
Research article

Study on the design of PEMFC flow channel based on the mechanism of human heartbeat in plateau environment

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Abstract: Low-pressure conditions significantly affect the performance of Proton exchange membrane fuel cell (PEMFC) in a plateau environment. In this study, a new serpentine flow channel with an intermediate inlet form was designed based on the traditional serpentine flow channel, drawing on the physiological mechanisms of increasing heart rate and increasing cardiac output in the human heart under a plateau environment. Parameters such as current density, power, water activity, and conductivity of the two flow paths at different atmospheric pressures were analyzed and compared using numerical simulation. The results showed that the decrease of atmospheric pressure leads to the uneven distribution of reactant concentration in the fuel cell, which in turn affects its performance. The new serpentine flow field design effectively solved this problem, especially at a current density of 1 A/cm² and an atmospheric pressure of 0.67 atm; the power was increased by 34.8%, 0.61 S/m increased the conductivity, and the distribution of the current density and water activity was more uniform compared with that of the traditional serpentine flow field. Here, we provide a new design idea for the application of PEMFC in a plateau environment, which is conducive to promoting the progress of fuel cells in commercial applications.

Keywords: plateau environment; PEMFC; heartbeat mechanism; serpentine flow channel; numerical simulation

1. Introduction

With the continuous growth of global energy demand and increasing environmental problems, the limited availability of traditional fossil energy sources and environmental pollution have attracted much attention [1]. Despite the renewable and environmentally friendly characteristics of clean energy sources such as solar, wind, and hydro energy, there are challenges of poor stability and low conversion efficiency due to weather and geographical conditions [2]. In contrast, hydrogen energy, as a secondary energy source with the advantages of multi-source access, high energy density, and high conversion efficiency, is regarded as an ideal energy option [3–6].

PEMFC is an advanced hydrogen energy utilization technology, which is a complex chemical reaction power source with multiple inputs and outputs. It has the advantages of high efficiency, no pollution, and low noise [7]. This power supply technology is applicable to a variety of industrial fields, especially in the field of new energy vehicles, such as Toyota's Mirai hydrogen fuel cell vehicle and Changan Deep Blue C385 hydrogen fuel cell vehicle [8]. Although several automobile companies have invested in the research and development of hydrogen fuel cell vehicles, PEMFC, as the core component of hydrogen fuel cell vehicles, faces many technical problems, such as uneven distribution of reaction gases, difficulties in water management, and challenges in output power [9–12].

In the structure of a PEMFC, the bipolar plates serve the functions of conducting electricity, providing mechanical support, achieving a seal, and separating the gas channels [13]. The flow channel design of the bipolar plates is critical to the performance and lifetime of the fuel cell, as it is required to ensure uniform distribution of reactive gases and effective water management to maintain a stable power output [14]. The size and shape design of the flow channel structure of the bipolar plates has a direct impact on the performance and efficiency of the fuel cell [15]. Researchers have continuously explored the optimization of these parameters to enhance gas transfer efficiency and cell power density. Huang et al. [16] improved the single-channel serpentine flow channel by introducing a conical slope "U"-shaped corner structure, which resulted in a more uniform distribution of reactant gases, lower pressure drop, higher drainage efficiency, and higher power density. Wang et al. [17] designed a conical single runner with a decreasing cross-section was designed; when the ratio of inlet side length to outlet side length is 1.2, the concentration of reactants and current density are more uniformly distributed, and the output power is enhanced. Li et al. [18] studied the serpentine runner with different cross-sectional shapes and found that when the runner's cross section is changed from trapezoidal to triangular, the concentration of oxygen and the heat of reaction are increased, and the current density is significantly enhanced, but the uniformity is reduced.

In addition to the size and shape of the flow channel, the arrangement of the flow channel is crucial to the overall performance of the PEMFC. A more uniform distribution of reactive gases and generated water can be achieved through innovative arrangements, thus improving the efficiency and stability of the cell. Limjeerajarus et al. [19] designed a hybrid serpentine interleaved flow field (HSI) and investigated three different inlet and outlet configurations compared to a conventional single-channel serpentine flow field. The results showed that the two-input and two-output HSI flow field performed best at an operating potential of about 0.6 V, achieving a more uniform oxygen distribution, current density, and water distribution, as well as a significant reduction in the cathode voltage drop and an improvement in the net power output of about 6%. Karthikeyan et al. [20] introduced porous inserts of different sizes and types into the serpentine flow field and evaluated their effects on the battery performance through numerical simulations. It was found that the modified flow field configuration significantly increased the power density of the cell, especially the larger-sized porous sponge inserts,

which performed well in improving water management and cell performance. Heidary et al. [21] introduced obstructions in the flow field channel of a PEM fuel cell. In their study, they compared the effects of straight and staggered obstruction configurations on the performance of fuel cells in a parallel flow field, and the results showed that the staggered configuration can improve the performance by 28% compared to the baseline case and 18% compared to the straight line configuration. Dong et al. [22] introduced different shapes of obstructions in the flow channel, which produced a nozzle-like effect and significantly enhanced the performance of the fuel cell. Compared with the conventional non-obstructed flow channel, the obstruction design improved the electrochemical conversion efficiency and adequate power by 15.58% and 15.77%. Further optimization of the height and spacing of the obstructions can further enhance the energy performance to 17.09% and 16.95%.

Nowadays, the traditional simple flow field structure design and arrangement are not enough to meet the needs of high-performance fuel cells, so the porous media flow field design and bionic flow field design have become the hot direction of the current research. Chen et al. [23,24] established a multiphase flow model with a three-dimensional wave flow channel. They found that the wave flow channel can effectively promote reactive gas transport, reduce the accumulation of water in the micropore layer, and avoid the thermal stress concentration phenomenon of the membrane effectively. Dong et al. [25] proposed a new flow field plate structure and verified its superiority by numerical simulation. The results show that the new structure significantly improves the uniformity of gas distribution and reduces the pressure drop in the flow channel, resulting in a 114% increase in the maximum output power of the fuel cell under the same conditions. Xuan et al. [26] proposed a new three-dimensional biomimetic cathode flow field design inspired by the structure of the small intestinal villi. They analyzed its effects on reactive gas transport, liquid water exclusion, and cell polarization performance through three-dimensional numerical simulations. The improvement effect on reactive gas transport, liquid water exclusion, and cell polarization performance was analyzed by 3D numerical simulation. It is shown that the bionic flow field significantly enhances the gas transfer efficiency and improves the uniformity and power density of the cell.

Although significant progress has been made in optimizing the performance of PEMFCs in terms of bipolar plate structure and flow field arrangement, most of these studies are based on experimental and simulation analyses in plain environments. In contrast, relatively few studies have been conducted on plateau environments. Famous plateau regions in the world, such as the Tibetan Plateau in China, the Andean Plateau in South America, the Ethiopian Plateau in Africa, and the Pamir Plateau in Central Asia, all face low atmospheric pressure and low oxygen environments, which affect the performance and reliability of fuel cells and limit their use in these regions. Therefore, it is essential to solve the adaptability problem of fuel cells in plateau environments before their large-scale promotion. In this paper, a novel serpentine flow channel with an intermediate intake form is designed based on the beating mechanism of the human heart in a plateau environment. The new runner can improve the adaptability of PEMFC in low-pressure and low-oxygen environments, thus promoting its wide application in plateau regions. The improved adaptability to the plateau environment will provide critical support for applying fuel cell technology in complex working conditions and further promote the development of clean energy.

2. Model description

2.1. Mechanisms of cardiac pumping

The human cardiac blood circulation system is based on the heart pumping oxygen- and nutrient-rich blood to tissues and organs throughout the body. The heart pushes blood from the heart through the arteries into the body circulation through contraction (systole) and relaxation (diastole) of the heart muscles, which deliver oxygen and nutrients to the tissues through the capillaries [27]. The schematic diagram of blood bursting from the heart is shown in Figure 1. The needs of the tissues determine the distribution of blood flow, and the direction and rate of blood flow are regulated by vasoconstriction and dilatation of blood vessels to meet the needs of different tissues [28]. For example, during exercise or hypoxia, blood is preferentially supplied to the lungs to increase the transport of oxygen; after eating is complete, blood is heavily concentrated in the gut to provide more energy to consume physical objects [29].

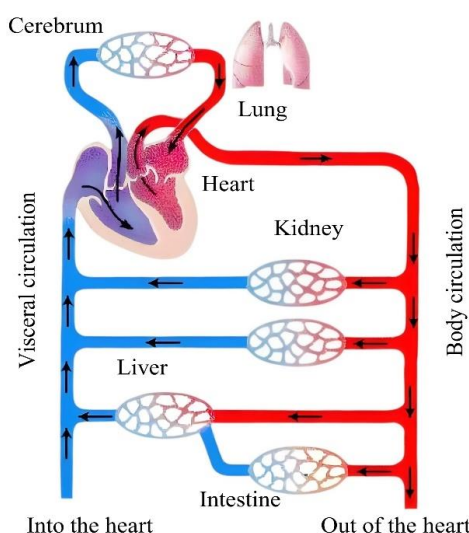


Figure 1. Schematic diagram of the burst of blood from the heart.

At high altitudes, the oxygen concentration in the blood vessels decreases significantly due to the reduction in the partial pressure of oxygen in the atmosphere, resulting in the organism needing to adapt to a hypoxic environment [30]. The organism copes with the lack of oxygen supply in the early stages of hypoxia by increasing the number of heartbeats to increase the amount of blood delivered to the tissues. Furthermore, the cerebrovascular system ensures the normal functioning of the brain in a prolonged hypoxic environment by vasodilatation and prioritizing blood supply to the brain. For example, when the human body is at an altitude of more than 2,500 meters above sea level, the concentration of oxygen in the blood decreases significantly, and the body compensates for this hypoxia by increasing the heart rate and cerebral vasodilation [31]. Specific data show that at an altitude of about 3500 m, the human heart rate can increase by 30%, while the cerebral blood flow increases by about 40% [32]. The frequency of cardiac contractions is closely related to the increase in blood flow velocity. The heart rate adjusts the blood flow velocity to enhance the supply of blood. Therefore, the variation in flow velocity can be described by the following relationship:

$$v_{\text{new}} = v_{\text{base}} \cdot (1 + k \cdot \Delta f) \quad (1)$$

where v_{new} represents the flow velocity after the heart rate increases, measured in cm/s (centimeters per second). v_{base} is the baseline flow velocity, measured in cm/s. Δf is the increase in heart rate (for example, if the heart rate increases by 30%, $\Delta f = 0.3$). k is the proportionality coefficient between the flow velocity and the heart rate change.

According to the continuity equation in fluid mechanics, we know that the gas flow rate (Q) is related to the flow velocity (v) and the cross-sectional area of the flow path (A) by the following relationship:

$$Q = A \cdot v \quad (2)$$

where Q is the flow rate, measured in m³/s (cubic meters per second). A is the cross-sectional area of the flow path, measured in m² (square meters). v is the flow velocity, measured in cm/s (centimeters per second).

In this study, during the simulation, the flow rate at the main inlet is set to 50% of the total flow, while each of the intermediate inlets accounts for 25% of the total flow rate. Therefore:

$$Q_{\text{main}} = \frac{1}{2} \cdot Q_{\text{total}} \quad (3)$$

$$Q_{\text{mid}} = \frac{1}{4} \cdot Q_{\text{total}} \quad (4)$$

The formula for the new flow rate is as follows:

$$Q_{\text{new,main}} = A_{\text{main}} \cdot v_{\text{new,main}} = A_{\text{main}} \cdot v_{\text{base,main}} \cdot (1 + k \cdot \Delta f) \quad (5)$$

$$Q_{\text{new,mid}} = A_{\text{mid}} \cdot v_{\text{new,mid}} = A_{\text{mid}} \cdot v_{\text{base,mid}} \cdot (1 + k \cdot \Delta f) \quad (6)$$

The total flow rate $Q_{\text{total,new}}$ can be expressed as the sum of the flow rates at each inlet:

$$Q_{\text{total,new}} = Q_{\text{new,main}} + 2 \cdot Q_{\text{new,mid}} \quad (7)$$

$$Q_{\text{total,new}} = A_{\text{main}} \cdot v_{\text{base,main}} \cdot (1 + k \cdot \Delta f) + 2 \cdot A_{\text{mid}} \cdot v_{\text{base,mid}} \cdot (1 + k \cdot \Delta f) \quad (8)$$

2.2. Bionic flow field modeling

Conventional serpentine flow channel designs often result in the formation of high pressures close to the intake manifold, with a gradual decrease in pressure within the channel as reactants are fed along the length of the channel. This pressure gradient leads to a loss of reactant concentration, which in turn directly affects the performance of the fuel cell and is not conducive to the drainage and management of water in the channel [33]. To overcome these problems, in this paper, a serpentine flow channel is designed based on the beating mechanism of the human heart in a plateau environment, and an air inlet is added in the middle part. The intermediate inlet is used to simulate the beat rate during a heartbeat and the increased blood supply during vasodilatation to improve the uniform distribution of reactants within the flow channel and optimize the performance of the fuel cell. In particular, it should be noted that the gases injected at the intermediate inlet are the same type as the conventional inlet and outlet gases, i.e., pure hydrogen and pure oxygen. The three-dimensional structure of the novel serpentine flow channel designed in this paper is shown schematically in Figure 2. The structure of this geometric model includes hydrogen and oxygen flow channels, gas diffusion layer (GDL), catalyst layer (CL), proton exchange membrane (PEM), and two intermediate inlets on both sides of the hydrogen and oxygen channels. For the three-channel serpentine flow field bipolar plate, only two intermediate air inlets are set up based on a combination of performance optimization and structural complexity. The two intermediate inlets can effectively improve the gas distribution in the flow channel and alleviate the uneven concentration of reactants due to the pressure gradient, and realize the best performance improvement while maintaining the simplicity of fabrication and controlling the cost. Two inlets can adequately cover different areas within the flow channel to avoid excessive depletion or enrichment, while adding more inlets will increase the manufacturing difficulty and gas management complexity. Therefore, the design of two inlets is an optimal balance between performance, structure, and manufacturing cost. The effective area of the two flow fields is $71\text{ mm} \times 71\text{ mm}$, and the channel depth, width, and rib width are all 1 mm. The specific geometric parameters and structural characteristics are detailed in Table 1.

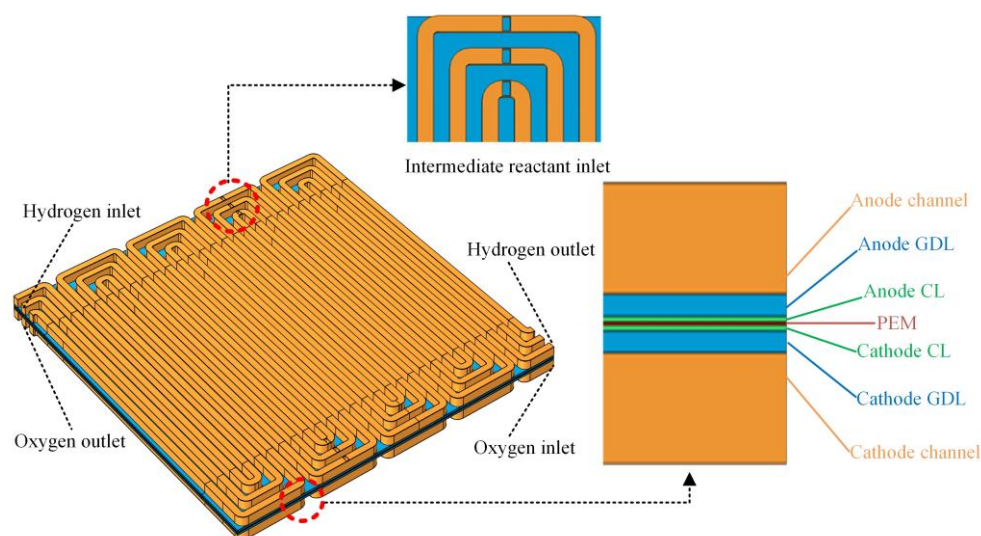


Figure 2. Geometrical model of serpentine flow channel PEMFC with intermediate inlets.

Table 1. Geometric parameters of the PEMFC.

Parameters	Value
Effective area of the fuel cell/mm ²	71 × 71
Gas flow path width/mm	1
Height of gas flow path/mm	1
Width of the spine/mm	1
Thickness of GDL/mm	0.2
Thickness of CL/mm	0.05
Thickness of membrane/mm	0.0275

2.3. Control equations

The operation of a PEMFC involves a complex electrochemical process involving the oxidation of hydrogen at the anode and the reduction of oxygen at the cathode, generating electric current and water. This process is affected by the coupling of several physical fields, such as temperature, gas transport, and liquid transport, which together determine the performance and efficiency of the fuel cell. Due to the complexity of the actual PEMFC mechanism and in order to simplify the calculations while ensuring the accuracy of the model, the following major assumptions are made for the PEMFC model used in this paper:

- (1) The gas in the channel is incompressible, and the fluid flow is laminar.
- (2) The PEMFC operates under steady-state conditions.
- (3) The effect of gravity is ignored.
- (4) The porous domains of the GDL, CL, and membrane are homogeneous and isotropic, and they do not enable gases to penetrate the membrane.

2.3.1. The continuity equation

$$\frac{\partial(\varepsilon\rho)}{\partial t} + \nabla \cdot (\varepsilon\rho\mathbf{U}) = S_m \quad (9)$$

$$S_m = \begin{cases} 0 \\ -\frac{M_{H_2}}{2F} R_{an} \\ \frac{M_{H_2O}}{2F} R_{ca} - \frac{M_{O_2}}{4F} R_{ca} \end{cases} \quad (10)$$

where M_{O_2} , M_{H_2} and M_{H_2O} are the molar masses of oxygen, hydrogen, and water vapor, respectively; R_{an} and R_{ca} are the anodic and cathodic transfer current densities per unit volume, respectively. S_m in the gas channel, and GDLS is 0; S_m in the anode CL is $-\frac{M_{H_2}}{2F} R_{an}$; and S_m in

the cathode CL is $\frac{M_{H_2O}}{2F} R_{ca} - \frac{M_{O_2}}{4F} R_{ca}$ [34].

2.3.2. Momentum conservation equations

$$\frac{\partial(\varepsilon \rho \vec{u})}{\partial t} + \nabla \cdot (\varepsilon \rho \vec{u}) = -\varepsilon \nabla p + \nabla \cdot (\varepsilon \mu \nabla \vec{u}) + S_u \quad (11)$$

where S_u denotes the momentum source term. When the fluid flows in the channel, S_u is zero. For fluid flow in a porous medium, S_u can be:

$$S_u = \frac{\varepsilon^2 \mu}{K_p} \vec{u} \quad (12)$$

where K_p is the permeability of the porous layer [35].

2.3.3. Energy conservation equations

$$\frac{\partial(\varepsilon \rho c_p T)}{\partial t} + \nabla \cdot (\varepsilon \rho c_p \vec{u} T) = \nabla \cdot (k_{eff} \nabla T) + S_e \quad (13)$$

where c_p is the constant pressure specific heat and S_e is the energy source term, including ohmic heat, heat of generation of water, latent heat of the aqueous phase, and conductive electric heat. It can be expressed as [36]:

$$S_e = I^2 R_{ohm} + \beta S_{H_2O} h_{react} + r_w h_{lg} + R_{an,ca} \eta_{an,ca} \quad (14)$$

2.3.4. Species transport equation

$$\frac{\partial(\varepsilon \rho C_i)}{\partial t} + \nabla \cdot (\varepsilon \rho \vec{u} C_i) = \nabla \cdot (D_i^{eff} \nabla C_i) + S_i \quad (15)$$

where S_i is the concentration source term for species i ; D_i^{eff} is the effective diffusion coefficient for species i ; C_i is the concentration of the substance; and S_i is equal to zero in the channel and GDLs. S_i in aCL and cCL can be expressed as [37].

$$S_{H_2} = -\frac{M_{H_2}}{2F} j_{an} \quad (16)$$

$$S_{O_2} = -\frac{M_{O_2}}{4F} j_{ca} \quad (17)$$

$$S_{H_2O} = \frac{M_{H_2O}}{2F} j_{ca} \quad (18)$$

where j_{an} , j_{ca} are the anode and cathode volume exchange current densities, respectively.

2.3.5. Current conservation equation

$$\nabla \cdot (\sigma_{sol} \nabla \varphi_{sol}) + R_{sol} = 0 \quad (19)$$

$$\nabla \cdot (\sigma_{mem} \nabla \varphi_{mem}) + R_{mem} = 0 \quad (20)$$

where σ is the conductivity; φ is the potential; *sol* is the solid phase; and *mem* is the membrane phase. The following Butler-Volmer equation can be used to calculate j , which is the volume transfer current [38].

$$j_{an} = \zeta_{an} j_{an}^{ref} \left(\frac{C_{H_2}}{C_{H_2}^{ref}} \right)^{\gamma_{an}} \left[\exp \left(\frac{\alpha_{an} F}{RT} \eta_{an} \right) - \exp \left(\frac{-\alpha_{ca} F}{RT} \eta_{an} \right) \right] \quad (21)$$

$$j_{ca} = \zeta_{ca} j_{ca}^{ref} \left(\frac{C_{O_2}}{C_{O_2}^{ref}} \right)^{\gamma_{ca}} \left[-\exp \left(\frac{\alpha_{an} F}{RT} \eta_{ca} \right) + \exp \left(\frac{-\alpha_{ca} F}{RT} \eta_{ca} \right) \right] \quad (22)$$

where j^{ref} is the reference exchange current density; ζ is the active specific surface area; η_{an} and η_{ca} are the local activation losses at the anode and cathode, respectively. Here, η_{an} and η_{ca} can be calculated by the following equation [39].

$$\eta_{an} = \varphi_{sol} - \varphi_{mem} \quad (23)$$

$$\eta_{ca} = \varphi_{sol} - \varphi_{mem} - V_{oc} \quad (24)$$

2.3.6. Liquid water transport equation

$$\frac{\partial(\varepsilon \rho_l s)}{\partial t} + \nabla \cdot (s \rho_l \vec{u}_l) = r_w \quad (25)$$

where s is the volume ratio of liquid water [40]. The movement of water in a porous medium occurs by capillary action and can be expressed as.

$$\frac{\partial(\varepsilon\rho_l s)}{\partial t} + \nabla \cdot \left(\rho_l \frac{Ks^3}{\mu_l} \frac{dp_c}{ds} \nabla s \right) = r_w \quad (26)$$

$$r_w = c_r \max \left(\left[(1-s) \left(\frac{p_{wv} - p_{sat}}{RT} \right) M_{w,H_2O} \right], [-s\rho_l] \right) \quad (27)$$

where p_c is the capillary pressure, which can be calculated by the following equation [41].

$$p_c = \begin{cases} \frac{\sigma_t \cos \theta_c}{(K/\varepsilon)^{0.5}} [1.417(1-s) - 2.12(1-s)^2 + 1.263(1-s)^3]; \theta_c < 90^\circ \\ \frac{\sigma_t \cos \theta_c}{(K/\varepsilon)^{0.5}} (1.417s - 2.12s^2 + 1.263s^3); \theta_c > 90^\circ \end{cases} \quad (28)$$

In order to obtain good proton conductivity, PEM requires a specific water content, which is calculated as:

$$\lambda = \begin{cases} 0.043 + 17.18a - 39.85a^2 + 36a^3; a \leq 1 \\ 14 + 1.4(a-1); a > 1 \end{cases} \quad (29)$$

where a is the water activity, calculated as:

$$a = \frac{p_{wv}}{p_{sat}} + 2s \quad (30)$$

2.4. Boundary conditions

Proton exchange membrane (PEM) fuel cells produce water during the chemical reaction. It is mainly concentrated in the cathode measurement, and the amount of water content will affect the performance of PEM fuel cells. Therefore, hydrogen gas with a relative humidity of 100% was fed into the anode. Oxygen with a relative humidity of 10% was fed at the cathode. The cathode relative humidity was set to 10%, reflecting the typical low-pressure and low-humidity conditions in high-altitude areas. This value was intended to simulate a worst-case scenario, particularly in high-altitude environments, where lower air humidity can cause rapid evaporation of moisture in the cathode region. Therefore, setting the relative humidity at 10% helped us assess the fuel cell's performance under low-humidity conditions and ensures that it can maintain stable operation even in the most unfavorable environments. The gas and cell temperatures are controlled at 343.15 K. The bipolar plate walls were set as adiabatic boundaries. The anode surface was electrically grounded, the cathode surface potential was 1 V, and the electrode current was 0.25 A. The fuel cell performance was observed at different average cell current densities; the initial scan parameter was 0.01 A/cm², the step size was set to 0.1 A/cm², and the

final average current density of the scan was 1 A/cm². The mass flow at the anode and cathode inlets was defined as [42]:

$$\dot{m}_{inlet,an} = \frac{\xi_{an} I_{ref} A_{MEA}}{2x_{H_2} F} \quad (31)$$

$$\dot{m}_{inlet,ca} = \frac{\xi_{ca} I_{ref} A_{MEA}}{4x_{O_2} F} \quad (32)$$

where ξ is the stoichiometric ratio, A_{MEA} is the active area of the MEA, I_{ref} is the reference current density, and x is the mass fraction. Table 2 lists the operating conditions and detailed parameters required for the PEMFC simulation. Table 3 lists the units of the variables used in the control equations

Table 2. Detailed parameters for simulation operation.

Parameters	Value
Hydrogen flow metering factor	1.2
Oxygen flow metering factor	2.5
Inlet RH, anode side	1
Inlet RH, cathode side	0.1
Operating temperature	343.15 K
Initial average current density of the scan	0.01 A/cm ²
Final average current density of the scan	1 A/cm ²
Exchange current density, hydroxide	0.01 Ac/m ²
Exchange Current Density, Oxygen Reduction	1×10^{-8} A/cm ²
Specific surface area, catalytic layer	5×10^7 1/m
In-surface conductivity, gas diffusion layer	5000 S/m
Out-of-plane conductivity, gas diffusion layer	200 S/m
Gas permeability, gas diffusion layer	5×10^{-12} m ²
Anode transfer coefficient, oxygen reduction	3
Gas phase volume fraction, gas diffusion layer	0.6
Solid phase volume fraction, gas diffusion layer	0.4
Total Current for Chemical Calculated Flow Calculations	2.5 A
Total cell current	0.25 A
Hydrogen molar flow rate	1.5×10^{-5} mol/s
Vapor molar flow rate, anode side	1.3×10^{-6} mol/s
Vapor molar flow rate, cathode side	2.3×10^{-5} mol/s
Nitrogen molar flow rate	6.1×10^{-5} mol/s
Oxygen molar flow rate	1.6×10^{-5} mol/s
Total mass flow rate, anode side	5.4×10^{-8} kg/s

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Parameters	Value
Total cathode mass flow rate	2.6×10^{-6} kg/s
Hydrogen mass flow rate	3.1×10^{-8} kg/s
Vapor mass flow rate, anode side	2.3×10^{-8} kg/s
Vapor mass flow rate, cathode side	4.1×10^{-7} kg/s
Nitrogen Mass Flow Rate	1.7×10^{-6} kg/s
Oxygen mass flow rate	5.1×10^{-7} kg/s
Mass fraction of anode material flowing	0.8
Cathode feed stream mass fraction	0.02
Nitrogen mass fraction in cathode feed stream	0.75
Hydrogen mass fraction of anode stream	0.69
Mole fraction of vapor in anode stream	0.31
Mole fraction of cathode stream vapor	0.03
Mole fraction of nitrogen in cathode stream	0.76
Mole fraction of oxygen in cathode stream	0.2

Table 3. Variable names and units.

Variable	Unit
Mass source term S_m	Kg/m ³ /s
Molar mass of M_{O_2} , M_{H_2} , M_{H_2O}	Kg/mol
Volumetric transfer current density (anode/cathode) R_{an} , R_{ca}	A/m ³
Momentum source term S_u	N/m ³
Permeability of porous layer K	m ²
Specific heat at constant pressure c_p	J/kg/K
Energy source term (ohmic heat, etc.) S_e	W/m ³
Concentration source term S_i	Mol/m ³ /s
Effective diffusion coefficient D_i^{eff}	m ² /s ¹
Species concentration C_i	Mol/m ³
Electrical conductivity σ	S/m ¹
Electric potential ϕ	V
Active specific surface area ζ	m ⁻¹
Anode/Cathode activation loss η_{an} , η_{ca}	V
Faraday constant F	C/mol ¹
Capillary pressure p_c	Pa

2.5. Modeling of altitude and atmospheric pressure

According to Article 8.2.5 of the “Electric Power Industry Standard of the People’s Republic of China: Technical Specification for Design and Calculation of Combustion Systems in Thermal Power Plants (DL/T 5240-2010)” issued by the National Energy Administration (NEA), the empirical formulas between atmospheric pressure and altitude are expressed as [43]:

$$P_a = 101.3 \times \left[1 - 0.0255 \times \frac{H}{1000} \left(\frac{6357}{6357 + \frac{H}{1000}} \right) \right]^{5.256} \quad (33)$$

where P_a is the local average atmospheric pressure, and H is the local altitude. The relationship between altitude and atmospheric pressure is shown in Table 4, and the graph is shown in Figure 3.

Table 4. Altitude and atmospheric pressure.

Altitude (m)	Pressure (kPa)	Altitude (m)	Pressure (kPa)
0	101.3	2600	70.65
200	98.61	2800	68.64
400	95.99	3000	66.69
600	93.42	3200	64.78
800	90.90	3400	62.91
1000	88.44	3600	61.09
1200	86.04	3800	59.31
1400	83.69	4000	57.57
1600	81.39	4200	55.87
1800	79.14	4400	54.22
2000	76.94	4600	52.60
2200	74.79	4800	51.03
2400	72.70	5000	49.49

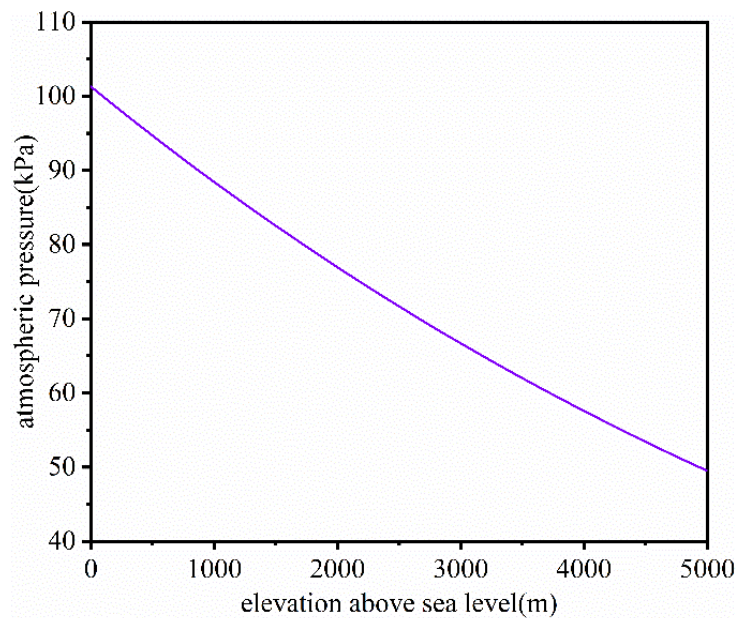


Figure 3. Relationship between altitude and atmospheric pressure.

2.6. Numerical calculations and experimental tests

The operation of PEMFC is a complex chemical reaction process involving multiple physical fields coupled with each other. COMSOL Multiphysics is a multiphysics field solver capable of solving a wide range of fundamental models and sub-models, including matter transport, heat transfer, chemical reactions, and electrochemical reactions [44]. In this study, a three-dimensional multiphase non-isothermal model was developed using the PEMFC module in COMSOL to simulate the performance of a PEMFC operating with a cardiac bionic flow channel design at a steady state. The governing equations were discretized by the finite element method, solved in steady state using MUMPS with automatic error estimation checking turned on, with a maximum mesh refinement of 15 and an error rate of 0.5, and an iterative solution algorithm was used to deal with the pressure-velocity coupling problem. To improve computational accuracy, matter transport and charge transfer equations were discretized in a higher order. Adaptive mesh encryption and relaxation techniques improved the convergence speed and stability of the calculations.

In this study, the results of Huang et al. [45] on the polarization curves of the conventional serpentine flow field are referred to as the experimental references in this paper. The experimental results of Huang et al. provide the polarization characteristics of the traditional serpentine flow field under different operating conditions, which provide a benchmark for the design of the new serpentine flow field in this study. The simplified flow chart of the corresponding experiment is shown in Figure 4.

The experimental platform mainly consisted of a gas flow control module, a humidification module, a gas heating module, a back pressure module, and some valves and sensors. During the experiment, hydrogen and oxygen were controlled by manual ball valves, and the gas pressure and flow rate were monitored by pressure sensors and flow meters. Then, the gases were humidified by a humidifying tank and then heated to the preset reaction temperature by a gas heating module. Finally, the polarization curve data were measured by the constant flow method and recorded by the control and analysis software.

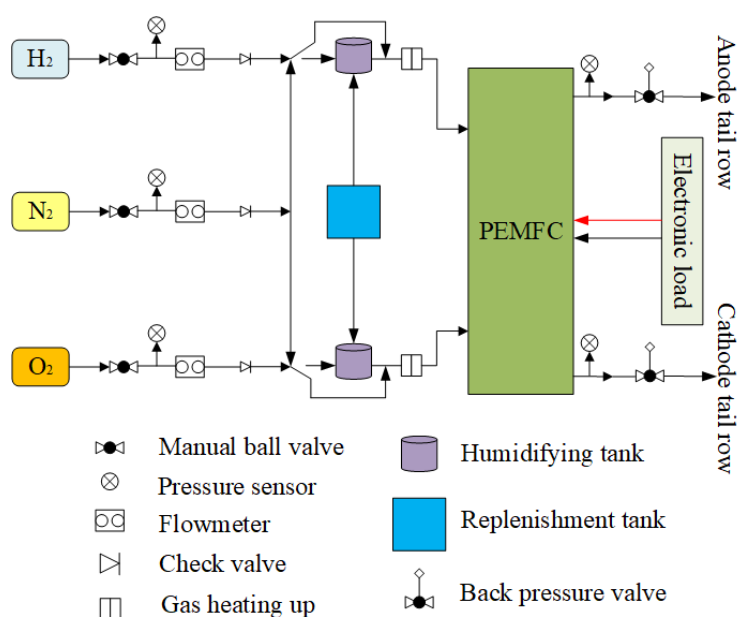


Figure 4. Schematic diagram of the experimental test.

2.7. Lattice independence tests and model validation

In finite element simulation and analysis, the number of meshes is a crucial factor affecting the computational accuracy and computational speed. Therefore, the examination of mesh independence is crucial. Figure 5 demonstrates the polarization curves for mesh numbers 330073, 674476, and 1381235, respectively, in comparison with the experimental parameters of Huang et al. [45]. The trends of the polarization curves at different grid numbers agree with the experimental results. However, the variation in the number of grids leads to a deviation from the experimental results. According to Table 5, the relative simulation errors at a working voltage of 0.6 V for grid numbers of 330073, 674476, and 1381235 are 0.053%, 0.0237%, and 0.106%, respectively. Therefore, to minimize the error, the grid number with the smallest relative error, 674476, was chosen as the model for the subsequent simulations.

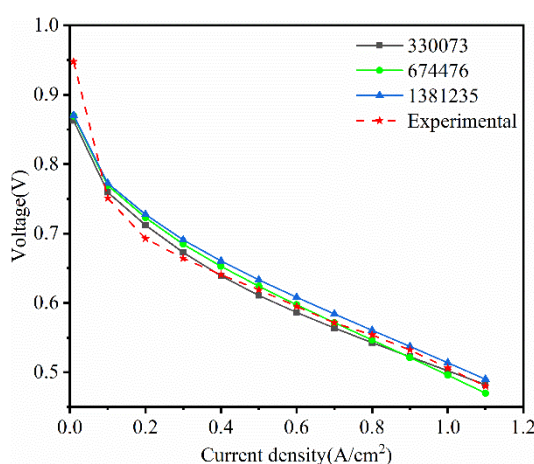


Figure 5. Polarization curves for different numbers of grids vs. experimental data.

Table 5. Effect of the number of grids on the numerical results.

Parameter	Grid number	Current density (A/cm ²)	Relation deviation
Mesh1	330073	0.54103	0.053%
Mesh2	674476	0.58489	0.0237%
Mesh3	1381235	0.63196	0.106%
Experimental	-	0.57134	-

3. Results and discussion

3.1. Effect of atmospheric pressure on current density and power of fuel cells

According to the model on the relationship between altitude and atmospheric pressure in Section 2.5, the atmospheric pressures (1 atm, 0.88 atm, 0.77 atm, 0.67 atm, and 0.58 atm) corresponding to the more universally adapted altitudes were selected as the working conditions in this study. The current densities and power outputs of the PEMFC were analyzed in detail.

Figure 6 illustrates the impact of atmospheric pressure on the polarization and power output curves of PEMFC at various altitudes. The results show that as altitude increases and atmospheric pressure decreases, the current density curves decline significantly. This is due to the reduced partial

pressure of oxygen at higher altitudes, which slows the oxygen transfer rate in the cathode catalyst layer, thereby impairing electrochemical reaction efficiency. Additionally, the power output curves also decrease with increasing altitude, primarily due to the reduced oxygen concentration and increased mass transport resistance. At high altitudes, the decrease in oxygen concentration worsens concentration polarization at the cathode, increasing overpotential and reducing power output. Furthermore, slower gas diffusion intensifies mass transport resistance, reducing the reaction efficiencies for both oxygen and hydrogen, which further lowers the fuel cell's power output.

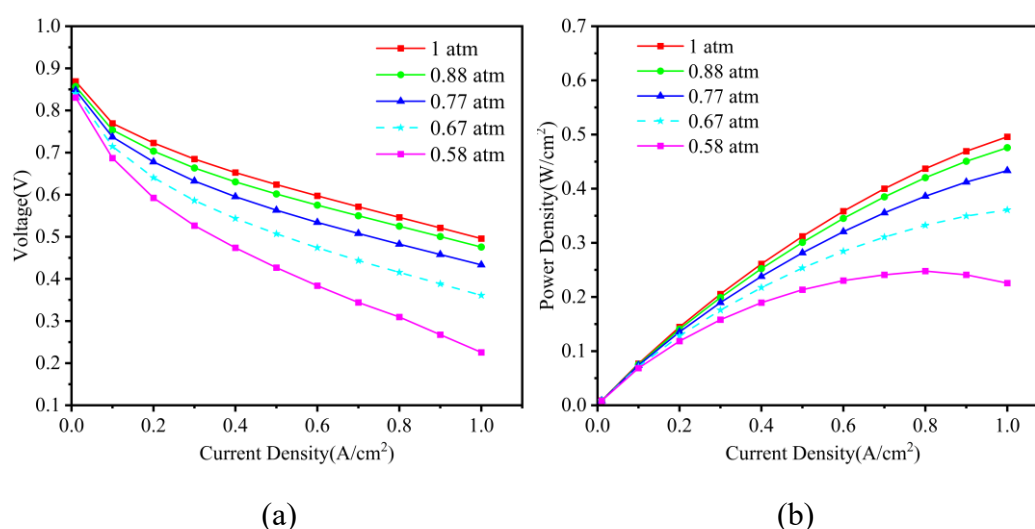


Figure 6. Conventional serpentine flow field: (a) polarization curve and (b) power curve.

The effect of altitude change on the performance of the PEMFC can be quantified by analyzing the magnitude of power decrease at different altitudes corresponding to atmospheric pressure at a current density of 1 A/cm². Table 6 shows the total percentage decrease in power at different altitudes, with the results indicating a total power loss of 4%–54% at each specified altitude compared to the power at standard atmospheric conditions.

Table 6. Percentage decrease in power.

Altitude (km)	Pressure (atm)	Power (W/cm²)	Percentage drop
0	1	0.50	-
1000	0.88	0.48	4%
2000	0.77	0.43	14%
3000	0.67	0.36	28%
4000	0.58	0.23	54%

Figure 7 illustrates the polarization and power output curves of the novel serpentine flow field featuring intermediate inlets. The results show that a decrease in atmospheric pressure similarly leads to reductions in polarization and power output curves. However, at a current density of 1 A/cm², the novel flow field shows improvements in polarization and power output compared to the traditional serpentine flow field. Table 7 provides a detailed comparison of power parameters under both flow fields. The data indicate that the novel serpentine flow field with intermediate inlets can significantly

enhance fuel cell power under high-altitude conditions (e.g., at an altitude of 4,000 meters with an atmospheric pressure of 0.58 atm), with an increase of approximately 34.8%. This improvement is primarily attributed to the intermediate inlets, which enhance gas distribution and effectively mitigate oxygen concentration polarization within the flow channels, thereby reducing cathode overpotential and improving reaction efficiency. Moreover, the introduction of intermediate inlets results in a more uniform supply of reactants, helping to reduce mass transport resistance and further boosting power output. These findings demonstrate that the novel serpentine flow field offers significant advantages in enhancing PEMFC performance under high-altitude conditions.

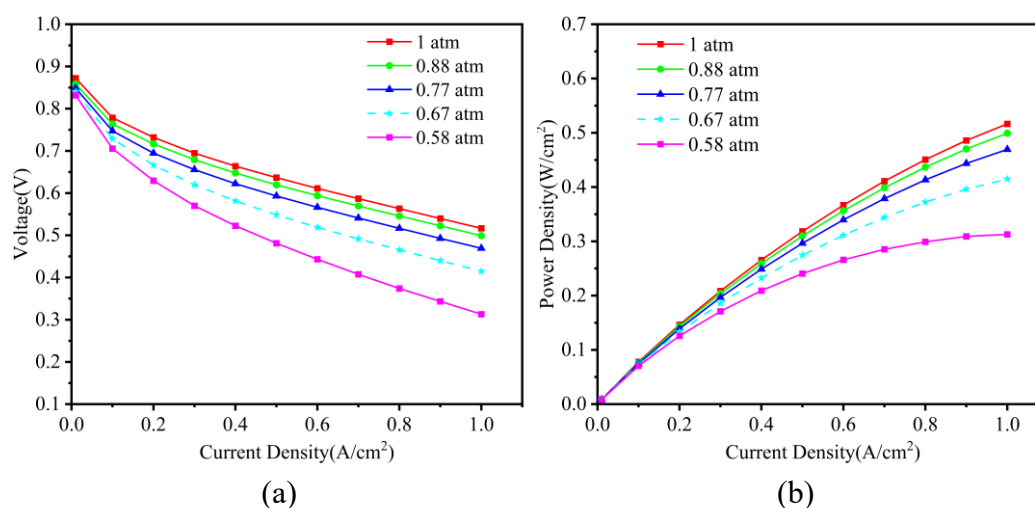


Figure 7. New serpentine flow field: (a) polarization curve; (b) power curve.

Table 7. Comparison of power parameters under different flow fields.

Altitude (km)	Pressure (atm)	Traditional (W/cm ²)	New (W/cm ²)	Percentage lift
0	1	0.50	0.52	4%
1000	0.88	0.48	0.5	4.2%
2000	0.77	0.43	0.47	9.3%
3000	0.67	0.36	0.41	13%
4000	0.58	0.23	0.31	34.8%

Figure 8 shows the percentage change in voltage difference between the novel serpentine flow field and the traditional serpentine flow field under varying atmospheric pressures. The results indicate that at lower altitudes (1 atm and 0.88 atm), the voltage difference between the two flow fields exhibits minimal variation with increasing current density, suggesting comparable performance under standard atmospheric pressure conditions. However, at moderate altitude (0.77 atm) and higher altitudes (0.67 atm and 0.58 atm), the voltage advantage of the novel serpentine flow field becomes more pronounced. Notably, at 0.58 atm (corresponding to approximately 4,000 meters elevation), the voltage of the novel serpentine flow field significantly exceeds that of the traditional serpentine flow field, with the voltage difference reaching its peak.

This phenomenon is primarily due to the intermediate inlets in the novel serpentine flow field, which enhance the uniform distribution of reactant gases within the flow channels, thereby mitigating concentration polarization, especially under low atmospheric pressure conditions. This facilitates more

effective oxygen transport to the cathode, improving electrochemical reaction efficiency and reducing voltage losses. Importantly, at higher current densities and lower atmospheric pressures, increased mass transport resistance adversely affects the traditional flow field to a greater extent. The optimized channel structure of the novel flow field effectively alleviates this issue, resulting in a more pronounced voltage advantage. Consequently, the novel serpentine flow field demonstrates significant voltage superiority over the traditional design under high current density and low atmospheric pressure conditions.

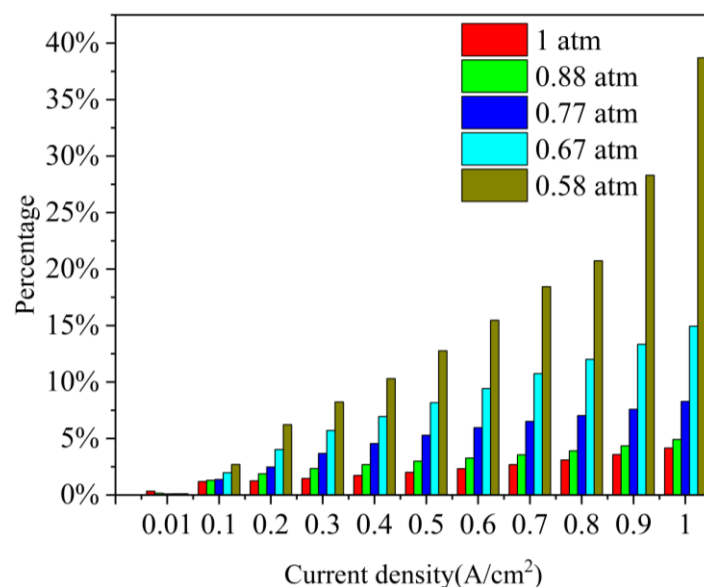
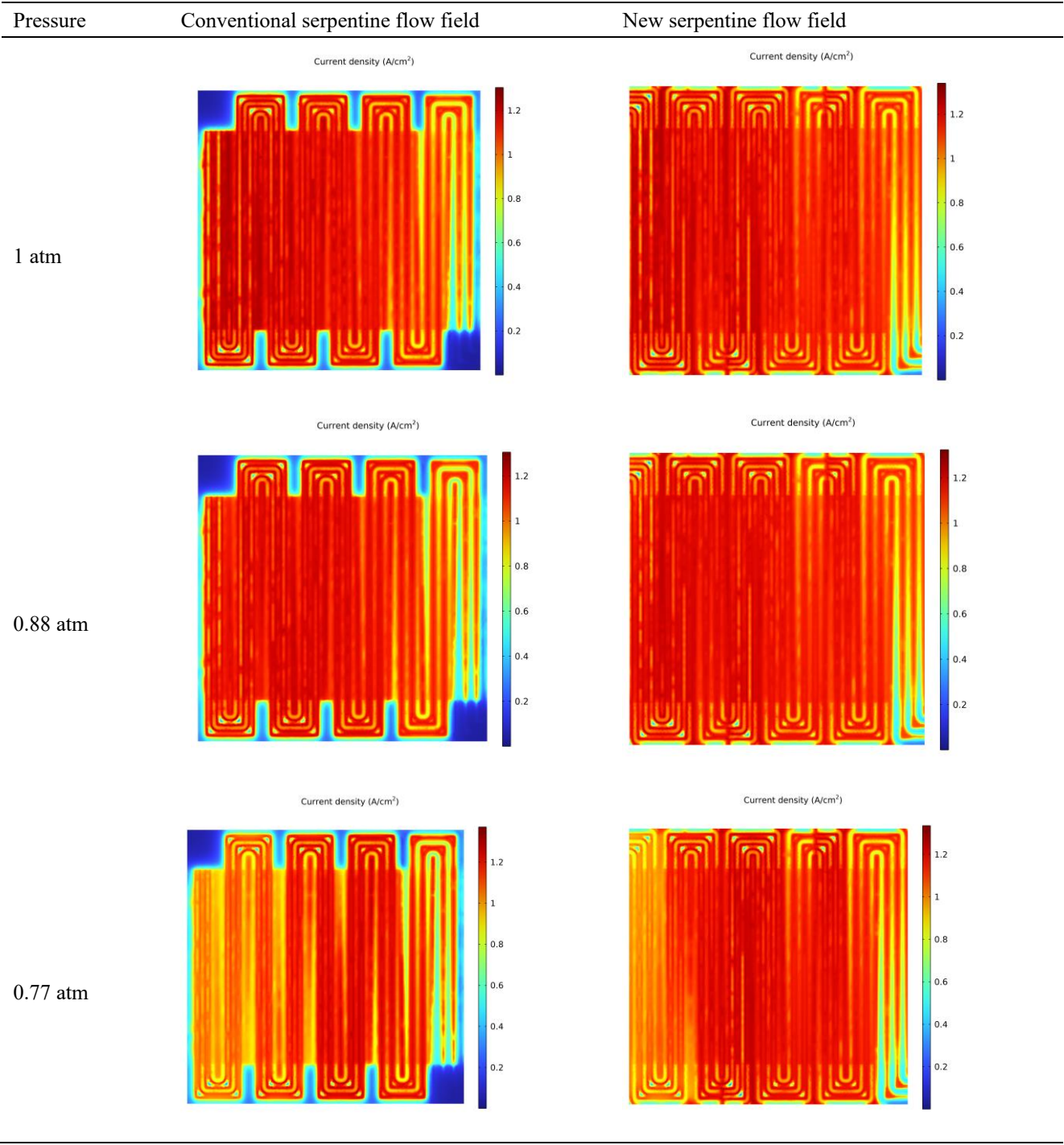


Figure 8. Percentage of voltage difference between the two flow fields.

Figure 9 depicts the current density distribution within the gas diffusion layer and catalyst layer for both the traditional serpentine flow field and the novel flow field. As atmospheric pressure decreases, current density declines to varying extents in both flow fields. In the traditional serpentine flow field, lower current densities are observed near the inlet and outlet, primarily due to the placement of the oxygen and hydrogen inlets on opposite sides of the cell, resulting in uneven reactant concentrations in these regions, which negatively impact reaction efficiency. In contrast, the novel serpentine flow field addresses this issue by introducing intermediate inlets, promoting a more uniform distribution of reactant concentrations throughout the flow field, and mitigating the concentration non-uniformity observed at the inlet and outlet in the traditional design. This configuration optimizes gas transport and diffusion, reduces overpotential caused by concentration polarization, and enhances electrochemical reaction efficiency. A comparison of current density distributions and voltage data under varying atmospheric pressures demonstrates that the novel flow field exhibits superior performance under high-altitude, low-pressure conditions, significantly increasing the fuel cell's power output. These findings indicate that the novel flow field design offers significant advantages in improving PEMFC performance in high-altitude environments, particularly under mass transport-limited conditions, effectively mitigating performance degradation.



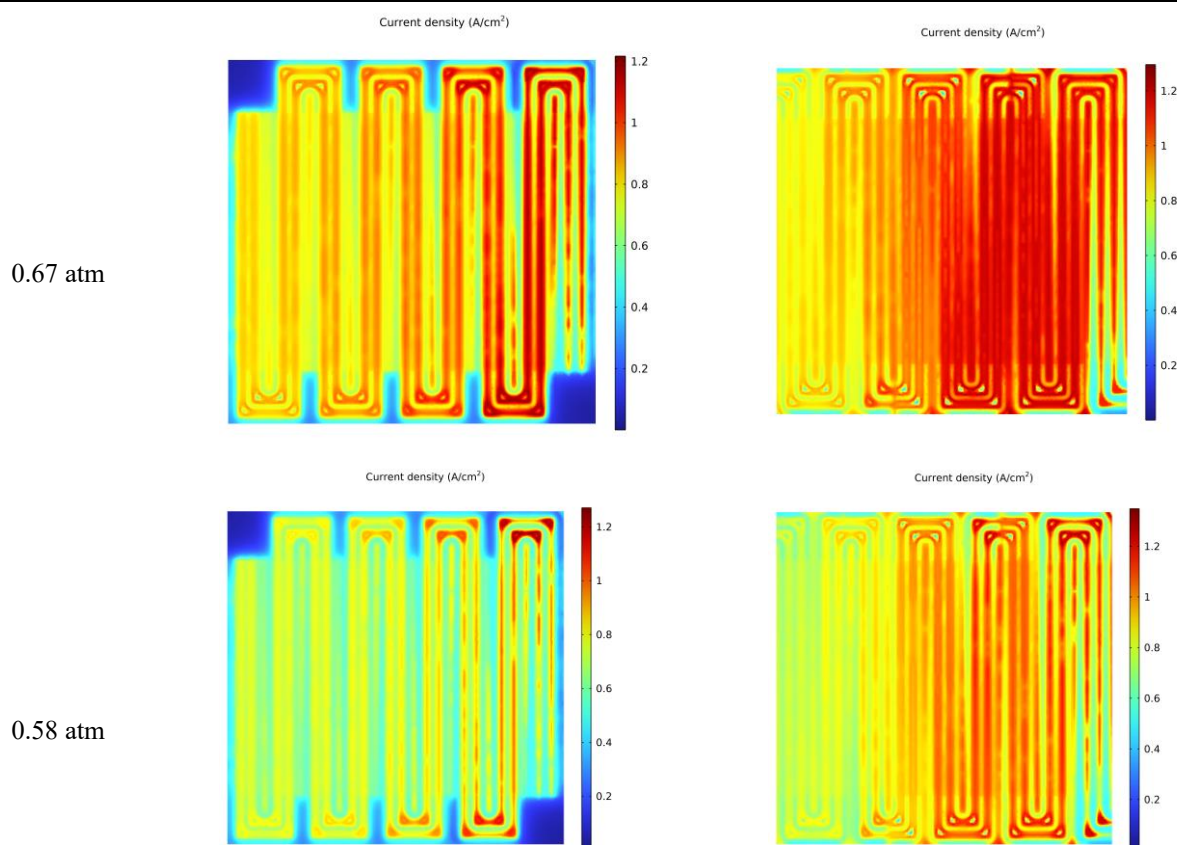


Figure 9. Current density of conventional serpentine flow field and new serpentine flow field in CGDL/CCL.

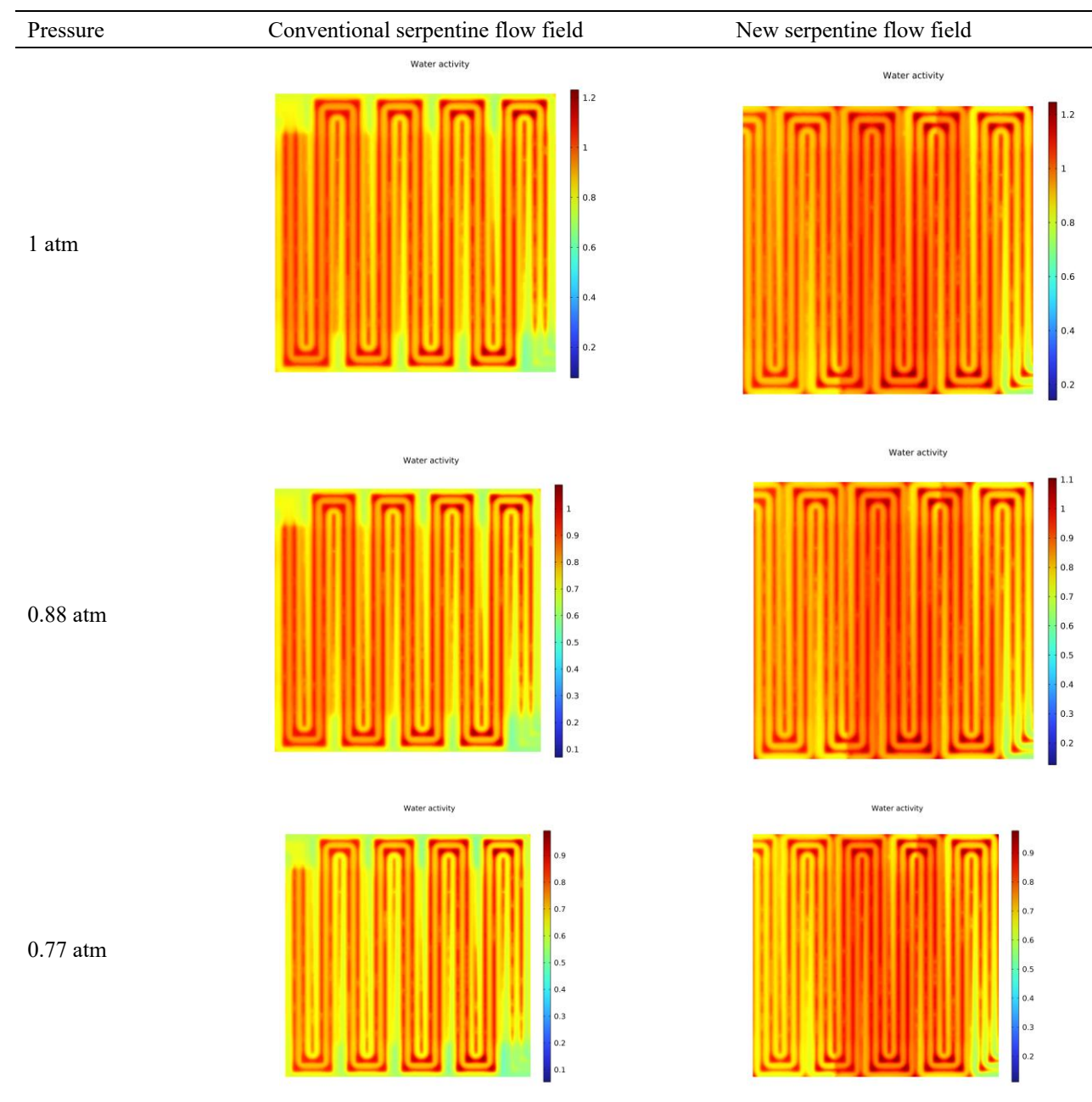
3.2. Effect of atmospheric pressure on GDL water activity

Water is a key parameter affecting the PEMFC. The water content directly affects the proton conductivity of the membrane and the transport of reactants (e.g., hydrogen and oxygen) in the gas diffusion and catalytic layers. A proper water activity maintains good wettability of the GDL, which contributes to the reactant transport and electrochemical reactions. Figure 10 illustrates the distribution of water activity in the traditional and novel flow fields under varying atmospheric pressures. As atmospheric pressure decreases, water activity significantly declines in both flow fields. At 0.58 atm, the maximum water activity is 0.8, representing a 33% reduction compared to 1 atm. This marked decrease is primarily attributed to the reduced oxygen partial pressure in high-altitude environments, which diminishes the cathode reaction rate, consequently lowering water production. Under standard atmospheric pressure, the novel serpentine flow field with intermediate inlets exhibits a more uniform water distribution compared to the traditional design, indicating enhanced water generation and management during fuel cell operation, thereby improving overall performance.

Water production in both flow fields is primarily concentrated near the outlet and regions with relatively high current density, where electrochemical reactions are more active, leading to increased water generation. However, under low-pressure conditions, the reactant concentration in the central region of the fuel cell notably decreases in the traditional serpentine flow field, resulting in reduced

water production and decreased reaction efficiency. This suggests inferior performance of the traditional flow field under low-pressure environments.

By ensuring uniform reactant distribution throughout the flow field, the novel serpentine flow field improves electrochemical reaction efficiency and water production in the central region, maintaining high reaction efficiency and cell performance even under low-pressure conditions. These findings demonstrate that the intermediate inlet design is critical in enhancing water management, particularly by effectively mitigating uneven water distribution under low-pressure conditions, thereby boosting fuel cell performance and stability.



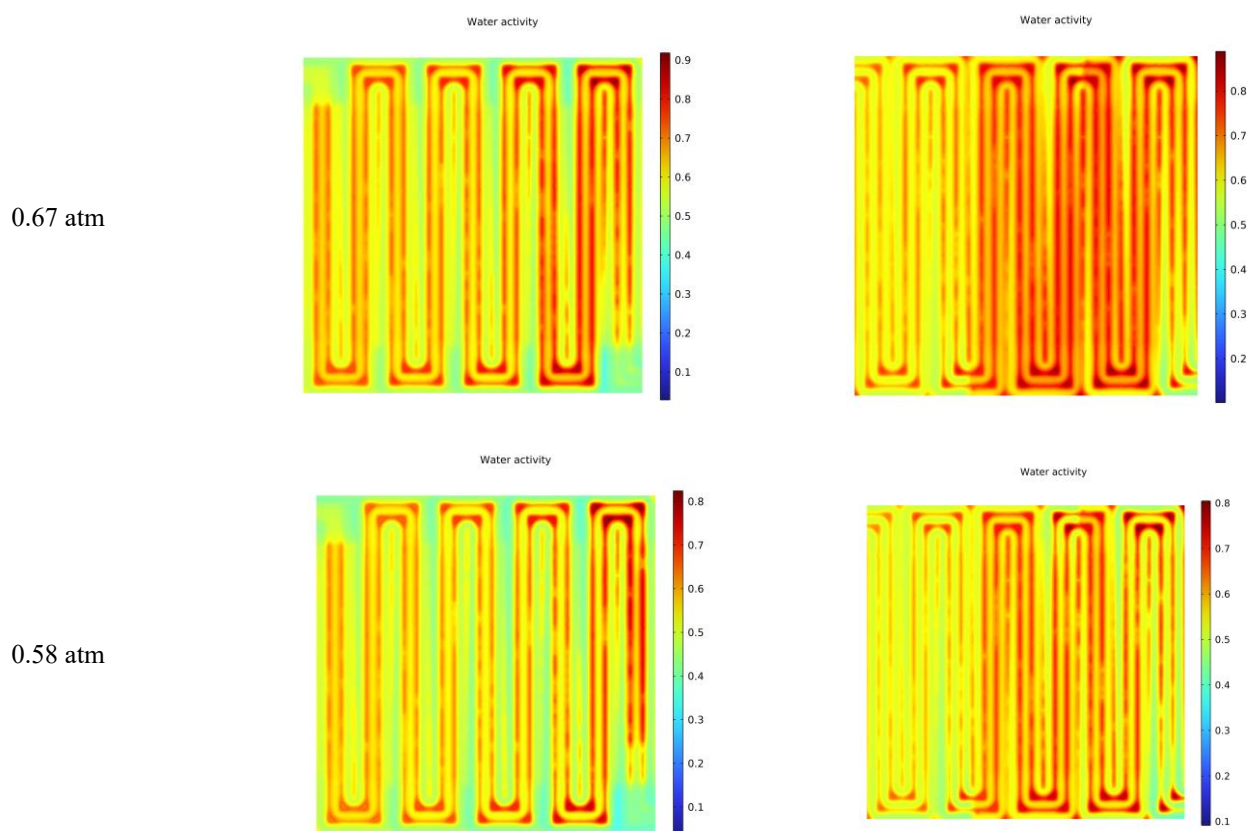


Figure 10. Water activity of the conventional serpentine flow field and novel serpentine flow field in CGDL/CCL.

3.3. Effect of atmospheric pressure on the oxygen mole fraction in GDL

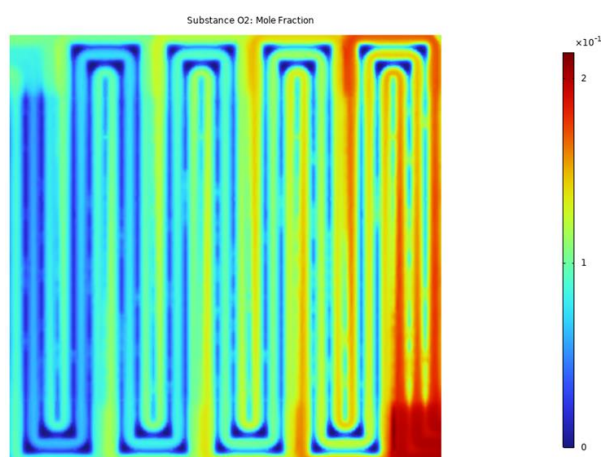


Figure 11. O_2 mole fraction map in the traditional flow channel at 0.58 atm.

As shown in Figure 11 is the O_2 mole fraction map in the traditional flow channel at 0.58 atm. The oxygen mole fraction distribution in the traditional flow channel reveals significant non-uniformity. At

the inlet of the oxygen flow channel, the oxygen mole fraction is relatively high, but it decreases rapidly in the central region of the channel, particularly near the outlet. This decrease in oxygen concentration leads to concentration polarization, resulting in insufficient oxygen supply to the reaction zone, which in turn reduces the overall efficiency of the fuel cell. Due to the uneven distribution of oxygen concentration, regional imbalances in oxygen consumption and water production may occur within the fuel cell, affecting its efficiency.

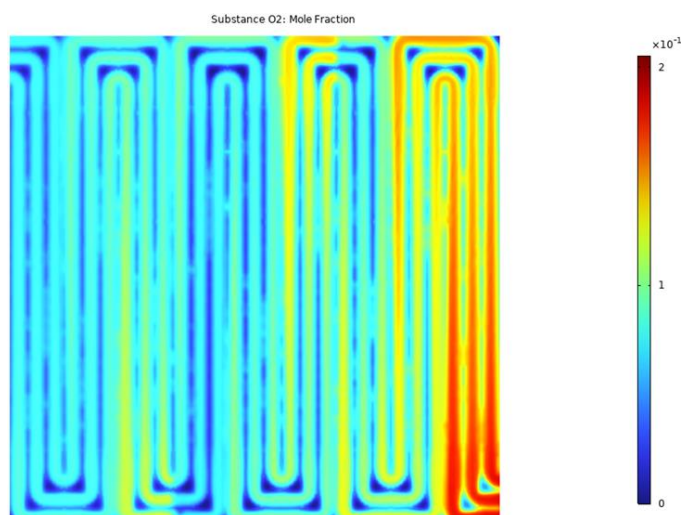


Figure 12. O₂ mole fraction map in the novel flow channel at 0.58 atm.

Figure 12 shows the O₂ mole fraction map in the novel flow channel at 0.58 atm. Compared to the traditional flow channel, the oxygen mole fraction distribution in the new flow channel is significantly more uniform. The design of the new flow channel effectively suppresses the phenomenon of concentration polarization. Oxygen concentration is more evenly distributed along both sides and the center of the channel, ensuring adequate oxygen supply to the reaction zone and reducing the occurrence of local oxygen depletion.

By comparing the two graphs, we see that the oxygen mole fraction distribution in the new flow channel at 0.58 atm is significantly superior to that in the traditional flow channel. The variation in oxygen concentration in the new flow channel is smaller, indicating that the uniform distribution of oxygen improves the reaction conditions within the channel. In the traditional flow channel, the oxygen concentration rapidly decreases in the central region, which intensifies concentration polarization and leads to a decline in battery performance. In contrast, the oxygen concentration distribution in the new flow channel is more uniform, effectively suppressing concentration polarization and ensuring efficient fuel cell operation under low-pressure conditions.

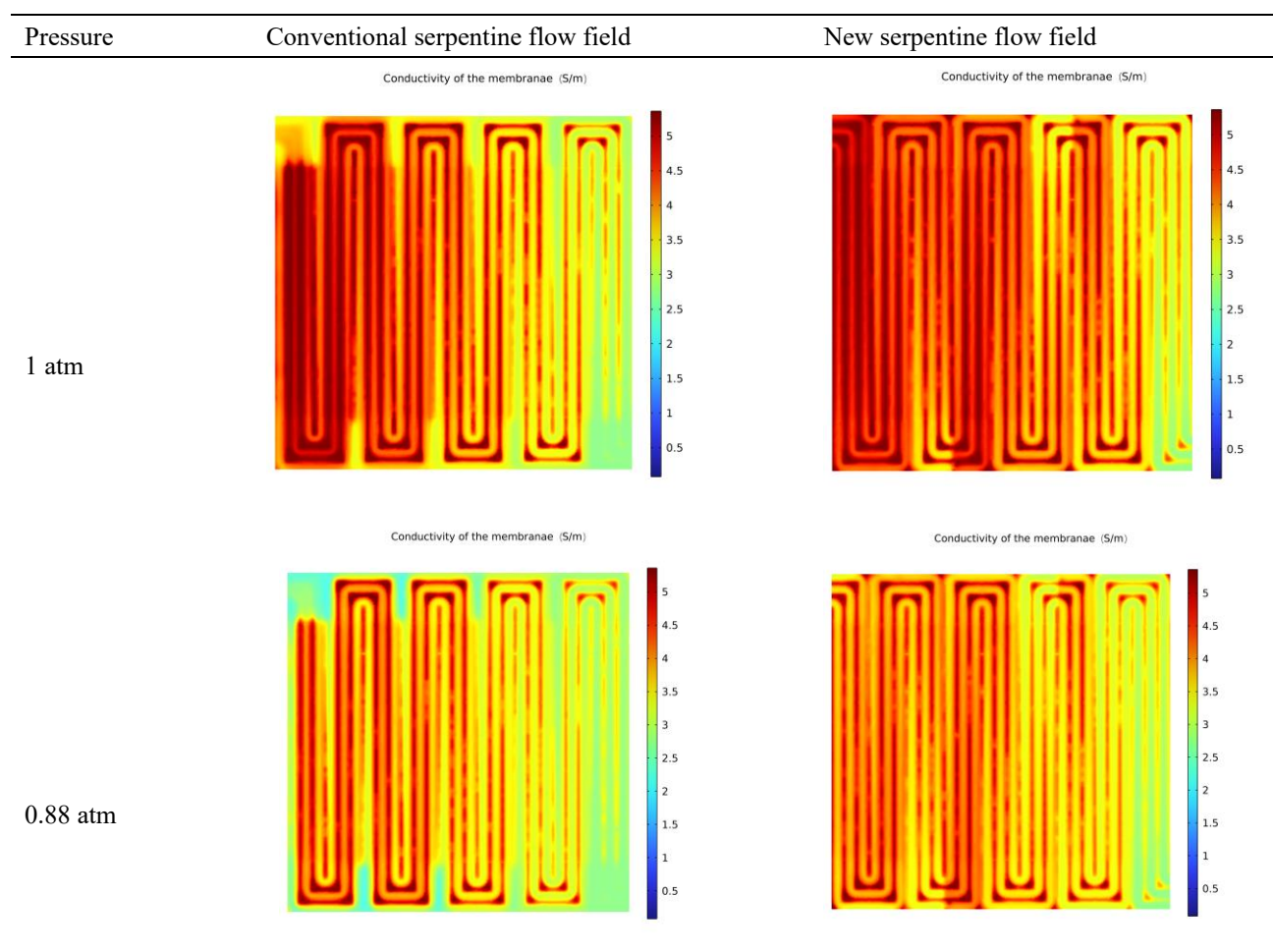
3.4. Effect of atmospheric pressure on the conductivity of GDE

The conductivity of GDE reflects the ability to conduct electrons and protons in the electrode. GDE is usually composed of porous materials that allow the reactive gases to diffuse into the catalytic layer and generate water and electric current through electrochemical reactions. The conductivity of GDE depends on the nature of its material, porosity, and water content. Higher water content not only

helps proton conduction but also enhances the electronic conductivity of the electrode.

Figure 13 presents the conductivity distribution of the traditional and novel serpentine flow fields under different atmospheric pressures. Analysis of the water activity contour maps and conductivity distribution plots reveals that regions of higher conductivity in both flow field designs primarily correspond to areas with elevated water activity. This is because the presence of water facilitates proton conduction, thereby enhancing conductivity. Regions characterized by high reactant concentrations and active electrochemical reactions typically exhibit increased water generation, further boosting local conductivity. As atmospheric pressure decreases, conductivity gradually declines due to the reduced oxygen partial pressure in low-pressure environments, which slows reactant transport, diminishes electrochemical reaction efficiency, reduces water production, and lowers membrane hydration; factors that collectively contribute to decreased conductivity.

Research indicates that under low atmospheric pressures, the uniformity of conductivity distribution in the traditional serpentine flow field is inferior to that in the novel serpentine flow field, especially at 0.77 atm and 0.67 atm, where the disparity is most pronounced. Under these conditions, non-uniform reactant distribution intensifies in the traditional serpentine flow field, particularly near the inlet and outlet, resulting in significant reductions in conductivity in those regions. In contrast, the novel serpentine flow field, by incorporating intermediate inlets, improves reactant distribution and ensures more uniform conductivity throughout the cell. This design effectively enhances conductivity under low-pressure conditions, thereby improving overall fuel cell performance.



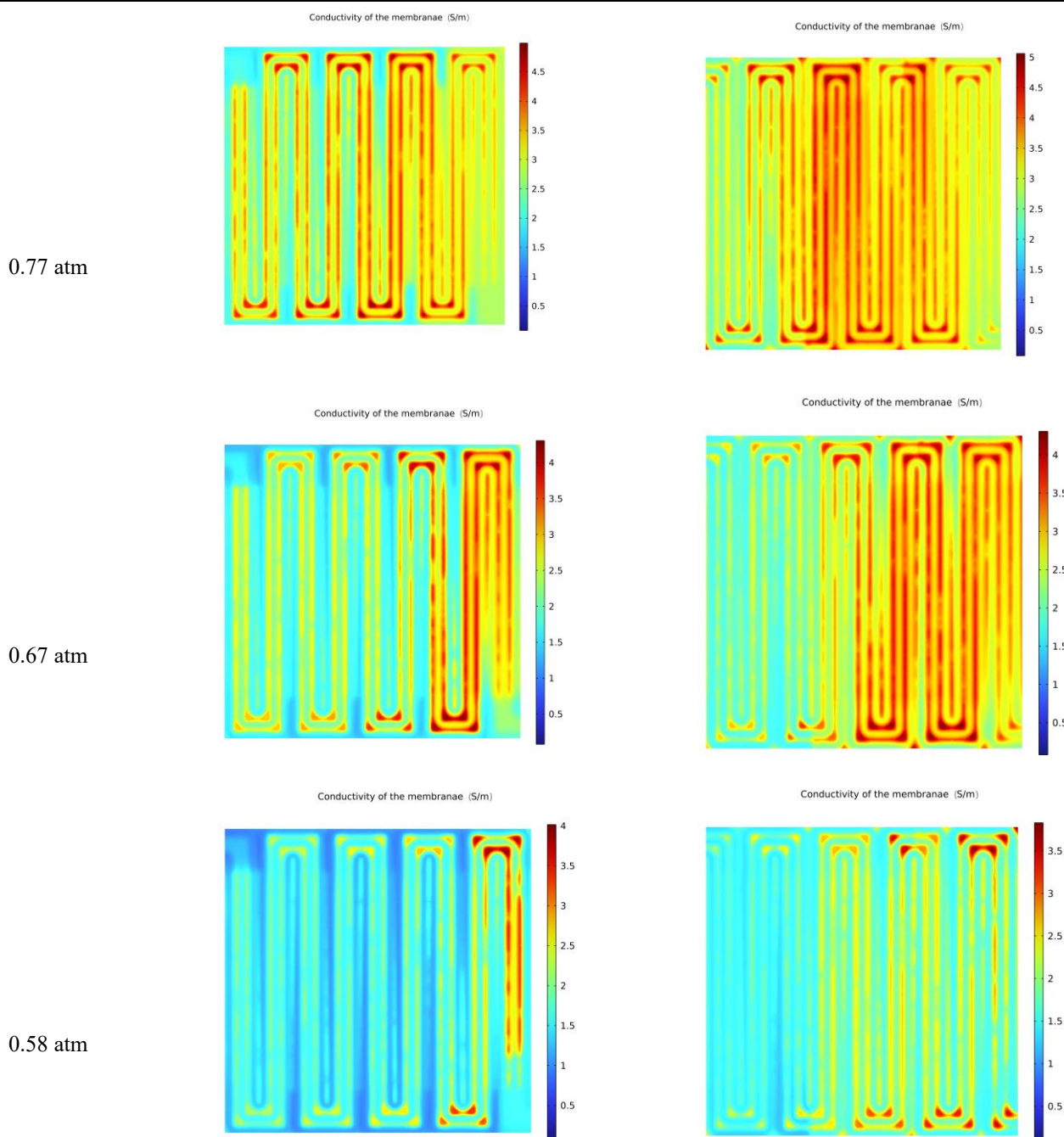


Figure 13. Conductivity of the conventional serpentine flow field and new serpentine flow field at GDE.

The Pearson Correlation Coefficient quantifies the linear relationship between water activity and conductivity. Its formula is as follows:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (34)$$

x_i and y_i represent the individual observations of water activity and conductivity, respectively, while $\bar{x}$ and $\bar{y}$ represent the mean values of water activity and conductivity, respectively.

Spatial variance can be used to quantify the spatial uniformity of water activity and conductivity. The formula is as follows:

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \mu)^2 \quad (35)$$

x_i represents each data point of water activity or conductivity, μ denotes the mean value of water activity or conductivity, and n refers to the number of data points.

Table 8. Comparison of key indicators between traditional and new flow channel designs.

Indicator	Traditional flow channel	New flow channel
Pearson Correlation Coefficient	0.968	0.9235
Water Activity Variance	0.009016	0.009464
Conductivity Variance (S ² /m ²)	1.6059	1.3396

As can be seen from the comparison of key indicators of traditional and new flow channel designs in Table 8. Although there is little difference between the two flow channels in terms of the Pearson correlation coefficient and water activity variance, the new flow channel exhibits superior conductivity stability, with a smaller conductivity variance. This indicates an advantage in the performance uniformity and stability of the fuel cell. Therefore, the new flow channel design offers a performance advantage, particularly in optimizing conductivity and reducing fluctuations in conductivity.

Figure 14 illustrates the changes in conductivity for both flow fields under varying current densities and atmospheric pressures. The results show that under low-pressure conditions, the conductivity difference between the two flow fields is minimal. However, as atmospheric pressure decreases and current density increases, the novel serpentine flow field exhibits significantly higher conductivity compared to the traditional serpentine flow field. Notably, at a current density of 1 A/cm² and an atmospheric pressure of 0.67 atm, the conductivity of the novel flow field is 0.61 S/m higher than that of the traditional flow field. This indicates that the novel flow field can maintain higher conductivity under conditions of high current density and low pressure.

The difference is primarily due to the intermediate inlet design of the novel serpentine flow field, which optimizes reactant distribution and effectively reduces concentration polarization, especially in low-pressure environments. The reduction in concentration polarization lowers overpotential, enhances electrochemical reaction efficiency, and thereby improves proton conduction and electron conductivity. Moreover, at high current densities, the novel flow field design better addresses water management, helping to maintain adequate membrane hydration, which further improves conductivity.

Collectively, these factors enable the novel flow field to sustain higher conductivity under low-pressure and high-current-density conditions, enhancing overall fuel cell performance.

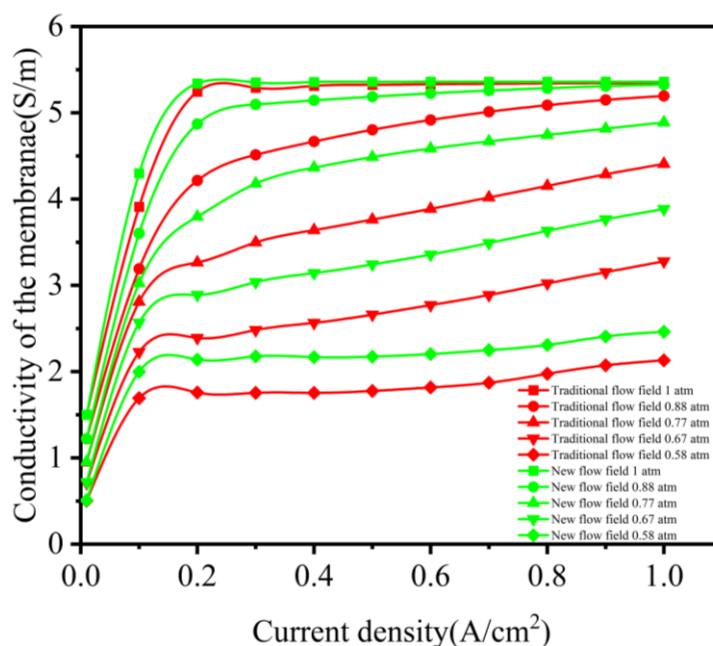


Figure 14. Conductivity of the two flow fields at different atmospheric pressures.

4. Conclusions

We introduce a new serpentine flow field design with an intermediate inlet, inspired by the human heart's beating mechanism, and evaluate its performance on PEMFC under varying atmospheric pressures using numerical simulations. Our major findings are:

1. Power and current density decrease significantly with increasing altitude and decreasing atmospheric pressure. The power output decreases by 4%–54% per kilometer increase in altitude, with the new flow field design improving power output by 34.8% at 0.58 atm compared to the conventional design.

2. At low pressures, the voltage difference between the two flow fields is small at higher current densities. However, the new flow field shows a distinct voltage advantage, especially at medium (around 1 atm) and high altitudes (e.g., 0.58 atm, ~4 km above sea level).

3. The new flow field design improves reactant distribution and enhances electrochemical efficiency, which leads to better water generation, especially under low-pressure conditions.

4. Conductivity is strongly influenced by water activity, and low pressure results in reduced conductivity due to uneven reactant distribution. The new design mitigates this issue effectively, particularly in high-altitude environments.

In this study, we enhance the adaptability of PEMFCs in low-pressure regions, providing opportunities for their use in plateau environments and other similar conditions. With further improvements, PEMFCs can contribute significantly to transportation, energy storage, and mobile devices, supporting the transition to sustainable energy solutions.

Use of AI tools declaration

Declaration: During the preparation of this work, the author used ChatGPT for language polishing. After using this tool, the author reviewed and edited the content as needed and assumes full responsibility for the content of the publication.

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Conflict of interest

The authors have no conflicts to disclose.

Contributions

Yalong Xu: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal); Writing—original draft (equal); Writing review & editing (equal). Zhiwen Ma and Yusong Zhou: Conceptualization (sup porting); Writing—review & editing (equal). Lizong Zhu Funding acquisition (lead).

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