Review Article

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Porous metal foam flow field and heat evaluation in PEMFC: A review

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Abstract: A proton-exchange membrane fuel cell (PEMFC) generates electricity, heat, and water from oxygen and fuel. Hydrogen is recommended as a fuel because it is a renewable fuel when manufactured, for example, by water electrolysis using renewable energy power. Porous metal has excellent characteristics such as controlled permeability, low density, and high porosity. Corrosion is now the most major hurdle to the use of porous metal in PEMFCs, and owing to the porous metal's complicated internal structure, additional challenges must be addressed in the coating preparation process. As a result, this article figures out how to successfully handle the porous metal corrosion problem in a PEMFC setting, which increases the porous metal utilization in the fuel cell industry. This article also examined the flow field in PEMFC and important characteristics. The influence of flow field in the fuel cell was also investigated.

Keywords: PEMFC, hydrogen fuel cell, heat transfer, corrosion, porous metal flow

1 Introduction

Hydrogen energy is currently one of the most ideal energy carriers and clean energy providers in the world and is known as the ultimate energy source [1]. According to the report "Hydrogen Scaling Up" [2] of the International Hydrogen Energy Commission, industry, transportation, and building heating and power supply are the key areas of hydrogen energy application. It is predicted that hydrogen energy will account for about 18% of global energy demand in 2050. The development of hydrogen energy can provide assistance [3]. In 2019, the total national hydrogen production was about 2×10^7 t [4]. By 2050, hydrogen energy will be widely used in transportation, energy storage, construction, and other fields; the demand for hydrogen will increase from 2×10^7 t to 6×10^7 t; and the total industrial output value will exceed 10 trillion USD [5].

The current hydrogen energy preparation technologies are mainly hydrogen production from fossil energy (coal, natural gas, and petroleum) and low-carbon hydrogen [6–8]. Renewable energy represented by photovoltaics and wind power has the characteristics of time-space mismatch, and direct grid connection will bring risks to the stable operation of the grid. Therefore, stable and reliable energy storage equipment must be equipped on the power generation side. The use of water electrolysis equipment to produce hydrogen and transfer hydrogen to energy storage has also become an important direction for the application of water electrolysis technology. When renewable resources cannot meet the load demand, the hydrogen can be transported to the fuel cell for subsequent energy or traffic power [9].

Using renewable energy to electrolyze water to produce hydrogen technology, electrical energy can be converted into chemical energy (hydrogen energy), and the high-pressure hydrogen energy is transported to the energy center. Deployment transports hydrogen to various hydrogen refueling stations and finally can be applied to fuel cells for power. Through the form of renewable energy-hydrogen energy-electric energy, the low energy density and unstable intermittent renewable energy is transformed into a high energy density and sustainable and stable power generation energy. There are three main types of electrolytic water hydrogen production technology: alkaline electrolytic water, solid polymer electrolytic water (namely, proton exchange membrane electrolysis cell), and solid oxide electrolysis (namely, high-temperature steam electrolysis technology) [10].

The integrated management of gas–water–heat is the key issue for the efficient and stable operation of proton

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exchange membrane fuel cells (PEMFCs), and the flow channel structure profoundly affects the gas–water transport and heat transfer of PEMFCs. A bipolar plate (BP) with a poor channel structure will lead to uneven distribution of reaction gas in the flow field [11–13] and uneven distribution of reaction gas from the diffusion layer to the catalytic layer, resulting in different electrochemical reaction intensities on the electrolyte surface, which in turn leads to reaction. There is a large difference between the generated water and heat, and the uniformity of the current density becomes poor [14–16], which affects the performance of the fuel cell. In severe cases, it is more likely to cause water flooding (pores in the gas diffusion layer – most of the volume is occupied by liquid water), and the electrolyte creates local hot spots. Water flooding will cause negative feedback to the gas transport in most active regions, further degrading the fuel cell performance [17]. In addition to affecting the transport of reactants, water flooding can also cause irreversible damage to the fuel cell and cause safety problems. For example, when the fuel cell is working below 0°C, the accumulated liquid water may form ice that may pierce the membrane, and direct contact between the cathode and anode reactants may lead to serious consequences of catalytic combustion [18]. In addition to water and gas management issues, local hot spots are also factors that must be considered in the design of the PEMFC flow channel structure; otherwise, it may cause hygrothermal deformation and creep of the membrane, platinum dissolution, and BP corrosion [19]. The commercialization of PEMFCs is hindered by technical problems such as the above. In order to achieve the expected performance of PEMFC, the reactants must be uniformly distributed and effectively diffused into the catalytic layer where the electrochemical reaction occurs. An important solution to these problems, a reasonable channel structure design, can ensure that the fuel cell has better performance and stability [20].

BP is one of the core components of PEMFCs. The volume accounts for more than 70% of the total weight of the stack, the volume reaches about 50% of the total volume, and the cost is 30 to 50% of the fuel cell cost [21,22]. As an important part of the BP, the flow field has the functions of distributing the reaction gas, discharging the reaction water, and conducting the current and heat. Therefore, a reasonable flow field design is very important for the improvement of the fuel cell performance. The traditional flow fields are generally point-like flow fields, parallel direct current fields, serpentine flow fields, interdigital flow fields, etc. Among them, the multi-channel serpentine flow field can enhance the gas mass transfer and promote the uniform distribution of gas, current, and heat. It has become the most widely used flow field form for commercial vehicle fuel cells [23–25].

However, the traditional flow field, especially the complex flow field form, has a high processing cost, and there are wide banks/ridges in the flow field, which compress the corresponding gas diffusion layer, resulting in lower gas diffusion layer porosity drop, and liquid water tends to accumulate here, thus hindering the distribution and mass transfer of the reaction gas. However, if the width of the bank/ridge is small, it is possible to squeeze the gas diffusion layer into the flow channel, thereby further reducing the discharge of water and gas mass transfer. Therefore, it is necessary to develop new flow field forms to solve such problems [26,27].

The remainder of this article is organized as follows. In Section 2, the literature review is discussed. In Section 3, the properties of porous metal flow field are described. In Section 4, the existing problems are elaborated. In Section 5, the conclusions are discussed.

2 Literature review

Porous metal materials have a unique porous three-dimensional structure, which can enhance the uniform distribution and mass transfer of substances (gas, liquid), and the metal itself has good thermal conductivity and electrical conductivity, so as to enhance the electrical and thermal conductivity. In addition, porous metals have the characteristics of low density (high porosity, >90%) and adjustable mechanical strength, and are especially suitable as field structures for BP flow [28–31]. At the same time, the study found that the lower permeability (10^{-10}–10^{-12} m^2) of porous metal can increase the material transport path, enhance the material dispersion and mass transfer ability, and the decrease in permeability can also reduce the waste heat generated by the fuel cell, thereby improving the efficiency of the fuel cell [32]. Kumar and Reddy [33] used stainless steel porous metal as the flow field, and at the same time used the porous metal as the gas diffusion layer and as the support structure of the catalytic layer, and replaced the traditional flow field and gas diffusion layer (carbon paper) with a porous metal. The structure of fuel cells is simplified and the production cost of fuel cells is reduced. Yuan et al. [34] used a special turning tool to cut a pure copper rod to generate fibers, and then formed a porous structure as a flow field structure by sintering, and compared it with a serpentine graphite flow field BP, and found that the surface contact resistance of the plate is lower than graphite BP, and the porous copper flow field has strong hydrophobicity (contact angle: 136.4°), which is conducive to the discharge of fuel cell product water. Shin et al. [35] used gold-plated porous nickel as the flow field structure, and compared it with the traditional flow channel, and found that the power density of the porous metal flow field was higher than that of the traditional flow field, and when the porous metal pore size reached a certain value, its power density can reach the highest.

The PEMFC power system is an integrated electric energy supply device, mainly composed of a hydrogen source system and a PEMFC. The hydrogen source system provides fuel for the PEMFC to generate electric energy. The traditional hydrogen source system mainly uses high-pressure hydrogen storage technology or low-temperature liquid hydrogen storage technology to store hydrogen first. When the PEMFC needs hydrogen, the hydrogen is released to supply hydrogen to the PEMFC. However, traditional hydrogen energy storage technology has constraints such as large system size, large energy loss, high cost, and low safety [36,37]. Compared with traditional hydrogen storage technology, chemical adsorption hydrogen storage is an efficient new indirect hydrogen storage method. Its hydrogen storage principle is that hydrogen storage materials react chemically with hydrogen to absorb hydrogen. When the outside world provides certain conditions for hydrogen storage, the reaction proceeds in reverse, and hydrogen is released. Different from traditional hydrogen storage methods, the characteristics of the chemical adsorption hydrogen storage hydrogen source system are controlled by the hydrogen storage reactor. The temperature and pressure of the hydrogen flow will change as the operating conditions of the hydrogen storage reactor change. The hydrogen output by the hydrogen source system is used as the inlet fuel of the fuel cell, and its temperature, pressure, flow, and other parameters will have a great impact on the output characteristics of the fuel cell.

Dukhan and Patel [38] conducted experiments to study the relationship between the optimal operating temperature of air-cooled PEMFC, ambient temperature, humidity, and output current. The results show that under certain environmental conditions, the optimal operating temperature T_{opt} increases with the increase in output current. When the output current is less than 50 A, the ambient humidity R_H has little effect on T_{opt}. Hossain and Shabani [31] used the fuel cell tester of the American Arbin Instrument Company as the fuel cell test system to study the impact of hydrogen intake on fuel cell performance. The experimental results showed that when the hydrogen flow rate increased, in addition to the limit current density except for a slight increase, the battery performance remains stable, so controlling the air intake within a certain range does not have a great impact on the fuel cell. Kumar and Reddy [39] established a mathematical model including the electrochemical model and temperature model of the PEMFC, analyzed in detail the impact of various parameters on the fuel cell, and controlled its output unstable voltage. As a PEMFC power system, the hydrogen storage reactor provides hydrogen to the PEMFC. The hydrogen supply characteristics of the hydrogen storage reactor will directly affect the performance of the PEMFC, and the output characteristics of the PEMFC determine the energy conversion efficiency of the entire hydrogen power system. However, currently based on solid-state hydrogen storage reaction, the coupling characteristics of the chemical adsorption hydrogen storage device and PEMFC are not yet clear.

Therefore, this article reviews the current state of research on the flow field structure of a PEMFC BP, as well as the challenges encountered in its use, in order to provide a reference for the development and research of porous metal flow field BP.

3 Properties of porous metal flow field

The PEMFC is mainly composed of a BP and a membrane electrode assembly. It consists of the polar plate itself and the flow field structure (Figure 1) [36]. The use of porous metal as the BP flow field structure can effectively avoid the problem of banks/ridges in the traditional straight channel serpentine flow field. At the same time, its unique three-dimensional structural characteristics increase the uniform distribution and mass transfer of fuel gas. In addition, the porous metal flow field has open pores and many water discharge paths, which can effectively enhance the drainage capacity of the fuel cell under high power density and improve the stability of the stack operation under high power density. The performance of porous flow field is generally closely related to porous metal parameters (pore size and porosity, etc.), flow field structure design, and fuel cell service parameters.

3.1 Influence of porous metal parameters on its flow field performance

In the porous metal flow field, two media, gas and moisture, need to be mass-transferred at the same time. Due to the capillary phenomenon in the flow field of porous metal, some water tends to remain in the pores. Especially when the pore size of porous metal is small, the water in the pores

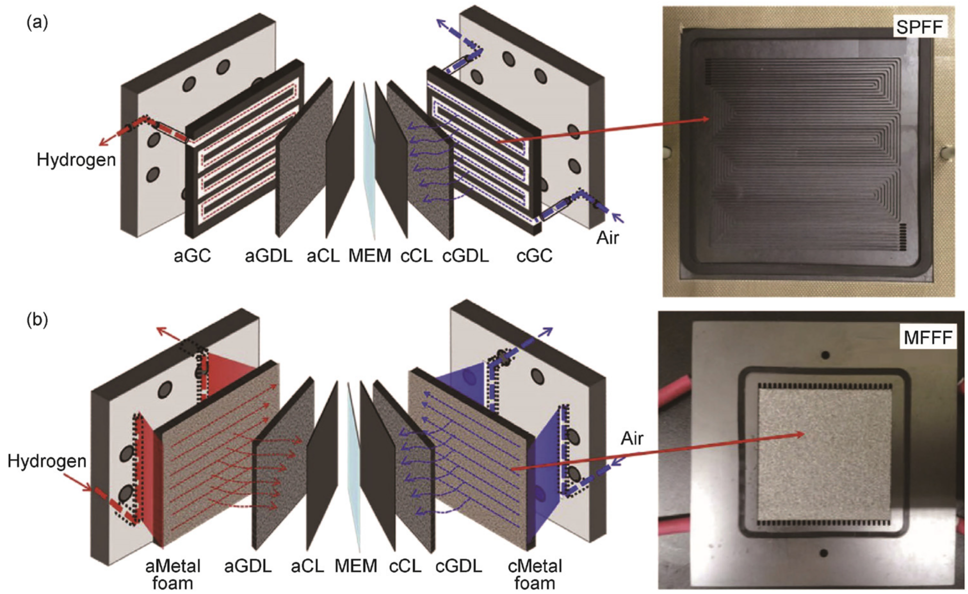

Figure 1: Illustration of a single cell of serpentine flow field: (a) porous metal flow and (b) SPFF-porous metal flow [36].

is easily saturated and blocked, thereby reducing the discharge of water and the dispersibility of gas. If it is large, the uniformity of gas distribution and mass transfer effect will be reduced. Figure 2 shows the comparison of the pressure drop between porous metals with different pore sizes and the traditional serpentine flow field. Due to the many transmission paths and short strokes of the porous metal, the gas transmission resistance is much smaller than that of the traditional serpentine flow field. In addition, the residual moisture in the pores increases the gas transport resistance. In addition, it can also be found that as the cell current increases, the moisture produced by the reaction increases, and the gas transport resistance increases, and the smaller the pore size of the porous metal, the greater the gas transport resistance. Diani et al. [37] also confirmed

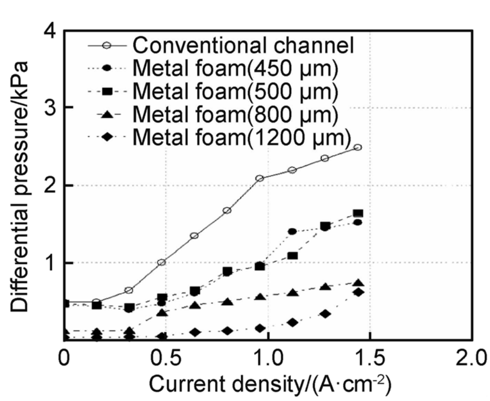

Figure 2: Differential pressure evaluation.

this phenomenon through a combination of computer simulations and experiments.

In addition, the water produced by the cathode reaction of the fuel cell often flows from the gas inlet to the outlet, so the water content around the outlet is high, while the water content at the inlet is small, so when designing the flow field, you can choose a small amount at the inlet. Porous metal with a pore size (450 μm) increases the conductivity of the electrode plate, and a porous metal with a larger pore size (800 μm) is selected at the outlet to increase its drainage capacity. This composite porous metal flow field structure has a great effect on improving the power density of the fuel cell.

The flow resistance of liquid in porous metal is not only related to the pore size of the porous metal but also related to the length/width of the porous metal. Dukhan and Patel [38] studied the flow field performance of porous aluminum (Figure 3) with similar porosity, different thicknesses, and pore size (Table 1) and found that the fluid pressure drop decreased with the increase of the thickness of the porous metal, but when the thickness increased. To a certain extent (the thickness is 100 times the aperture), the influence of the thickness on the fluid pressure drop decreases.

In addition, the study also found that the porous metal with the same thickness, the smaller the pore size, the greater the pressure drop, and the flow resistance of the porous metal increases almost linearly with the increase of the fluid flow rate. The flow transport of liquid and heat in porous metals is very complex, and the unique structure of

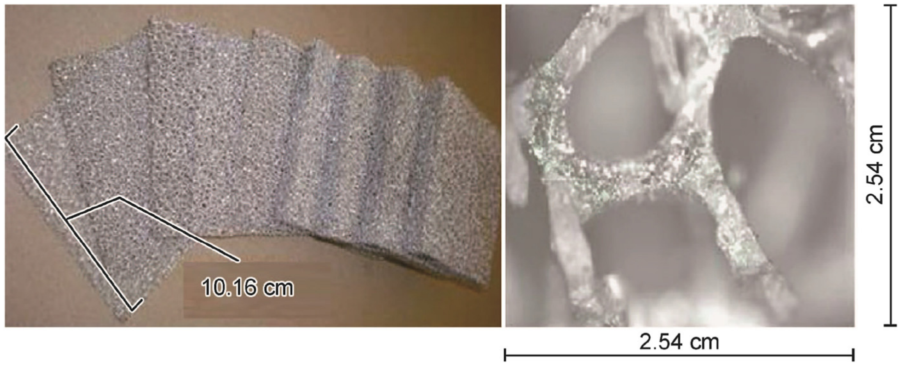

Figure 3: Flow field performance evaluation [38].

porous metals has the potential to cause mixing of liquid and heat, such as due to blockage, deflection, recirculation, and eddy currents in the fluid flow. In addition, the high specific surface area of porous metal is also conducive to the diffusion and discharge of heat through the porous material in the way of thermal conduction, and this transport effect is enhanced to some extent with the decrease of the porous metal pore size (pore size >100 μm) [31]. Therefore, choosing the appropriate porous metal pore size and porosity is crucial for the enhancement of gas mass transfer in the flow field, as well as the uniform distribution of current and temperature and the discharge of moisture and heat from fuel cell products.

The flow field of the traditional channel is limited by its processing method, and its permeability is difficult to be lower than the limit value of 10^{-8}, while the porous metal can transmit and penetrate the material by changing its own parameters (such as pore size, porosity, and pore distribution). The low permeability can promote the increase of material transport paths, thereby enhancing gas dispersion and mass transfer and improving fuel cell performance [39]. Hontanon et al. [40] studied the effect of porous metal and traditional flow field on the performance of PEMFCs and found that the cell performance can be improved by reducing the permeability of the flow field. It can be seen from Figure 4 that the permeability of porous metal is much lower than that of the traditional flow field. The permeability of porous metal can be obtained by reducing the pore size and adjusting the pore type. As the permeability decreases, the gas mass transfer and distribution uniformity are enhanced, thereby increasing the power of PEMFC. Although the reduction of gas permeability helps to improve the fuel cell performance, it increases the gas transmission pressure drop, which increases the energy consumption of the air compressor and hydrogen transmission pump. Therefore, the porous metal permeability should be appropriately reduced to help improve the PEMFC system power.

3.2 Structure design

Like traditional serpentine flow field, reasonable flow field structure design, such as flow channel parameters (number of flow channels, flow channel length, flow channel shape, flow channel width, bank/ridge width, flow channel depth, flow channel form, etc.) change of the flow field will have an important impact on the performance of the flow field. For example, increasing the number of flow channels and reducing the length of the flow channels can increase the effective contact area between the gas and the gas diffusion layer, reduce the gas pressure drop, and increase the uniformity of gas mass transfer and gas distribution [41]. Changing the shape of the flow channel from a straight channel to a wavy one can increase the disturbance in the gas transmission process and increase the gas mass transfer efficiency [42]. Gradually reducing the cross-sectional area of the flow channel from the gas inlet to the outlet is also beneficial to reducing the gas pressure drop at the inlet

Table 1: Parameters of flow field

Diameter of cell (mm)	PPI	Porosity (%)	Thickness (mm)
4.23	10	92.9	3, 6, 9, 12, 16, 22, 25, 31, 34, 47, 63, 75, 91, 123, 179, 242, 305, 356, 106, 508
2.12	20	92.5	3, 8, 11, 17, 20, 23, 26, 29, 43, 58, 72, 86, 100, 172, 242
1.06	40	93.5	2, 4, 6, 10, 12, 20, 24, 30, 41, 50, 60, 70, 80, 130, 171

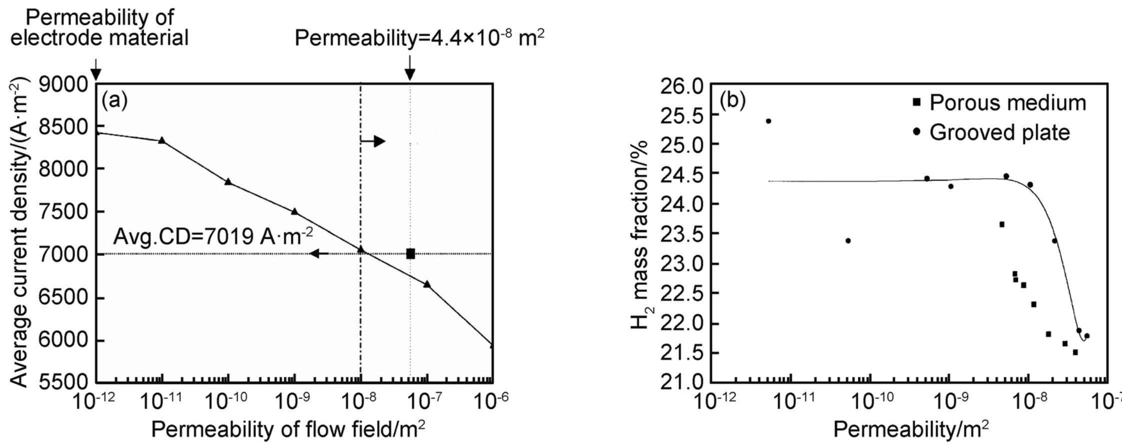

Figure 4: Comparison of average current density and mass fraction of H_2 [40]. (a) Current density and (b) Mass fraction.

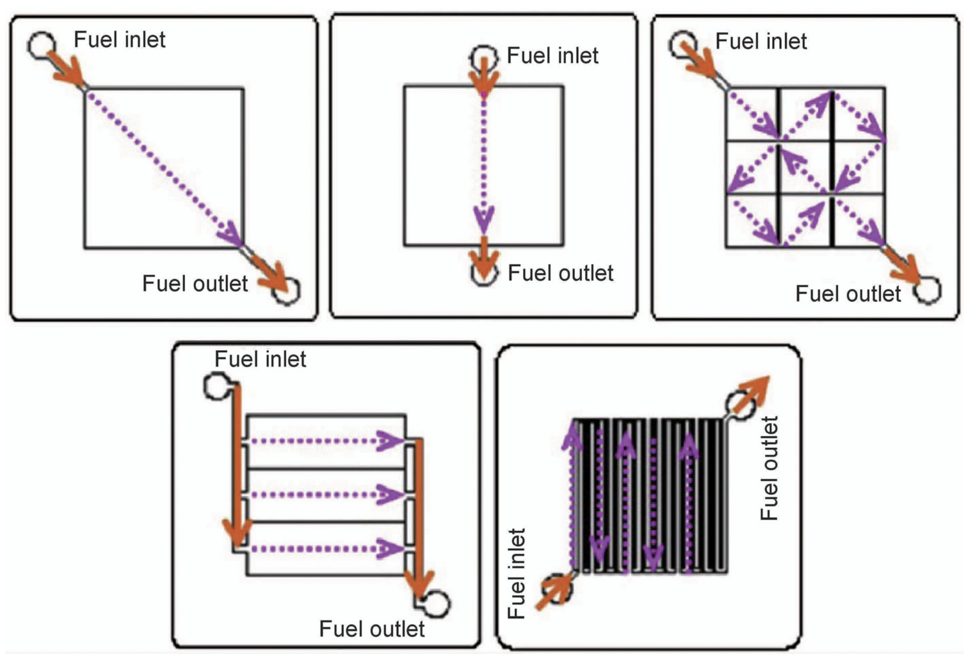

Figure 5: Illustrations of various flow fields in fuel cells [44].

and outlet and enhancing the uniformity of gas distribution [43]. For the porous metal flow field, reasonable flow field structure design also plays an important role in the improvement of fuel cell performance. Power has a key impact. Tsai et al. [44] compared the performance of five porous metal flow field structures and the traditional serpentine flow channel BP (Figure 5). Although the air utilization rate of the three models is higher than that of the first and second models, the gas flow path is too long, which increases the gas transmission resistance and is not conducive to the discharge of water. Therefore, the air utilization rate of the three models is lower than that of the third model flow fields. The fuel cell power density test shows that the power density of the porous metal flow field is much higher than that of the serpentine flow field structure, and the fourth flow field of the three regions has the highest power density of the fuel cell.

Baroutaji et al. [45] used a computer fluid dynamics model to study the effects of four different air intake modes on the pressure distribution and liquid velocity distribution of the porous metal flow field. The results found that the first model flow field has a large pressure at the inlet and outlet. The second and third models have poor uniformity of fluid velocity distribution, and there are vortices in them, while the fourth model flow field structure has a uniform distribution of pressure and flow velocity in each region, and the gas inlet and outlet pressure drop is the lowest (Figure 6). Therefore, the researchers used the fourth flow field structure as a model, fabricated BP grooves, and added porous metal to form a porous metal flow field BP. It was found that the improvement of fuel cell power density was much higher than that of traditional serpentine flow field.

3.3 Influence of service parameters on the flow field

As a power source for vehicles, PEMFC has to undergo the test of complex working conditions and harsh environments such as start-stop, high potential, low humidity, high current, and air impurities. Among them, the humidification conditions of fuel gas and air will have a great impact on the performance and stability of the fuel cell [46–49]. The performance of PEMFC needs to be fully humidified to achieve the best results. Since the ionic conductivity of the proton exchange membrane needs to be maximized in a humid environment, the gas entering the PEMFC often needs to pass through a humidifier (100% humidification).

Ahn et al. [50] studied the flow field BP and serpentine flow field BP of porous copper metal (average pore size: 167.3 μm, porosity: 83.13%) under 100 and 20% gas humidification conditions. It is found that the performance of porous metal and serpentine flow field cells are similar under the condition of complete humidification of gas, and the flow field performance of porous metal is slightly lower than that of the serpentine flow field structure only at high current density. Under the condition of 20% gas humidification, the performance of the serpentine flow field is much lower than that of the porous metal flow field. This is mainly due to the capillary phenomenon of the porous metal, and a certain amount of water often remains in the pores of the porous metal, which can humidify the passing gas to a certain extent to achieve the so-called "self-humidification" function (Figure 7), which enhances the proton exchange. The proton conductivity of the membrane is improved, thereby improving the performance of the PEMFC stack. In addition, under the condition of low humidification in the conventional flow field, as the temperature of the cell increases, the degree of vaporization of liquid water increases, resulting in a decrease in the water content in the proton exchange membrane, thereby reducing the membrane proton transfer rate. The use of a porous metal flow field can keep the fuel cell performance stable under low humidity, reduce the energy consumption of the humidifier, and improve the efficiency of the fuel cell system.

As a power source for vehicles, PEMFC will also face the problem of cold start in the severe cold environment in winter. The fuel cell will produce a large amount of water in the cathode oxygen reduction reaction. At subzero temperature, the water generated by the reaction will freeze on the electrode catalytic layer, gas diffusion layer, flow field channel, and gas outlet, which will seriously affect the gas mass transfer and water management, while reducing the active site of the catalytic layer affects the power generation performance of the fuel cell, and even leads to the failure of sub-zero startup [51–54]. The unique three-dimensional connected pore structure of the porous metal flow field, on the one hand, can accelerate the discharge of water and reduce the probability of icing. On the other hand, it can promote the uniform distribution of reaction gas and temperature and prevent the occurrence of local low temperature. In addition, its porous structure has a strong storage capacity for liquid/ice and has little effect on gas transport, so it will to a certain extent improve PEMFC cold start performance.

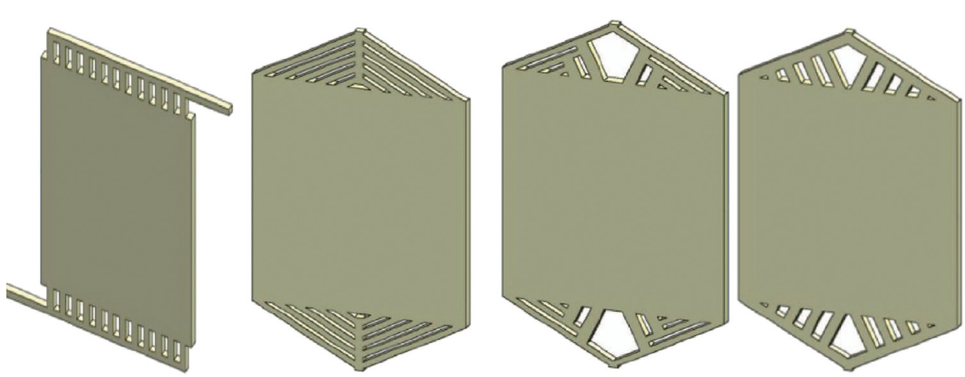

Figure 6: Illustrations of different types of air inlet in fuel cells [45].

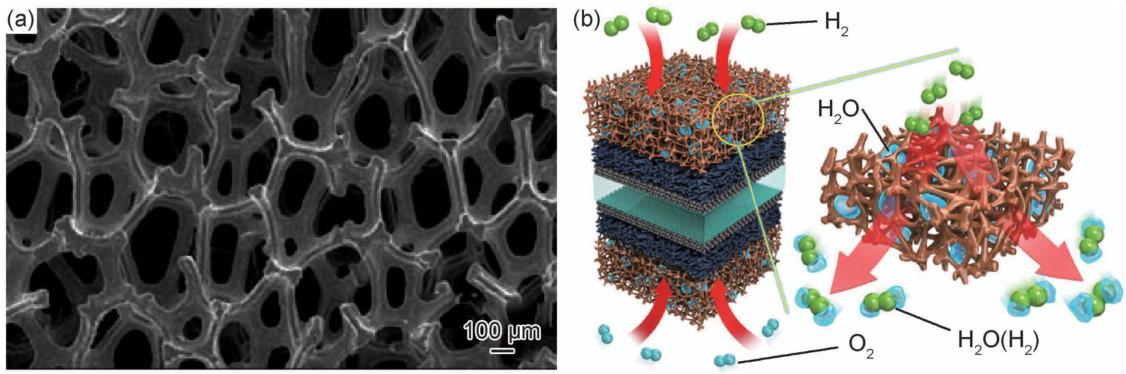

Figure 7: Pictorial representation of fuel cell: (a) foam field and (b) schematic [50].

Huo et al. [55] studied and compared the cold-start performance of porous nickel (porosity 88%) and parallel flow field at different temperatures and starting currents and found that under the conditions of starting temperature of −6°C and starting current of 200 mA, the porous PEMFC assembled with the flow field BP and the traditional flow field BP failed to start successfully, which means that the cold start of 200 mA starting current. The heat generated by the motion is not enough to eliminate the effect of water freezing, but the running time and the voltage generated during the startup of the porous flow field plate are higher than those of the traditional flow field. When the starting current increased to 400 mA, the PEMFC assembled with the porous flow field BP successfully started up, while the conventional flow BP assembled stack failed to start at 812 s, which was mainly due to the fact that under the same starting conditions, the porous metal gas mass transfer intensity in the flow field is high, the fuel gas and air can fully enter the catalytic layer, and a large amount of heat energy is accumulated inside it, which is enough to prevent the occurrence of icing.

In addition, the porous metal has many and short transmission paths, and the overall pressure drop is smaller than that of the traditional flow field, which can improve the uniformity of gas distribution and mass transfer strength, thereby improving the utilization rate of air and hydrogen, reducing the gas consumption and transmission rate, and can improve the gas distribution uniformity and mass transfer intensity. The performance of the fuel cell is ensured under the condition of a low gas introduction rate, and the energy consumption of the air compressor and hydrogen transfer pump is reduced [56]. Taherian [57] used a combination of computer simulation and experiment to study the gas transport pressure drop, water distribution in proton exchange membrane, and cathode catalysis of the traditional multi-channel serpentine flow field and porous metal (pore size of 110 PPI) under different inlet pressures. It is found that under different inlet pressures, the gas transport pressure drop in the porous metal flow field is smaller than that of the traditional flow field, the water content in the proton exchange membrane is more, and the oxygen concentration in the catalytic layer is higher than that in the traditional flow field, higher and more evenly distributed (Table 2). The fuel cell volt–ampere curve results show that when the inlet pressure is only 0.1 MPa, the power generated by the porous flow field BP assembled PEMFC is much higher than that of the traditional multi-channel serpentine flow field (Figure 8). When the intake pressure rises

Table 2: Comparison of the proposed and traditional method

Method	Pressure drop (Pa)	Inlet pressure (MPa)	Concentration of O_2 in CLs (mol·m^{-3})	Membrane ware quantity (mol·m^{-3})
Metal foam	4,220	0.1	5.713 (max) 1.462 (min)	6.768
	783	0.2	12.674 (max) 3.611 (min)	8.863
Traditional [36]	8,757	0.1	5.966 (max) 0.241 (min)	5.910
	1,547	0.2	13.001 (max) 1.335 (min)	8.290

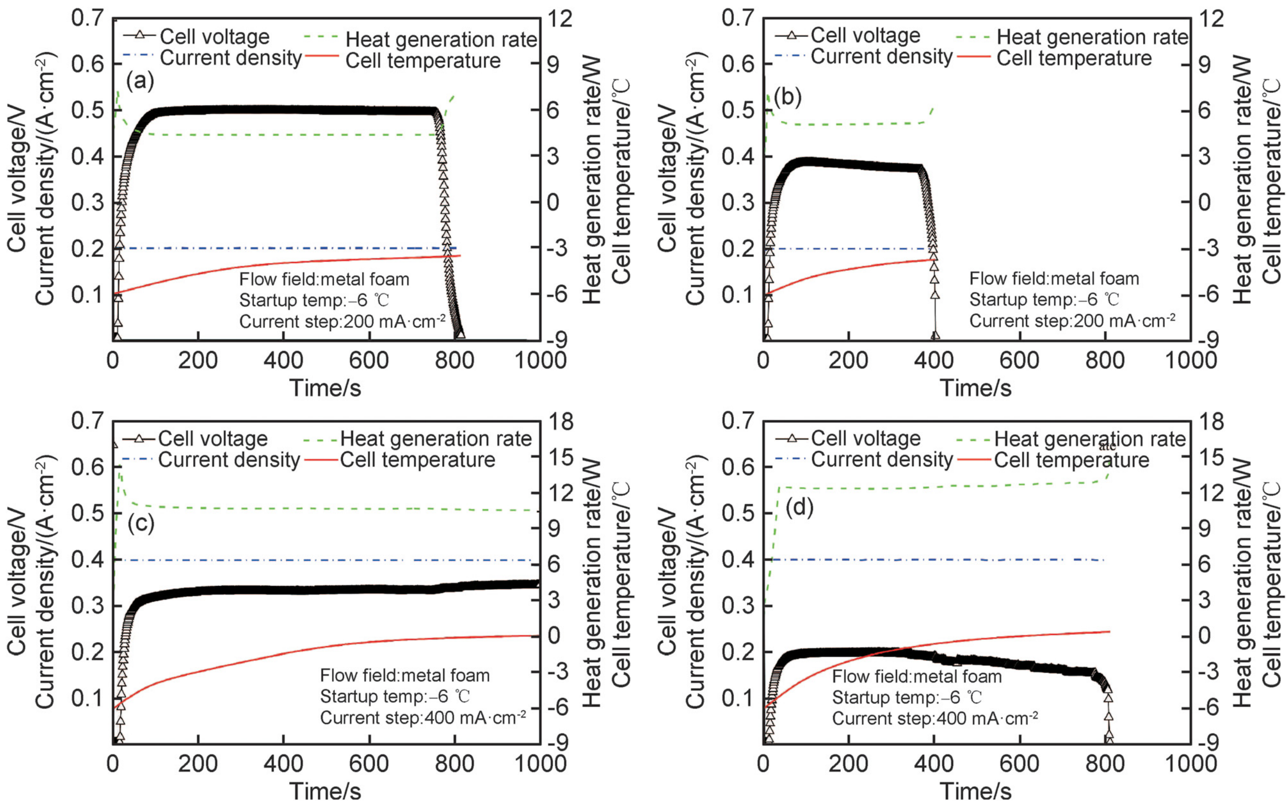

Figure 8: Variations of various parameters: (a) and (c) metal foams and (b) and (d) parallel flow channels [57].

to 0.1 MPa, its performance is still better than the traditional multi-channel serpentine flow field, but the difference between the two is reduced.

Figure 9 shows the *V*–*I* variation with different values of temperature. As can be seen from Figure 9, the *V*–*I* variation enhances with increasing temperature, indicating that the performance is controlled via variation in temperature.

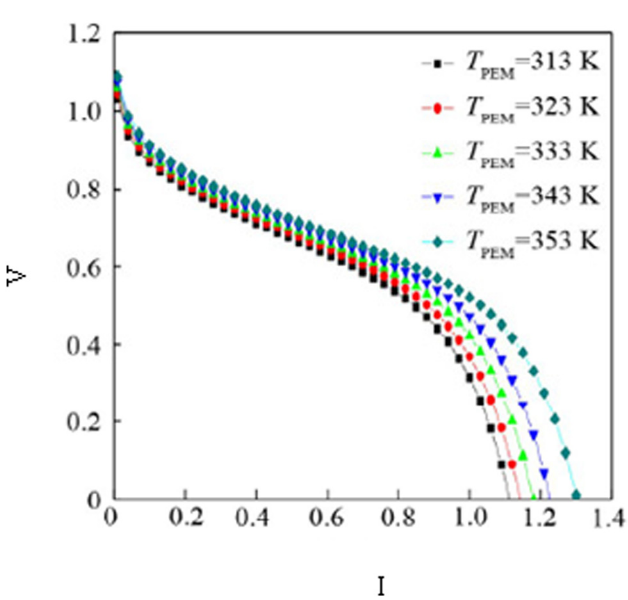

Figure 9: Variations of *V*–*I* with different temperatures.

Figure 10 illustrates the PEM prism pattern preparations by the imprinting method. The naflon membrane and prism mold are processed by catalyst spray and imprinted naflon membrane. Then, the catalyst-coated naflon membrane produces Pt carbon.

Figure 11 shows the voltage and power variation with different current densities. As can be seen from Figure 11, the voltage and power vary with increasing values of current densities. This also indicates a controlling parameter to optimize the PEMFC performance.

4 Existing problems

Because of the unique properties of porous metals in terms of structure and function, many scientific institutions have developed porous metal flow fields. For example, Porvair, which cooperates with the US Department of Energy, is committed to developing porous metal flow field plates with lightweight, high electrical conductivity, and high thermal conductivity. The materials are mainly metals or superalloys with high corrosion resistance. The research group

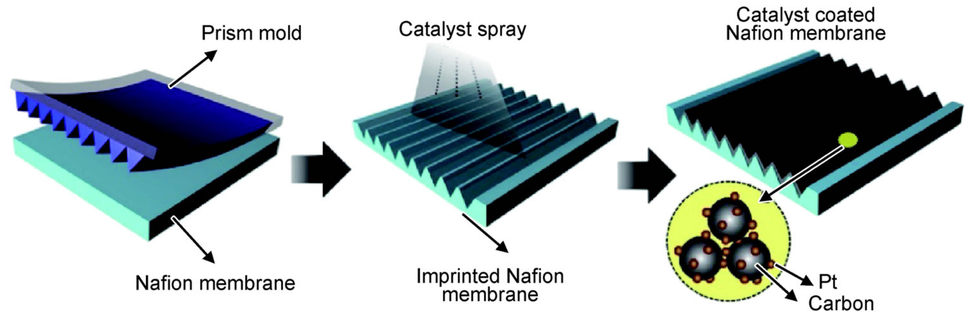

Figure 10: Illustrations of PEM prism pattern preparations by imprinting method [58].

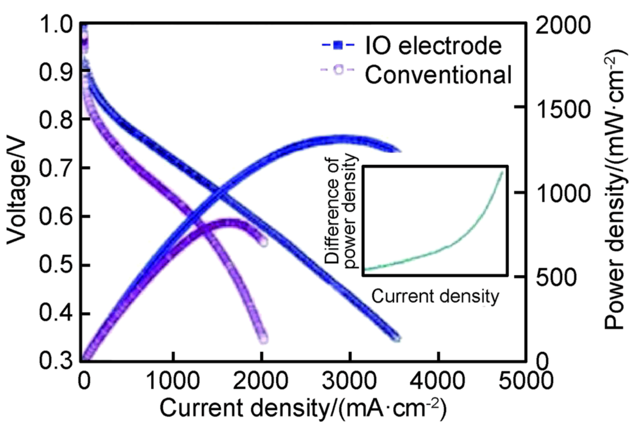

Figure 11: Variations of *V*–*I* with different current densities [59].

of Tang Yong from South China University of Technology in China also developed the porous copper flow field structure and applied it to direct methanol fuel cells [60]. However, the current application of porous metal flow fields in fuel cells still faces some problems, the most prominent of which is the corrosion of flow field materials in the fuel cell environment.

In PEMFCs, the environment where the BP is located is very harsh, it is in the environment of strong acid (pH value of 2–3) and 80°C, and the proton exchange membrane (Nafion membrane) will decay during service, thus producing SO_4^{2-}, F^-, HSO_4^- plasma. The anode voltage of the fuel cell is generally −0.1 V, and hydrogen is introduced into it, and its environment has strong reducibility. The cathode of the fuel cell is generally vented with air, and its voltage is usually 0.6 V. In addition, the presence of oxygen has a strong oxidizing property [61]. Like the traditional flow field metal BP, the porous metal flow field BP also needs to face certain corrosion problems in the PEMFC environment. In addition, the porous metal itself has a large specific surface area, and its rough and uneven surface and the channels connecting the large pores may increase the inhomogeneity of the passive film on the surface of the porous metal itself, and reduce the electrode potential stability, and these weak structures are electrolytes. The trapping provides naked active sites, promoting a corrosion generation similar to crevice corrosion mechanism and in the presence of cathode oxygen, the oxidation of the porous metal is more serious, and it is easy to produce an excessively thick oxide film, which reduces the conductivity of the porous metal. The corrosion problems faced by metals in the PEMFC bipolar environment are even more serious.

Once the porous metal corrodes, metal cations will be released into the fuel cell, and the metal cations will enter the proton exchange membrane to replace hydrogen ions or react with the sulfur groups of the proton exchange membrane to produce sodium sulfonate and sodium sulfonate easily absorbs moisture in the proton exchange membrane, reducing membrane conductivity. At the same time, metal ions can also enter the electrode catalytic layer, reducing the catalytic activity of Pt [62]. In order to solve such problems, it is necessary to coat the surface of the porous metal. Due to the excellent conductivity of the porous metal itself, the conductivity of the coating is not as high as that of the traditional metal BP, but its corrosion resistance demands are higher. Myo et al. [63] used porous nickel (95% porosity) as the matrix, coated gold, and hydrophobic coatings on its surface and compared the effect of the serpentine flow field on the performance of PEMFC. The performance is slightly lower than that of the serpentine flow field at densities and higher than that of the serpentine flow field at high current densities. The hydrophobic coating has low electrical conductivity, and its performance is much lower than that of gold-plated porous nickel and traditional serpentine flow field, but it does not mention the performance of uncoated porous nickel flow field.

Lee et al. [64] formed a graphene coating with excellent surface quality on the surface of the flow field prepared by porous metal nickel by the chemical vapor deposition (CVD) method and combined it with Au (electroplating) and TiN (physical vapor deposition) coatings. For comparison, due to the excellent electrical conductivity, chemical stability, and physical barrier properties of the graphene coating, it has excellent corrosion resistance in the PEMFC bipolar environment and does not change with the increase of the ambient temperature, while the Au and TiN coatings have excellent corrosion resistance. The corrosion resistance decreases as the temperature increases, and the surface of the material is damaged after corrosion. In addition, the graphene coating also has good hydrophobicity, which can accelerate the discharge of water in the fuel cell. In addition to good corrosion resistance, the porous metal surface should also have a certain degree of hydrophobicity. Due to the existence of the capillary action of the porous metal itself, the porous metal tends to remain in the pores to a certain extent. If the material itself has poor hydrophobicity, the residual water in the pores is enough to hinder the gas transmission and water discharge, so the hydrophobicity of the porous metal material will also have a great impact on the performance of the stack [65]. Tseng et al. [66] prepared a polytetrafluoroethylene (PTFE) coating on the surface of porous nickel, and the excellent hydrophobicity of PTFE can greatly improve the drainage capacity of the flow field, thereby enhancing the power density of the fuel cell. Baroutaji et al. [67] also studied the effect of PTFE coating on the flow field performance of porous nickel and found that PTFE coating with poor conductivity not only did not reduce the power density of the fuel cell but greatly improved it at high current density. The fuel cell power density and the PTFE coating can also effectively improve the corrosion resistance of porous nickel. However, the PTFE coating has poor conductivity, and its improvement in fuel cell performance is limited. Therefore, there is an urgent need to develop corrosion-resistant, conductive, and hydrophobic multi-functional coatings for porous metals. Commonly used materials for porous metals are stainless steel, nickel, copper, and titanium. However, due to the large specific surface area of the porous metal and the rough surface of the porous metal, the ribs of the connecting holes are often discontinuous, and there are some micropores on the ribs, which often lead to serious corrosion of stainless steel, nickel, and copper. Although titanium metal has excellent corrosion resistance, it is easy to generate low-conductivity titanium oxide on the cathode surface of the fuel cell, which increases the contact resistance between the electrode plate and the gas diffusion layer, and the efficiency of the fuel cell decreases for every 25 $m\Omega \cdot cm^{-2}$ increase in the contact resistance decreased by 2 to 5%. Therefore, the porous metal flow field often needs an external coating in practical applications. At present, the coatings mentioned in the literature are mainly gold, PTFE, graphene and titanium nitride, etc. The cost of PTTE vinyl fluoride is high and has good corrosion resistance and vinyl fluoride has good corrosion resistance and hydrophobicity, its electrical conductivity is poor. The overall performance of graphene coating is the best, but high-quality coatings can be prepared only on nickel and copper, while graphene coatings prepared on other metal surfaces have many defects [68–70]. In addition to the coating material, the preparation process of the porous metal coating and the integrity and uniformity of the coating also have an important impact on the flow field corrosion resistance; however, the research literature on this aspect is rarely mentioned. Therefore, it is necessary to carry out in-depth research on the preparation process of porous metal coatings, expand the range of coating types, and improve the corrosion resistance, electrical conductivity, and hydrophobicity of coatings. In addition, it is necessary to start from the preparation process of porous metal to improve the connectivity of porous metal pores, increase the density of ribs and reduce their surface roughness, increase the mechanical strength of porous metal, and enhance the resistance to vibration and impact during service in the porous flow field [71].

5 Conclusion

High power density stacks have always been the goal of fuel cell researchers. However, at high power densities, a large amount of water is generated at the cathode of the fuel cell, and the traditional flow field has a limited ability to discharge water. The porous metal materials have a unique three-dimensional connected structure, increased drainage path, and great fuel cell drainage capability at high power densities. In addition, the porous metal as the flow field eliminates the banks/ridges existing in the flow field of the traditional flow channel and improves the utilization rate and mass transfer effect of the fuel gas. At the same time, the residual moisture in the pores of the porous metal can also humidify the reaction gas, thereby further enhancing the ionic conductivity of the proton exchange membrane and improving the power density and stability of the fuel cell. Therefore, porous metals have a strong application value in hydrogen fuel cells.

The applications of the proposed study also pay attention to the following aspects:

(1) Carry out research on the preparation process of porous metal. Porous metal flow fields require high open porosity (>80%), small pore size (100–500 μm), and a three-dimensional structure with uniform pore distribution. However, the compressive strength of porous metals

with high open porosity is often low and cannot effectively resist vibration and impact during service. Therefore, research on the preparation process of porous metals should be carried out to improve the open porosity, compressive strength, and pore size of porous metals. Currently, sintered metal fibers/filaments (pre-fabricated, wound), metal deposition methods, 3D printing, and more metals have high application value in the preparation of porous metals with high open porosity, small pore size, and high strength.

(2) Research and development of multifunctional composite coatings suitable for porous metals. Since porous metals face serious corrosion problems in the PEMFC environment, and their hydrophobicity needs to be improved, their coatings must have good corrosion resistance, electrical conductivity, and hydrophobicity. To meet these comprehensive properties, the coating structure needs to be improved, and in-depth studies were carried out in terms of components. At present, metal-carbon/nitride coatings (TiN, CrN, TiC, etc.) and carbon-based coatings (graphite, amorphous carbon, etc.) have good electrical conductivity, corrosion resistance, hydrophobicity, and great application potential.

(3) Carry out research on the porous metal coating process. Porous metal has a large specific surface area and a complex internal structure. It is necessary to carry out the research and development of the coating preparation process to solve the problems of the integrity and poor uniformity of the coating preparation. At present, the porous metal coating processes are basically electroplating, physical vapor deposition (PVD), CVD, etc. Among them, the coating prepared by the PVD method is affected by the void shielding effect of the porous coating, and the coating uniformity is poor. In the electroless plating method, the plating solution can be immersed into the inner pores of the porous metal. In addition, the porous metal prepared by the CVD method is also immersed in the porous metal. In a reactive atmosphere, the coatings prepared by electroless plating and CVD coating uniformity and integrity of the layer are high.

(4) The research on the heat and mass transfer model of porous metals was carried out. Gas, liquid, heat, electrons, and other substances are simultaneously transferred in the porous metal flow field. Therefore, the mass transfer process is extremely complex, and there is still a lack of reliable analytical models for the current study of porous metal flow fields. The existing mathematical models of heat transfer and fluid flow are not mature enough. The fluid flow model in porous media can be modified according to the geometry of metal foam, but due to its complex geometry, it is difficult to obtain a suitable mass transfer model. Furthermore, due to the complexity of numerical and mathematical analysis, researchers have to rely mainly on experimental data, and the reporting of experimental data is limited. Therefore, the research on the heat and mass transfer models of porous metals should be accelerated, and the porous metal flow field models should be continuously improved by comparing the experimental data and simulation results.

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