Three-Dimensional Numerical Study of the inlet Temperature Effects on the Performance of Planar PEMFCs

Abdallah Mohammedi[1], Youcef Sahli[2], Hocine Ben Moussa[1]

[1] Laboratoire des Etudes de Systèmes Energetiques Industriels (LESEI), Département de Mécanique, Faculté de Technologie, Université de Batna 2, Algeria

[2] Unité de Recherche en Energies Renouvelables en Milieu Saharien, URERMS, Centre de Développement des Energies Renouvelables, CDER 01000, Adrar, Algeria

*Corresponding author; Email: a.mohammedi@univ-batna2.dz.

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ABSTRACT

In the present study, a CFD (computational fluid dynamics) three-dimensional model is performed to investigate the effects of the inlet temperature on the power density, pressure and local transport phenomena of a single cell PEMFC (proton exchange membrane fuel cell) with straight channels. Deferent inlet temperatures of the reactants (333, 343 and 353 K) have been investigated using ANSYS-FLUENT. The interest of our work is focused on obtaining I-P and I-V curves as well as the pressure, hydrogen, oxygen and water mass fraction profiles to analyze the effect of the oxygen and hydrogen inlet temperature on the current, voltage and power densities of the studied PEMFC. From the results obtained its appears that the variation in the inlet temperature values of the PEMFC has a significant influence on the cell performances at medium and higher current density. Therefore, the results analysis of the three-dimensional and single-phase model indicates that the increase in the reactants' inlet temperature of the studied PEMFC shows a negative impact on the generated power densities, which have an inversely proportional effect.

I. Introduction

The need for new energy sources with less polluting emissions is the principal researchers' objective in the last decades. Owing to their higher efficiency and low emissions, fuel cells seem to be the best alternative technologies to produce clean energy [1, 2]. Additionally, the most regarded fuel cell technology recently is the Proton Exchange Membrane Fuel Cell (PEMFC) [3]. Even though existing of different types, the PEMFC has several advantages compared with other fuel cell types, from low operation temperature and high-power density to quick start-up and zero emissions. These advantages made this type the best adoption in the automotive sector and stationary power generation [4, 5].

Several works in the literature study the effects of the dimensional and physical parameters on the performance of this type of fuel cell. In this context, there are many experimental and numerical works that are conducted to improve the PEMFC performance based on the anodic and cathodic channel dimensions. Cooper et al. [6] have stuedied experimentally the effect of channel/land width and depth on PEMFC performances. Muthukumar et al. [7] have examined the impact of the width and height of the channels on PEMFC performances. Other works have concentrated on the study of the gas diffusion layer (GDL) and its characteristics such as porosity, thickness, permeability, water management and their impact on PEMFC performances. Fadzillah et al. [8] have realized a review paper concerned GDL and illustrates and better clarify the effect of the fiber diameter, porosity and thickness and polytetrafluoroethylene of the GDL on the performances. Chun et al. [9] have presented a one-dimensional numerical simulation to study the GDL properties and characteristics that influence the performances of the PEMFC. In another, the porosity, structure, thickness, and platinum loading of the catalyze layer (CL) presents also parameters affecting the PEMFC performances [10]. Hu et al. [11] have exposed a parametric analysis to optimize PEMFC performances, they have used many geometrical parameters, including the thickness of CL. Khajeh-Hosseini et al. [12] have presented a new mathematical model of the cathode CL to investigate the impact of several CL structural parameters. Furthermore, the impact of the membrane electrolyte assembly (MEA) is studied in a set of research to improve the PEMFCs performances. Khazee et al. [13] and Akyalçin et al [14] have investigated the membrane properties, including membrane thickness, and their impact on the performances. In addition, the impact of the flow arrangements (co-, counter-, and cross-flow) on the PEMFC performances is studied by Alaefour et al. [15-16]. Mohammadi et al. [17] have conducted a three-dimensional and steady-state simulation of a single cell of PEMFC to extract and conclude the optimal dimensions that permit the production of optimum performances. They have taken into account in their study the following dimensions: the ratio of channels' width and height, GDL, CL and membrane thicknesses as well as the flow arrangement. Additionally, to these dimensional parameters, the form of the channels' cross-section also presents a key parameter in the PEMFC performances' optimization. In this context, many shapes of the channels' cross-sections have been studied; Kumar and Reddy [18] have examined the hemispherical and triangular shapes' impact on the PEMFC performances. Ahmed and Sung [19] have studied the effect of the trapezoidal, parallelogram and rectangular cross-section channels formes on the PEMFC performances. Mohammadi et al. [20] have investigated the best shape of the cross-section channels comparing 30 forms of channel cross-sections. Also, the design of PEMFC's flow field channels, spiral, radial and bio-inspired, can contribute to improving the PEMFC performances [21-26]. For example, the tubular PEMFC with a twisted flow field is investigated by Mohammadi et al. [27].

In this work, and in a continuation of our previous work on the fuel cells [28-39], a three-dimensional (CFD) model is considered to study the impact of the inlet temperature on the current density, power density, pressure and hydrogen, oxygen, and water mass fractions' distributions of a single straight channel PEMFC. The considered three-dimensional model is supposed non-isothermal, single-phase steady-state and the domain of study is limited by a single PEMFC cell with straight channels according to co-flow arrangements. ANSYS-Fluent is used to solve the governing equations and to present the results of the three studied gases inlet temperatures (333, 343 and 353 K).

II. Physical and mathematical Model

The considered fuel cell in this work is limited to a single cell of PEMFC with straight channels and planar configuration. ANSYS-Design Modular Tool is used to create the geometries of the three-dimension single cell of the planar PEMFC. Fig. 1. The studied cell is composed of the current collectors, the gas flow channels, the gas diffusion layers, and the catalyst layers in both anodic and cathodic sides as well as the membrane in the middle of the sandwich. The dimensions of the components are given in Table 1. The simulation is carried out using the following assumptions:

-The system operates under isothermal and steady-state conditions.

- The reactants seeped in the anode and cathode channels are considered ideal and incompressible fluids.

- The flow regime is laminar and incompressible because the velocity and pressure gradients are very low.

- The membrane, catalyst (CL) and gas diffusion layer (GDL) are considered to be homogeneous and isotropic porous areas.

- The membrane is considered as an impermeable medium to the diffusion of reactant gases, and it is assumed to be fully hydrated.

- Butler-Volmer equation was taken into account for the electrochemical reactions and the species diffusion modeling.

- The elimination of the water liquid-phase produced from the electrochemical reactions and the phase change is not taken in consideration.

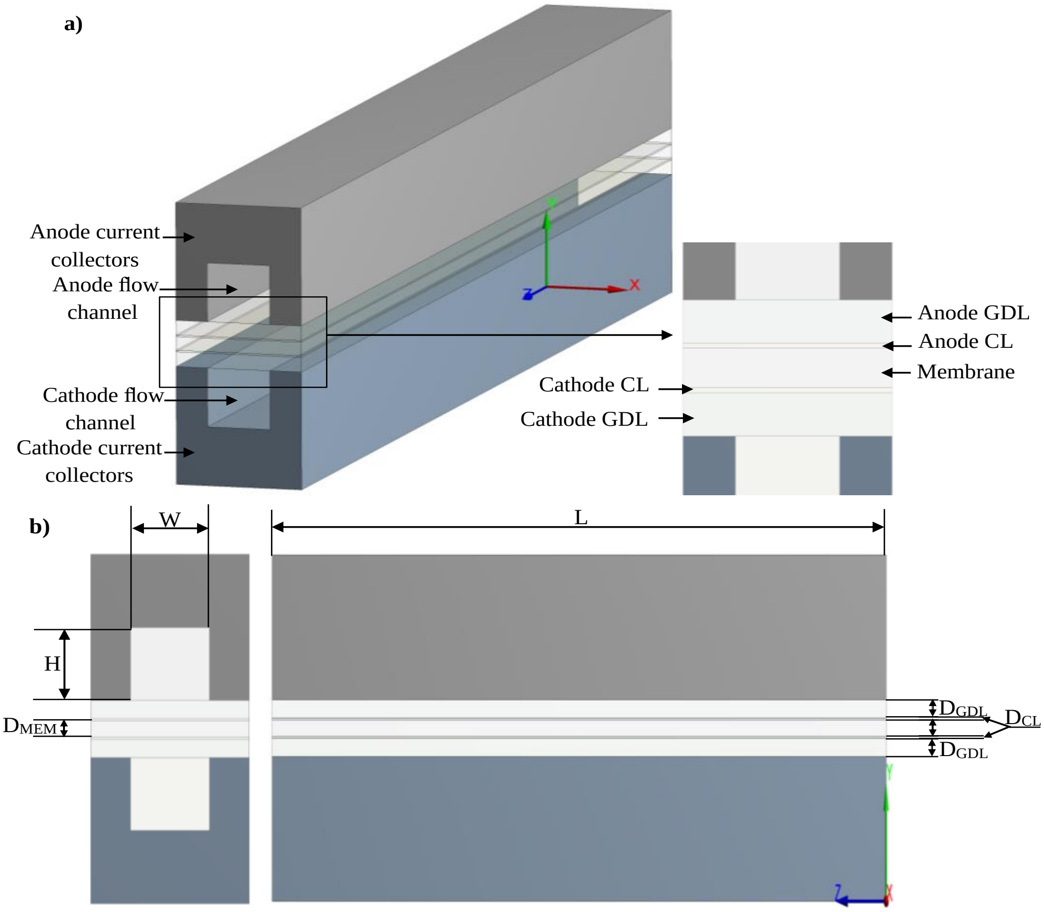

Figure 1. Studied PEMFC. [6]

In order to investigate the effect of the inlet temperature on the PEMFC performance, pressure drop and other transport characteristics, numerical simulations are carried out using the commercial CFD ANSYS-Fluent. The equations of the species transport, Navier-Stokes, energy, mass conservation, electrical charges, and Butler–Volmer are involved in the three-dimensional PEMFC model. The ANSYS PEMFC add-on Module manual describes and discusses in detail the model equations and the methods of implementation [17, 20 and 40].

Table 1. Geometric parameters

Parameters	Units	Dimensions
Cell length (L)	mm	100
Channel width/ height (W/H)	mm	0.8
Gas diffusion layer thickness (D_{GDL})	mm	0.25
Catalyst layer thickness (D_{CL})	mm	0.028
Membrane thickness (D_{MEM})	mm	0.23

Dirichlet boundary conditions are applied at the inlet of the anodic and cathodic channels' sides for the species concentrations, temperature, and mass flow. The mass flow rates are considered constant at the inlet of each channel in all cases of the realized simulations. On the other hand, Neumann boundary conditions are employed for the other parameters along. At the interfaces fluid/solid, the non-slip boundary condition and zero species flux are considered.

At the outlets of the channels, the pressure outlet boundary condition is used, and a zero gradient is assumed in the flow direction (OZ) for the rest of the parameters. At the outer surface of the PEM fuel cell, the wall boundary conditions are employed in the realized simulations.

II. Results and discussion

After the simulation of the PEMFC single cell with straight channels using the commercial CFD ANSYS-Fluent code, the mesh independency and the validation of the obtained results are conducted, in which the mesh independency test and the comparison of the simulation results with the experimental results are presented in our previous works [17, 20].

Figures 2, 3, 4 and 5 show the hydrogen, oxygen and water mass fraction distributions as well as pressure distribussions obtained by the carried-out simulations using ANSYS-Fluent for three deferent inlet temperatures of both gases, air and fuel, (333, 343 and 353 K).

From Figures 2 and 3 it appears that whenever the inlet temperature value is low, the reactant consumption become better. Logically, a good conversion of these reactants that results in significant production of water as shown in Figure 4. Inversely, when the inlet temperature of both reactants is great, the oxygen and hydrogen consumption become low (Figures 2 and 3), this is translated by bad conversion of both reactants that leads to a reduction of produced water as shown in Figure 4 and can result of a significant reduction of produced electricity of the PEMFC.

Figures 5 show that the pressure profile is the same for the three studied inlet temperature and it is independent of any inlet temperature change.

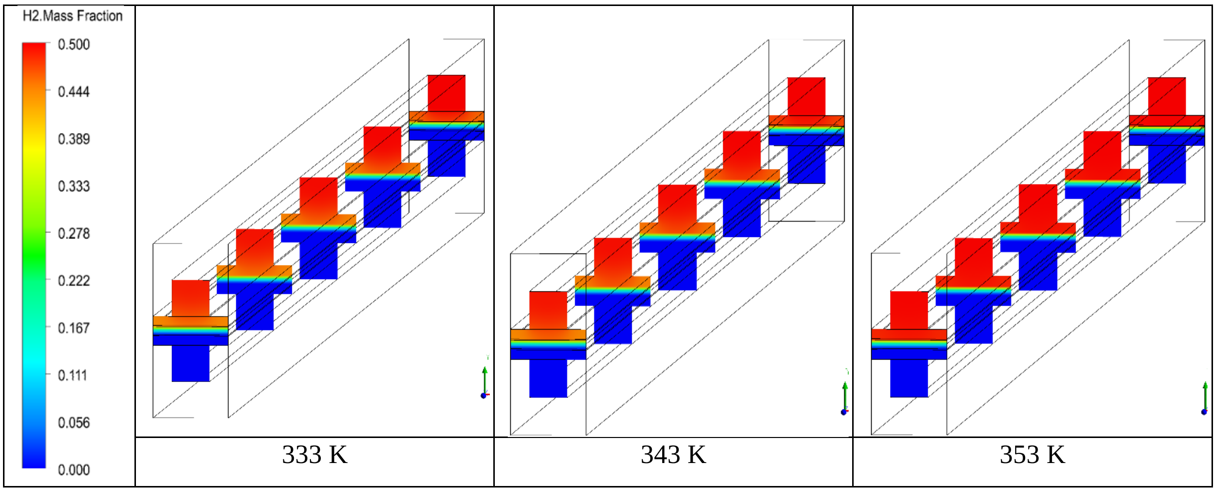

Figure 2. Hydrogen mass fraction distributions in the PEMFC single straight channels

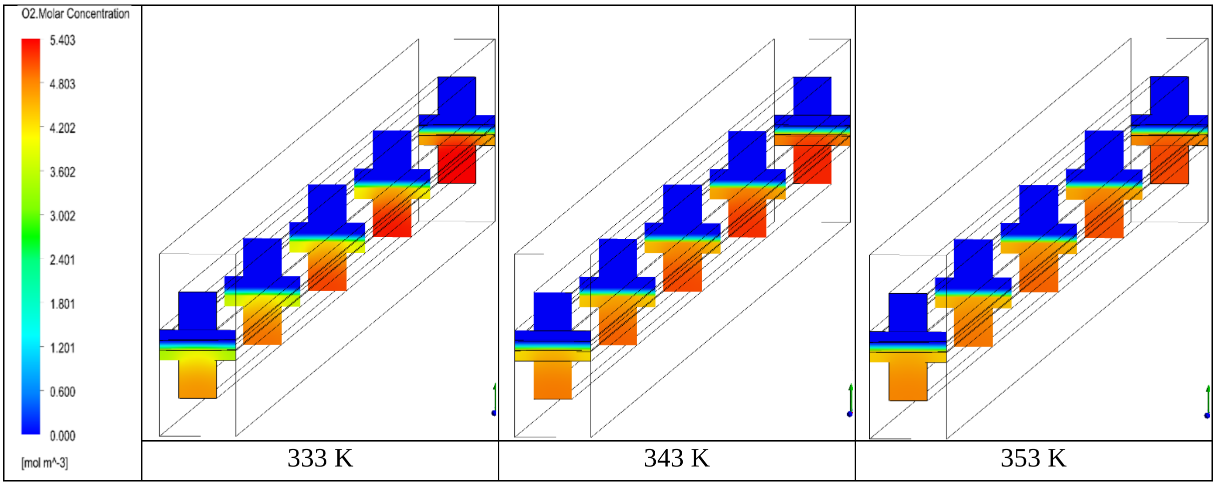

Figure 3. Hydrogen mass fraction distributions in the PEMFC single straight channels

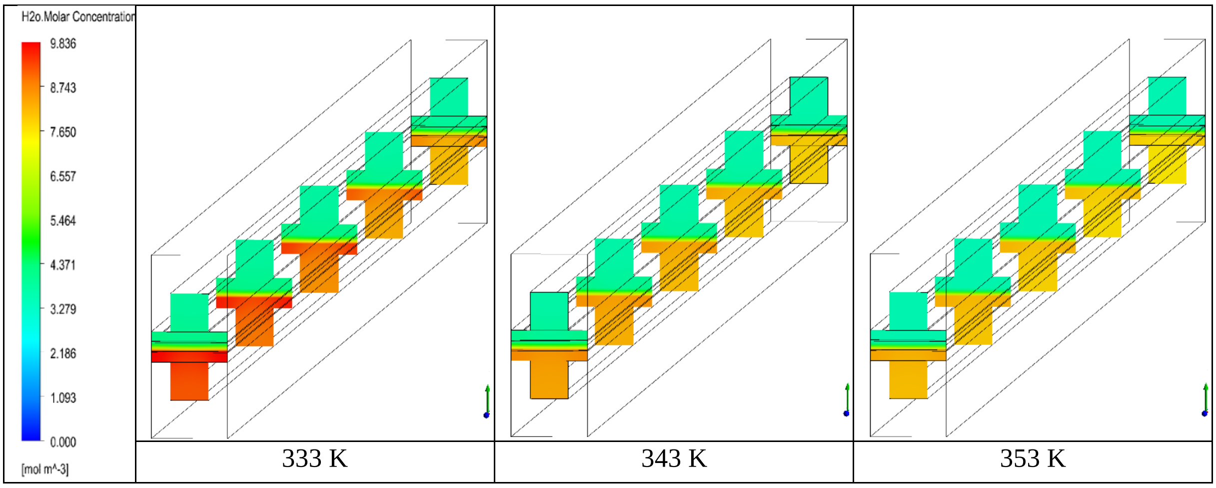

Figure 4. Water mass fraction distributions in the PEMFC single straight channels

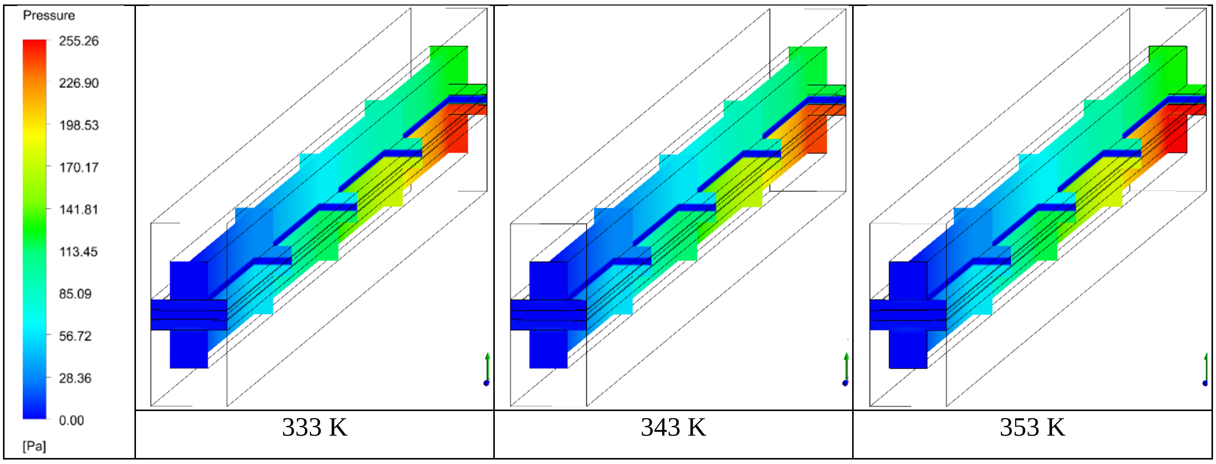

Figure 5. Pressure distributions in the PEMFC single straight channels

Figure 6 shows the polarization curves obtained by the carried-out simulations using ANSYS-FLUENT. Three deferent inlet temperatures of both gases, air, and fuel, (333, 343 and 353 K) have been investigated.

The lowest voltage and power density are obtained by the greater inlet temperature (353 K). The greater voltage and power density are obtained by the lowest inlet temperature (333 K). The variation in the inlet temperature values of the PEMFC has a remarkable influence on the cell performance at medium and higher current density as shown in Figure 6. Logically, the voltage and power density are inversely proportional to the inlet temperature of the studied PEMFC

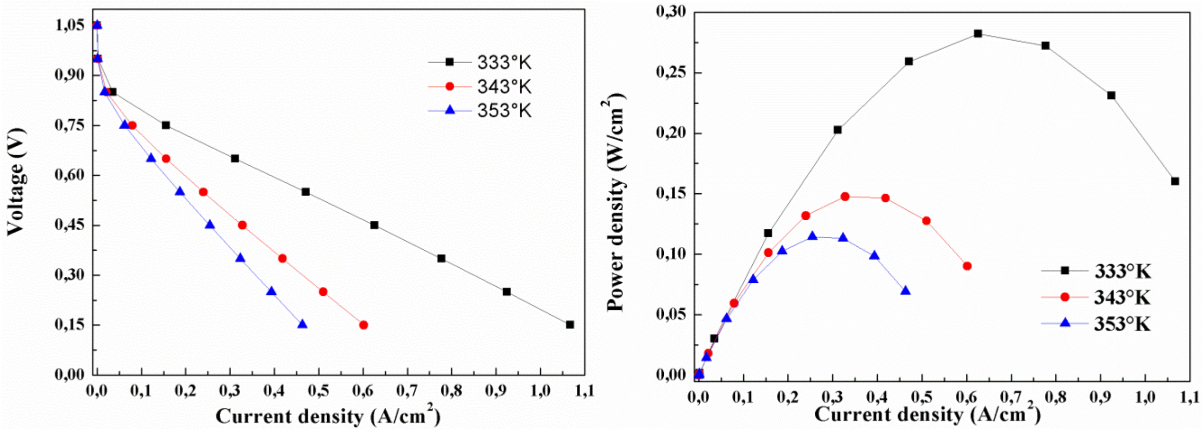

Figure 6. PEMFC polarization curves. a) Current density vs. voltage, b) Current density vs. power density

III. Conclusion

In this work that presents a continuation of our ones on the fuel cells, a three-dimensional CFD model is considered to investigate the impact of the inlet temperature impact on the current density, power density, pressure and hydrogen, oxygen, and water mass fractions' distributions of the single straight channel PEMFC. The considered three-dimensional model is supposed non-isothermal, single-phase steady-state and the domain of study is limited by a single PEMFC cell with straight channels according to co-flow arrangements. Fluent-ANSYS is used to solve the governing equations and to plot the results of the three studied gases inlet temperatures (333, 343 and 353 K).

From obtained results, it appears that whenever the inlet temperature value is low, the reactant consumptions become better. Logically, a good conversion of these reactants that results in significant production of water. Inversely, when the inlet temperature of reactants is great, the oxygen and hydrogen consumptions become low, this is translated by bad conversion of both reactants that leads to a reduction of produced water and can result in a significant reduction of produced electricity of the PEMFC. The pressure profile is independent of any inlet temperature change.

The results obtained show that the lowest voltage and power density are obtained by the greater inlet temperature (353 K). The greater voltage and power density are obtained by the lowest inlet temperature (333 K). The variation in the inlet temperature values of the PEMFC has a negative impact on the cell performance at medium and higher current density. Logically, the voltage and power density are inversely proportional to the inlet temperature of the studied PEMFC.

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