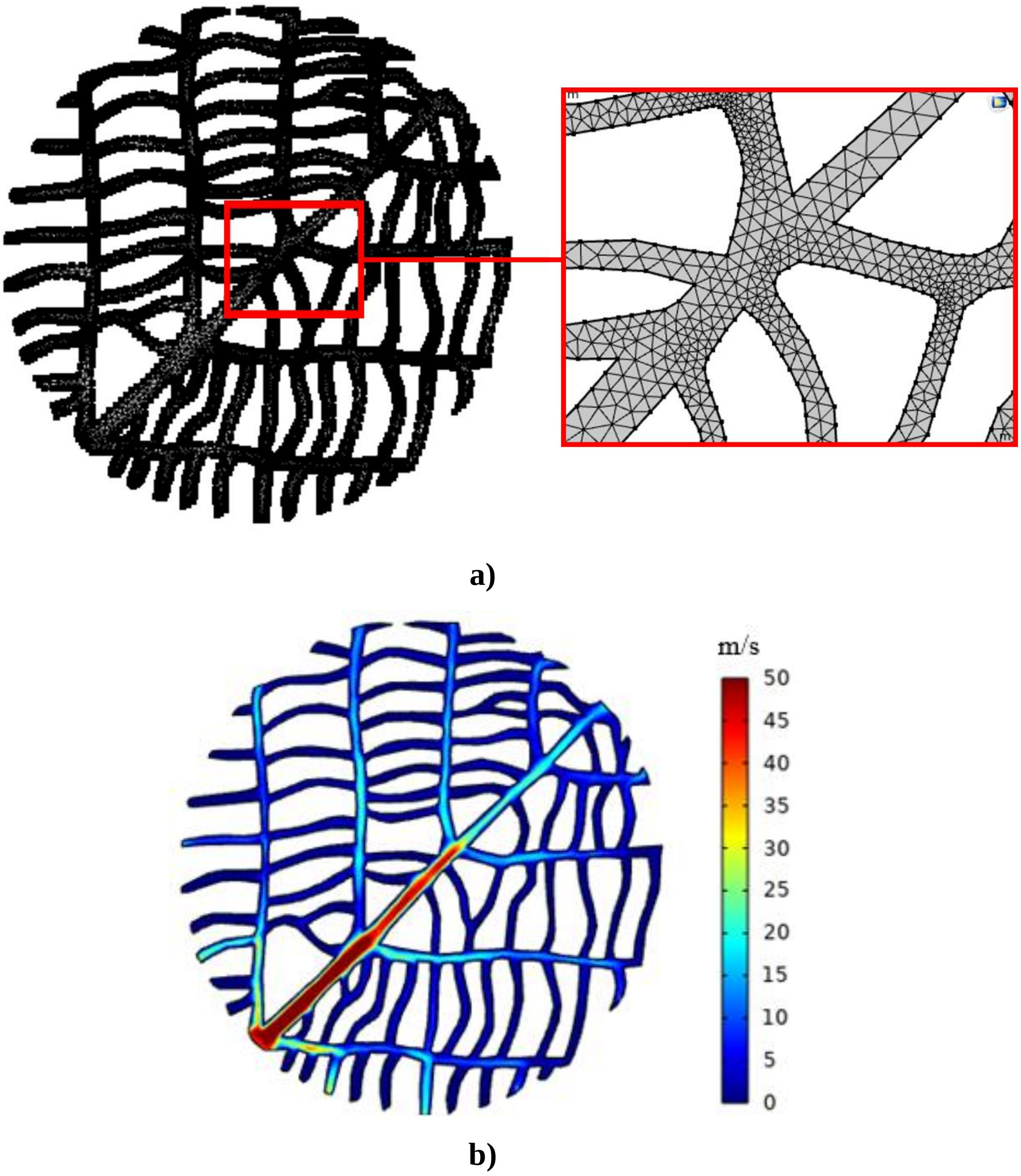


Figure 9. a) Bio-inspired Loquat leaf design with meshwork b) Reactant distribution depending on flow rate in the active area.

In Figure 9.a, the two-dimensional loquat leaf was made suitable for flow and pressure analysis by taking fine mesh in the Comsol Multiphysics program. As a result of the analysis, the Mesh number was calculated as 11333. In Figure 9.b, all other end points of the leaf, where the reactant flow is provided at a value of 50 m/s from the cross section of the main channel, has been determined as the exit.

3.2.3. Fig plant leaf mesh design, characteristics, and analysis results

Fig which is a subtropical fruit tree, has an annual average temperature of 16-19 ºC in the regions where it grows. Average rainfall of 600-700 mm is sufficient for the growth of the plant and for the formation of sufficient substance and water distribution. When the soil structures where growing of figs are examined, it is generally grown in deep soils that hold water in its slightly calcareous, clayey structure and moderately permeable structure. In terms of this feature, the plant has a high-water storage capacity and a high-water storage capacity for a long time in hot summer months. When the leaf structures are examined, its width is 15-25 cm on average and the canal structures are very prominent and the capillary channels show a good distribution on the entire leaf surface [36].

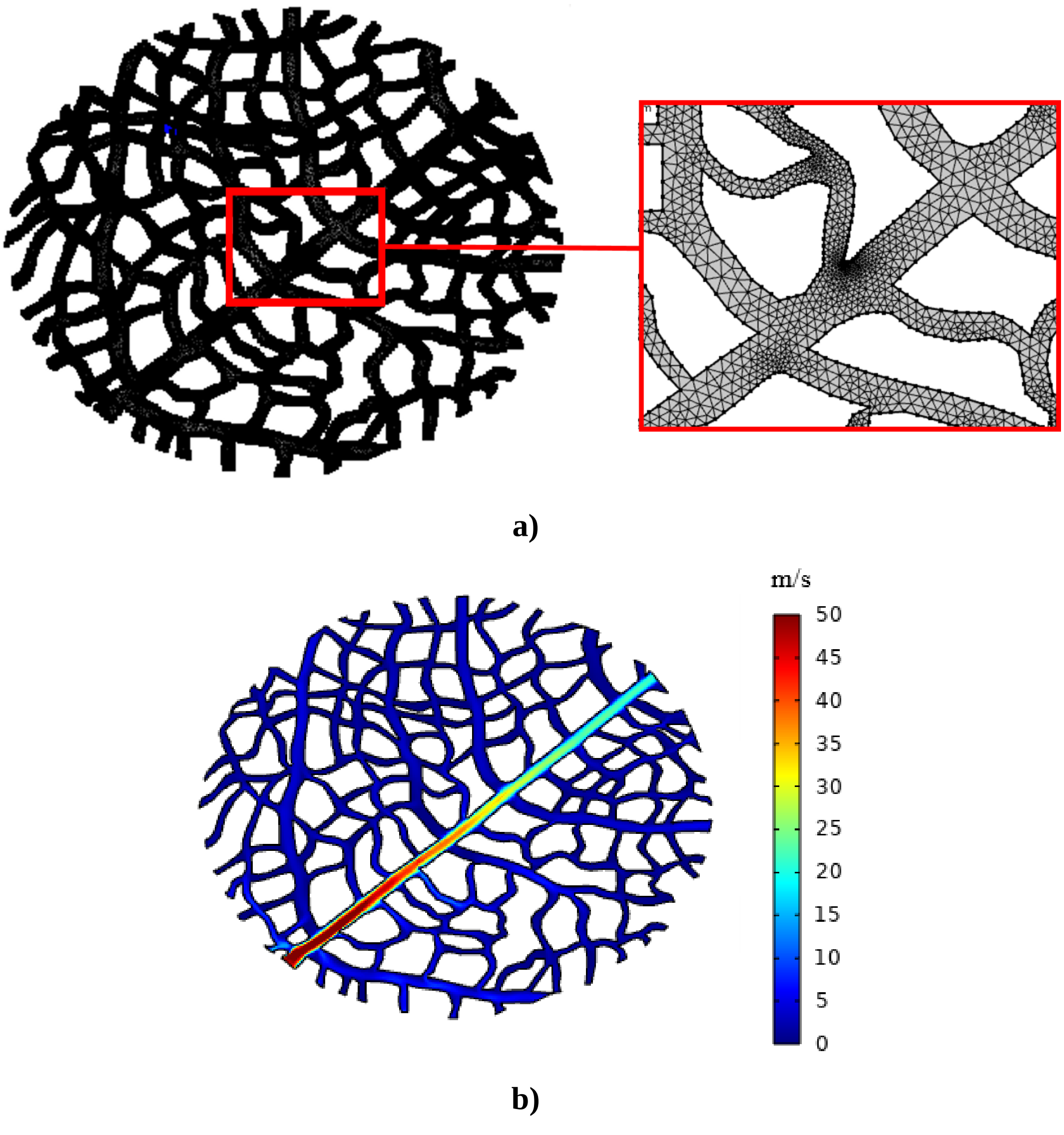


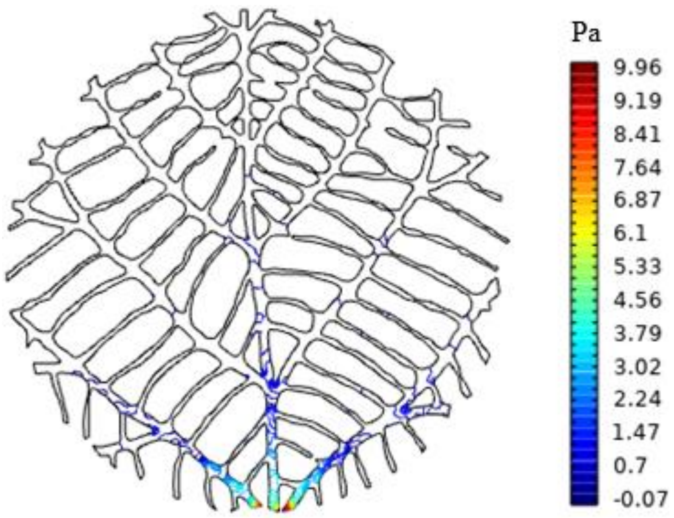
Figure 10. a) Bio-inspired Fig leaf design with meshwork b) Reactant distribution depending on flow rate in the active area

In Figure 10.a, two-dimensional Fig plant leaf was made suitable for flow and pressure analysis by taking extra fine mesh in the COMSOL Multiphysics program. As a result of the analysis, the mesh number was calculated as 33375. In Figure 10.b, similar to other designs, all other end points of the leaf, with a reactant flow of 50 m/s from the cross section of the main channel, are determined as outlets.

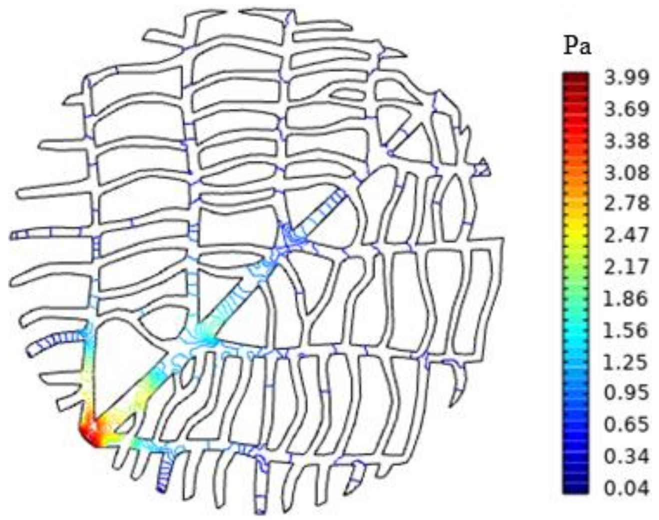
For the leaf design of Mulberry in Figure 8.b, Loquat in Figure 9.b, and Fig in Figure 10.b the distribution of the ambient air in the active area at a flow rate is given as 50 m/s. In these designs, the flow distributions were examined by determining the input and output channels to the cell. In general, it is observed that the flow rate decreases in the auxiliary channels, where the flow proceeds along the main vessel from the entrance. In the Fig leaf design, the channels are wide and well connected to each other has made the flow more balanced. In the Mulberry leaf design, the ends of some thin veins being too narrow or closed prevented the flow from being transmitted. The vein structure of the new world leaf design is less spread over the active area compared to the Fig design. This has caused from the pressure difference to increase.

3.2.4. Pressure distributions of preferred bio-inspired leaf designs

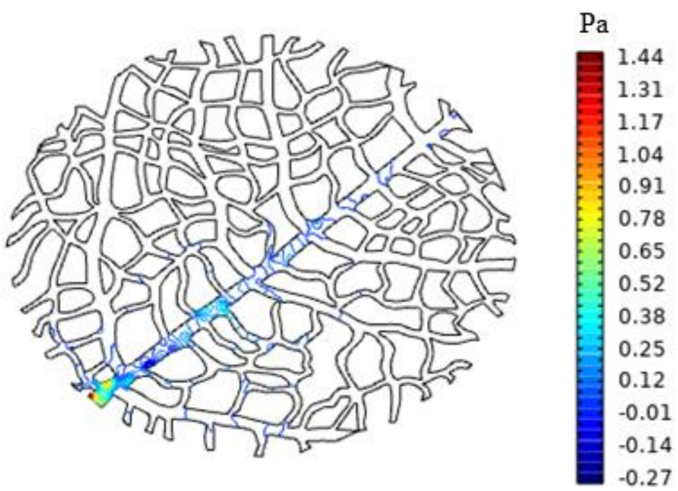
The pressure distribution of each three different preferred leaf designs is shown in Figure 11. The pressure distribution of the entire leaf flow area design from the inlet to the outlet is observed. In general, although there is intense pressure in the inlet region, it decreased in the outlet regions. This was observed with the color changes of the pressure. The leaf design with the highest pressure difference is Mulberry leaf with 9960 Pa. On the other hand, the least is the Fig leaf design with 1440 Pa. When the Mulberry leaf is examined, the leaf widths are narrow compared to other designs, and the veins towards the end parts are disconnected from each other. When the Fig and Loquat leaf designs are examined, the leaf channels are obvious and their connections are very good. At the same time, the mesh structure is better distributed in the active area. The pressure distribution tested with ambient air provides information about the distribution of bio-inspired leaf designs in the active area. In addition, it is aimed to remove the water formed in the cathode region from the environment more easily without creating too much pressure difference in the discharge.



a)



b)



c)

Figure 11. Pressure distribution of bio-inspired leaf flow field designs a) Mulberry b) Loquat and c) Fig leaf designs

In general, it is seen that the flow rate decreases in the auxiliary channels where the flow progresses along the main vein from the inlet. The wide and well-connected channels in the Fig leaf design did not change the pressure difference. In the Mulberry leaf design, on the other hand, the closed or non-obvious ends of some thin veins prevented the transmission and increased the pressure difference.

4. CONCLUSION

In this study, the environmental, physical and biological properties of DMFC were investigated and one-to-one leaf dimensions. Two-dimensional flow and pressure distributions of Populus, Large-surface Bamboo, Palm, Philodendron, Lotus, Mulberry, Loquat and Fig leaves were examined. According to the numerical simulation results, it was concluded that Mulberry, Loquat and Fig leaves were have a more homogeneous reactant distribution and would be more suitable in terms of manufacturability.

Compared to the other leaves investigated in general leaf dimensions, the Lotus leaf has the largest pressure difference of 1800 x 10^3 Pa due to its wide structure and higher number of channels. Also it is very difficult to produce a production that can create very thin channels as a result of the design. When the cross-sectional areas of the selected leaves were compared, the lowest pressure loss was obtained in the Fig leaf design with 1440 Pa, and the highest flow rate distribution was observed in the Mulberry leaf design with 9960 Pa.

A good flow field design of the leaf-inspired circulation system has a major impact on DMFC performance. In addition to practical numerical studies, the production of flow fields will give more realistic results in terms of comparison. In future studies, the performance variation in the cell structure of flow fields at different flow rates will be investigated experimentally. In addition, the effect of controlled variables on performance in different parameters such as temperature and concentration will be examined in the study.

NOMENCLATURE

E_{eq}	Equilibrium potential (V)
A	Ampere meter, or area (cm^2)
F	Faraday's constant (C/mol)
loc	Local current density (mA/cm^2)
U	Fluid speed (m/s)
L	Thickness (cm)
i_0	Change current density (mA/cm^2)
P	Pressure (Pa)
DMFC	Direct Methanol Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
R	Universal gas constant J/(mol·K), or resistivity (Ω)
T	Temperature (^oC)
V	Voltage (V)
ϕ_s	Electrode potential
ϕ_l	Electrolyte potential
σ_l and σ_s	Conductivity (S/m)
α_a and σ_c	Anodic and cathodic charge transfer coefficients

Subscript

A	Anode
C	Cathode
η	Activation overvoltage
FC	Fuel Cell
k	Permeability of porous media

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Mikail Yağız: Methodology and Numerical analysis.

Selahattin Çelik: Writing – original draft.

Ahmed Emin Kılıç: Formal analysis.

CONFLICT OF INTEREST

The authors acknowledge that there is no known conflict of interest or common interest with any institution/organization or person.

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