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Performance Analysis of Geometric Properties of Fuel Cell Components

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Abstract

In recent years, there has been an increase in health issues and environmental degradation, which has led to a greater need for renewable energy sources. Due to factors like low emission values, high energy efficiency and reduced environmental contamination, fuel cells have become more prominent. PEM fuel cells have gas flow channels for distributing reactant gases and removing water that is produced during the reaction from the fuel cell. For this reason, to obtain good performance requires careful consideration in the design of the gas flow channels in the cell. Ansys-Fluent was used to examine fuel cell models that were created in the SolidWorks program according to the dimensions specified. The model utilized in the reference rectangular flow channel had the maximum amount of current density and consequently, the best fuel cell performance, according to the results collected. Flow channel length does not change the oxygen concentration distribution. Therefore, this value remained constant in all models. In varied flow channel geometries with the same area, it has been found that the velocity distribution varies inversely with the current density. Here, the semicircular channel shape with the lowest radius had the highest velocity value recorded. Temperature distribution within the cell was consistent in analyses where the entrance and output temperatures were entered as 353 K. It has been observed as a result that fuel cells with higher active area gives better output performance.

Keywords: PEM fuel cells, Fuel cell performance, Channel section geometry.

Research Article

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1. Introduction

The demand for conventional fossil fuels has been rising in tandem with the rapid expansion of contemporary civilization. However, addressing environmental and socioeconomic challenges necessitates implementing more eco-friendly and effective energy systems [1]. In order to solve these problems, researchers highly support the use of hydrogen energy and fuel cell technology. A clean, renewable energy source is hydrogen. An energy-conversion device called a proton exchange membrane fuel cell (PEMFC) uses a chemical process to convert chemical energy and an oxidizer into electrical energy [2]. Fuel cells have received attention from researchers in recent years, as they do not depend on the efficiency of the Carnot cycle. In addition, it is in demand due to its low noise, non-polluting and high energy conversion efficiency features. The most accessible but infrequently gaseous element is hydrogen [3]. The reaction does not result in the release of SO_2 or polyaromatic hydrocarbons because it lacks carbon and sulfur. When ingested in the fuel cell, it does not impact the environment in this way. The excellent efficiency and quick operation of Polymer Electrolyte Membrane (PEM) fuel cells set them apart from conventional fuel cells [4]. PEM fuel cells function at temperatures as low as 0 to 125°C. Because it operates at low temperatures, is quick, and puts less strain on system components, it offers superior durability. The anode (a negatively charged electrode), cathode (a positively charged electrode), and membrane form the core of a PEM fuel cell (electrolyte). By flowing through the porous electrolyte, hydrogen ions (H+), which have been liberated from their electrons at the anode, are delivered to the cathode. Here, water is created via a reaction between oxygen ions from a different circuit and electrons. Electrical power is produced by electrons that enter a different circuit. The yield is between 45% and 60% [5]. Fuel cells with polymer electrolyte membranes (PEM) are generally utilized in mobile and stationary applications. PEM fuel cells are particularly well suited for usage in automobile applications, including light-duty trucks, buses, and cars [6].

Several factors can affect how well fuel cells function. Some of them are the operational circumstances [7], flow channel design

[8], fuel cell component size [9], material qualities, and operating conditions. The flow channel's design is crucial since it greatly affects how efficiently fuel cells function [10].

The desirable characteristics of a properly sized fuel cell include a balanced water management system in the flow channel, high efficiency and uniform distribution of flow density. The performance improvement of fuel cells with polymer electrolyte membranes by modifying the channel section area arrangement is examined in this work. Rectangular, triangular and semicircular channel section geometries were also developed to explore the impact of channel shape. The impacts of channel dimensions, channel cross-sectional area size, and the same area size but varied channel geometry on fuel cells were explored with the change in channel section geometry.

When the studies are examined, many researches and examinations have been made about fuel cells until today. Recently, researches on durability, cost, performance and system improvements related to fuel cells have been included [11]. At the same time, studies have been carried out on the flow channel design and the parameters affecting the performance.

Omeiri and Laouar conducted a three-dimensional optimization study for a PEM fuel cell under different operating conditions and channel geometries. In the model they worked on, they performed computational fluid dynamics (CFD) analyzes with continuity, momentum, conservation of energy and species conservation equations describing the flow and species transport of the gas mixture in the combined gas channels and electrodes [12].

Berning and Cilali present the results of a parametric study conducted with the previously described three-dimensional, non-isothermal model of a PEM fuel cell. As a result, it has been found that such parameters of the contact resistance in the cell have a significant effect on the performance of the fuel cell [13].

Ionescu used the finite element method-based Comsol Multiphysics tool to model the low-temperature PEM fuel cell for his research. By adjusting the channel width and height in specific ratios, he was able to assess the flow rates at various cathode sides [14].

Eker E. and Taymaz I. investigated the effect of different channel widths on the performance of a polymer electrolyte membrane fuel cell. In their study, they measured the current density in three different channel widths, keeping the width and channel height constant of a parallel flow fuel cell with an area of 25 cm^2. As a result, they stated that the current density decreases when the cell width is kept constant and the channel width is increased [15].

In a polymer electrolyte membrane fuel cell with a meshed flow field operated at various aspect ratios, Cooper et al. [16] discovered that the net power density increased with decreasing aspect ratio, taking losses into account. The PEM fuel cell, which has a parallel and unobstructed channel construction, was also tested, and the results showed that the channel width and height on the anode side as well as the shoulder width of the current collector plate had an impact on the fuel cell.

Ahmadi [17] investigated several kinds of gas channels and the impact of gas diffusion layers on the performance of polymer electrolyte membrane fuel cells through experimental and numerical study. As a result of the studies, it has been found that the reactant gases enter the fuel cell more intensely as pressure increases. He claimed that the electrochemical reaction rate and PEM fuel cell performance are enhanced by the more intensive penetration of reactant gases into the electrolyte.

These investigations show that the fuel cell's flow channel dimensions and channel section shape have an impact on performance. By putting obstacles along the channel or using different operating circumstances with various flow channel shapes, in addition to the data acquired here, the variation of parameters can be investigated. At the same time, it may be examined what kinds of electrochemical response losses and impacts the field change will have on cell performance.

2. Material and Method

2.1 Assumptions Made in the Fuel Cell Model

The performance of fuel cells can be influenced by a variety of factors. These include the experiment's operating parameters, the setting, how the reactant gas is distributed across the bipolar plates, and how the flow channel is designed to remove the reaction products from the cell.

The fuel cell geometry was first created using the SolidWorks CAD 2016 program. Following the definition of the essential assumptions, network generation, physical dimensions, initial, and boundary conditions, the model was subjected to the appropriate analyses using Computational Fluid Dynamics (CFD) in the Ansys-Fluent program. By contrasting the analysis results with other findings in the literature, the data's correctness was evaluated. These results might not agree with other data from the literature. This is because numerical models' working circumstances must span a large range [18].

The analyses on the fuel cell for which a physical model was created were conducted under the premise that.

- Ideal gas characteristics are a need for any species that react electrochemically.
- The flow of the reactive gas is laminar and incompressible.
- Ohmic (resistive) potential losses do not take into consideration current collection plates or fuel cell diffusion layers.
- There is system stability.
- The gas diffusion layer and the electrolyte's catalyst are thought to be homogeneous and isotropic materials [19].

Table 1. Values defined in the UDF.

P_0	101325 Pa
T_0	300 K
γ_p	1.0
γ_t	1.5
r_s	2.5

Electrochemical modeling is formed by proportioning and calculating the reactions in the anode and cathode catalyst. The surface over potential, which is fundamental in these reactions, is formed by the difference between the solid and membrane phase potentials. The reaction rate is calculated on the cathode and anode bases. It is solved with two electrical equations in the PEMFC and electrolysis model in the Ansys Fluent program. User defined functions (UDF) are provided in the Ansys Fluent PEMFC module. Defined values are as in Table 1.

In this study, a three-dimensional design of a flat and single-channel polymer electron membrane fuel cell has been investigated. A fuel cell with rectangular channel geometry is considered as a reference. The front view and components of this fuel cell are shown in Figure 1. The dimensions of the referenced rectangular channel design are given in Table 2.

Table 2. Referenced rectangular channel section dimensions.

Part Name	Unit	Value
Channel Length	mm	125.00
Channel Height	mm	0.60
Channel Width	mm	0.80
Membrane thickness	mm	0,036
Catalyst layer thickness	mm	0.012
Current collector plate thickness	mm	1.80
Gas diffusion layer thickness	mm	0.21

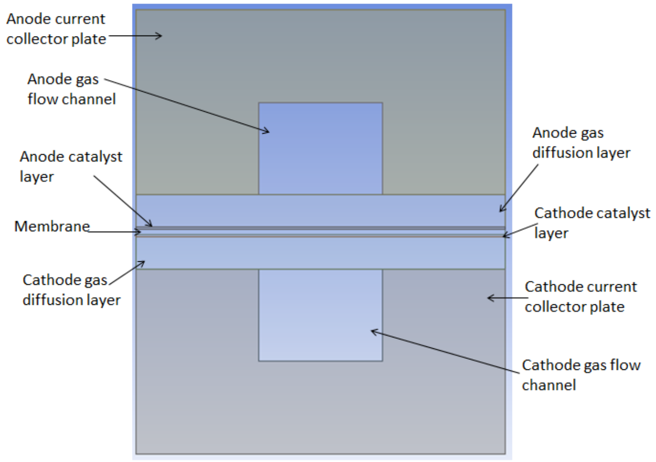

Fig. 1. Frontal schematic view of a single-channel quadrangular fuel cell.

The front view of the mesh structures of three distinct rectangular models are simultaneously shown. These models were created by altering the edge dimensions using the rectangular model used as a reference in Figure 2.

For the solution of the conservation equations, the model boundary conditions must be defined. The parameters of the fuel cell models used in this study are defined as follows: Anode and cathode reference currents; 7500 and 20 A/m^2, anode and cathode ref. mole concentration both; 1, porosity of GDL 0.95V, viscous resistance of GDL 1x10^{12} 1/m^2. These values were entered in the relevant fields in the Ansys program and the analyzes were compared and explained in the results section.

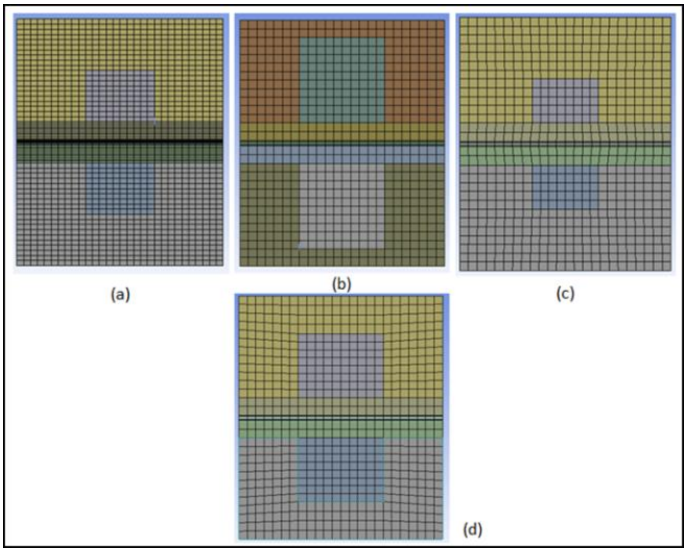

Fig. 2. The cross-sectional areas of the channel geometries in the front view are (a) 0.48 mm^2, (b) 1 mm^2, (c) 0.375 mm^2, and (d) 0.75 mm^2.

2.2 Model Mesh Formation

Mesh creation is an important step in the numerical simulation of a flow channel in a Proton Exchange Membrane Fuel Cell (PEMFC). A mesh is a collection of small elements, such as triangles or quadrilaterals, that are used to approximate the geometry of the flow channel. The mesh is used to solve the equations that govern fluid flow and heat transfer, and it plays a critical role in determining the accuracy of the simulation [20]. In this study, how the channel cross-section and geometry, among other factors, affect the performance of the PEM fuel cell was also investigated. Models are developed for fuel cells with triangular (Fig. 3), semicircular (Fig. 4), and rectangular flow channels. For three distinct geometries, ten different models were created. Gas diffusion plate, current collection plates, battery height, and membrane electron pair (MEP) were all held constant in all of these models.

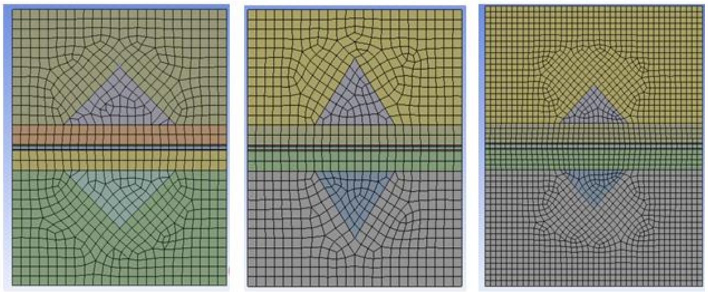

Fig. 3. Views of the triangle flow channel designs' mesh structures.

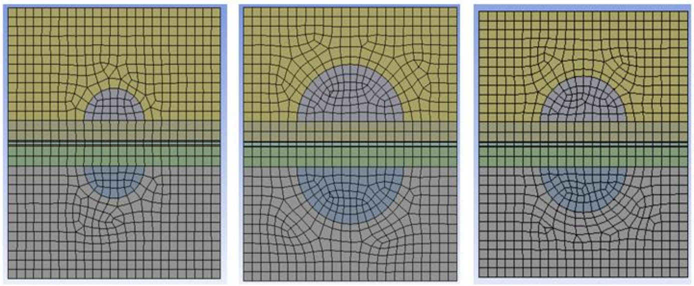

Fig. 4. Views of semicircular flow channel designs' mesh structures.

In order to perform numerical solution and analysis in the modeled PEM fuel cell, the geometric shape created is divided into a finite number of elements and boundary conditions are defined for each finite element. In line with these definitions, the conservation equations were solved and the results were obtained. The quality of the network structure in Ansys program is important to obtain accurate data. Therefore, it depends on the network structure, geometry shape and analysis parameters. Network structure; When the skewness value is at most 0.9 and the orthogonal quality value is at least above 0.1, we can understand that it is of good quality. As an example, the skewness and orthogonal quality values of the reference rectangular model are shown in Figure 5.

In the PEM fuel cell, each component is defined as a separate boundary region. The solution regions defined outside the anode and cathode current collector plates are fluid. The front, back and side surfaces of the fuel cell are of the wall boundary condition type in order to limit the fluid. In addition, constant surface temperature and source term conditions are defined for the battery potential on the upper surface of the anode side current collector plate and the upper surface of the cathode side current collector plate.

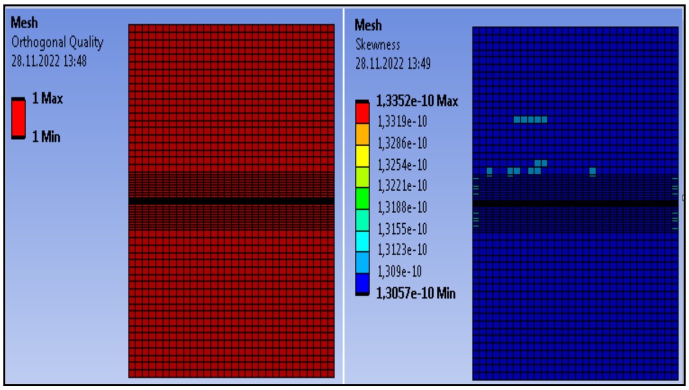

Fig 5. The skewness and orthogonal quality values of the rectangular model.

The fuel cell network construction is separated into four quadrangular regions in Figure 5. The fuel cell's network structure has 285138 nodes and 270000 components. For a more accurate solution, the entrance and exit portions of this fuel cell are separated into denser quadrangular sections.

2.3 Fuel Cell Losses

The efficiency achieved in real heat engines is never 100%. Because it is impossible to eliminate irreversibility in real heat engines. Therefore, the actual work obtained from a fuel cell is lower than the maximum work due to the irreversibility of the reactions. Operating voltage in fuel cells; temperature and current density. Instead of using current characteristically in fuel cells, the expression current density is used to make comparisons between cells of different sizes. Concentration losses due to the decrease in the hydrogen concentration on the electrode surface of the fuel cells, activation losses due to the slowdown of the chemical reaction on the electrode surface, and ohmic losses due to the resistance of the electrolyte liquid during good passage [21].

3. Analysis Results

In this study, ten different models were created in total and 300 iterations were made for each model. The reason for this is that the convergence criterion of the energy equation falls below the value of 10^{-9} in numerical analyzes and 10^{-4} in other equations. The iteration result for the reference model is shown in Figure 6. A total of ten analyzes were made and the working parameters of the reference model were defined as working parameters. In all models, the operating voltage was applied as 0.75 V and analysis values were obtained.

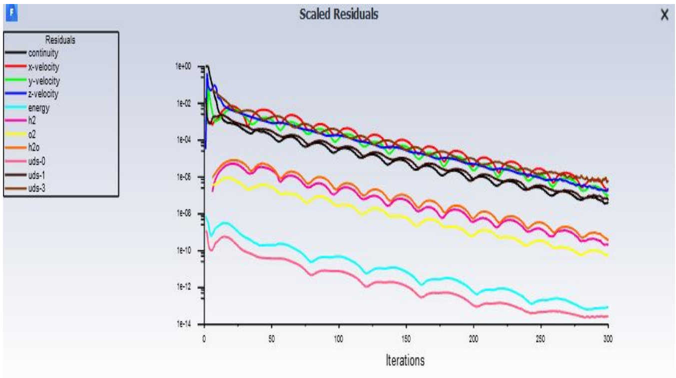

Fig. 6. Results of 300 iterations for the reference model.

3.1 Effect of Flow Channel Design on Cell Outputs

The analysis's results allowed for a four-region study of the quadrangular channel geometry's current intensity distribution. On the flow channel, the electrochemical reaction zones are where the current density distribution is higher, as shown in Figure 7. The results showed that when the flow channel area rose, the amount of current density increased as well. The current density distribution and battery performance are both enhanced in this case as the channel width is raised. Here, it is calculated to be 9.76x10-5 A/cm^2 in a rectangular flow channel with a height of 0.08 cm, a width of 0.06 cm, and an A value of 0.048 cm^2.

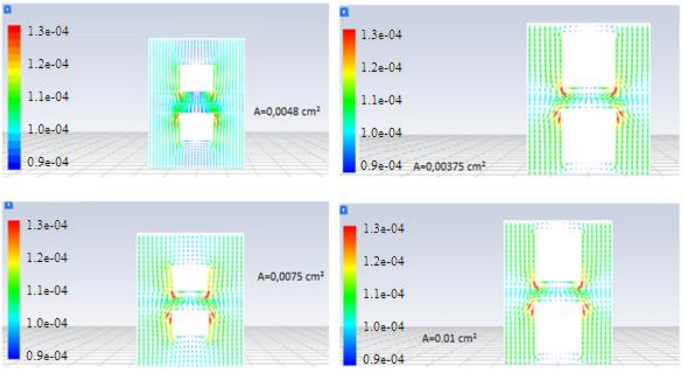

Fig 7. Current density distribution in the cathode gas diffusion layer for rectangular channel geometries.

The analysis's output allowed for examining the current density distribution of the triangle channel geometry's three distinct zones. According to the data, it was found that as the flow channel area increased, the amount of current density dropped. The channel in question had a height of 0.4 cm, a width of 0.075 cm, and a current density of 2.87x10-7 A/cm^2, with A = 0.0015 cm^2. The fuel cell operates most efficiently in the channel with the lowest height as reactant gas diffusion in the gas diffusion layer increases.

The quantity of current density decreases with the decrease in the flow channel area, as can be seen when the current density distribution of the semicircular channel shape belonging to three distinct regions is investigated. Here, 0.00000002 A/cm^2 was measured as the maximum current density in the channel with R=0.5 cm and A=0.00785 cm^2.

When the current density distribution of the channel types belonging to three different areas is examined, it is seen that the flow density is the least in the semicircular channel type with the change of the channel section geometry. Here, the maximum amount of current density was obtained as 0.0000896 A/cm^2 in rectangular channel section geometry with a=0.75 mm and b=0.5 mm, A= 0.00375 cm^2.

The O_2 mass fraction is evaluated for four distinct quadrilateral models, and it is discovered that the channel width and height have no effect on it. At a cell voltage of 0.75 volts, Figure 8 depicts the oxygen distribution in the quadrangular flow channels' cathode gas diffusion layer. With seen in the Figure, the oxygen distribution within the cell does not change as the flow direction. This is because neither the flow channel's length nor the amount of oxygen consumed changes throughout the reaction.

It was discovered that the oxygen concentration distribution did not change as a result of the analyses done since the channel length and the amount of oxygen consumed did not vary in various flow channel configurations.

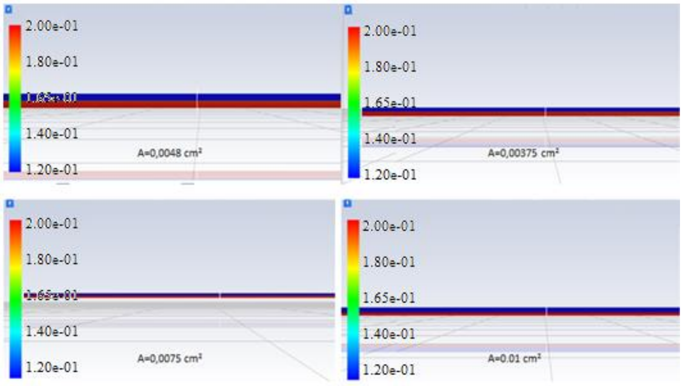

Fig 8. Oxygen distribution in the cathode gas diffusion layer for rectangular channel geometries.

The velocity distribution affecting different channel section geometries with the same area is shown in Figure 9. Here, the flow channel with the highest flow velocity is observed in the semicircular channel geometry of R=0.346 mm. According to the analysis results obtained, the current density and velocity distribution have changed inversely in these three models with the same area. In the quadrilateral model where the current density is the highest, the velocity distribution is the least amount and is shown in Figure 10.

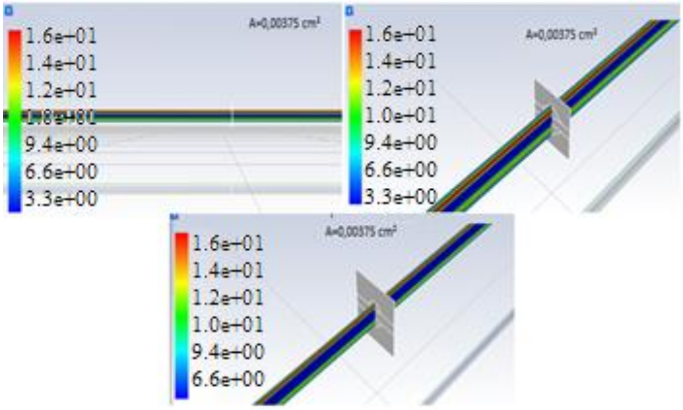

Fig 9. Velocity distribution in the cathode gas diffusion layer for different types of channel section geometries.

In the study of Ghasabehi et al. [22], density of electrons leaving the anode It is seen that the current collector plate is more at the channel corners. In this study, it is seen that the current density is more homogeneously distributed in the channel sections with the optimum adjustment of the section configurations. A lower current density in the study of Vazifeshenas et al. [23] was obtained due to the increased channel width narrowing the bar area in the two side regions of the gas channels. However, in this study, it was observed that the current density obtained with increasing channel width remained constant. These results show the success of the model made.

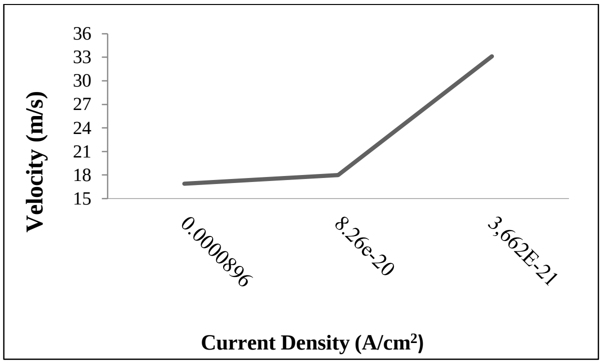

Fig 10. Current density and velocity distributions.

Figure 11 shows the temperature distribution results in different duct designs of the same area. In the analyzes made, the operating temperature was determined as 353 K. According to the results of the analysis, it is seen that the amount of temperature shows a regular distribution in the cell in all three models. Therefore, no comparison can be made for the temperature distribution. The temperature was measured as 353 K in the channel geometry of three different regions. In the other ten different analysis results, the temperature is measured as 353 K.

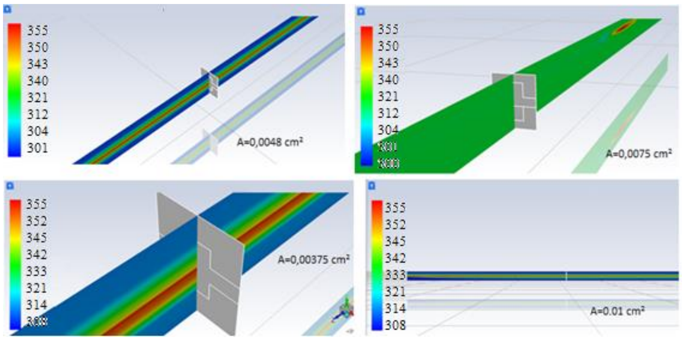

Fig 11. Temperature distribution in the cathode gas diffusion layer for different types of channel section geometries.

4. Conclusion and Recommendations

In this study, a three-dimensional model of a single-channel polymer electrolyte fuel cell was used to conduct 10 distinct modeling and analysis tests. The information gathered from the analyses was utilized to assess how varied channel sizes and flow channel shape affected the parameters for the fuel cell's flow density, oxygen concentration distribution, velocity mass fraction, and temperature. All analysis data have revealed the following conclusions:

- It has been understood that the flow channel design and dimensions do not affect the oxygen concentration distribution and this is due to the fact that the flow channel length and thus the amount of oxygen consumed do not change throughout the reaction.

- The triangular channel section geometry with the maximum velocity of 0.0015 cm^2 and the channel dimensions of 0.08 cm to 0.06 cm were found to produce the optimum current density performance.

- The flow channel width was increased, which improved cell performance. The findings of this study indicate that the fuel cell's performance is influenced by the flow channel's size and channel section geometry.

[7] Chu T, Xie M, Yu Y, Wang B, Yang D, Li B, et al. Experimental

The fluctuation of the parameters of various flow channel geometries under various operating conditions or by positioning obstructions along the channel can be explored in addition to the data gathered in this study. At the same time, it might be able to look at the types of electrochemical reaction losses and how the field change affects cell performance. The results of experimental research to be conducted in a lab setting should support these computer-based analyses.

Nomenclature

P_0 : Pressure (Pa)
T_0 : Temperature (K)
γ_p, γ_t, r_s : Pore barrier foundation

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

Credit Author Statement

Beyza Nur Yavuz: Conceptualization, Writing – Original Draft, **Hüseyin Kahraman:** Conceptualization, Validation, Supervision

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