REVIEW

Effects of flow field design on water management and reactant distribution in PEMFC: a review

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Abstract The performance of a proton exchange membrane fuel cell (PEMFC) stack is affected by many factors, including the operating conditions, flow field and manifold design, and membrane performance. To achieve the desired PEMFC performance, the reactant must be uniformly distributed and effectively diffused into the catalyst layer for the electrochemical reaction. Water management and reactant distribution in fuel cells are crucial because they affect the distribution and diffusion rate of the reactant. This paper reviews the important research results reported in recent years related to the effects of water and reactant distribution on the performance and life span of PEMFC stacks.

Keywords PEMFC · Water management · Reactant distribution · Flow field design · Manifold

Introduction

Global energy use has increased over the years due to the growing world population, and this situation is exacerbated

- The effect of flow field design on water management and reactant distribution
- The effect of manifold design on reactant distribution
- The impact of flooding and starvation on a PEMFC

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by the increasing energy use per person. A sustainable energy supply has become an issue because fossil fuels, which are one of the main global energy sources, have started to become insufficient for meeting energy demands; this situation has led to the need to find alternative energy sources. Hydrogen allows for clean, safe, and efficient energy storage [1, 2]. Fuel cells, which are devices that can produce electricity and heat from multiple fuels (biogas, propane, methanol, diesel, hydrogen, and natural gas), represent a promising alternative energy converters [3].

Overview of fuel cells

The first fuel cell to generate electricity from gaseous fuels was invented by Sir William Robert Grove in 1839 [4]. The development of fuel cells was halted for almost a century until 1960, when the fuel cell was introduced in the Gemini program by General Electric. The development of fuel cells for space applications continues to today. During the early stages of fuel cell development, fuel cells were not developed for daily life applications. In 1993, the Ballard Power System developed fuel cell-powered buses, and Energy Partners demonstrated a proton exchange membrane fuel cell-powered car. The automobile industry is still pursuing fuel cells, and the USA and Japan have increased the number of fuel cell-powered vehicles [5].

Fuel cells that convert chemical energy directly into electrical energy and heat produce only water as a byproduct [6]. Fuel cells have a 40–50 % higher energy conversion efficiency and generate less noise than internal combustion engines because fuel cells contain no moving parts [7]. There are six types of fuel cells that are available on the market: proton exchange membrane fuel cells (PEMFCs), alkaline fuel cells (AFCs), direct methanol fuel cells (DMFCs), molten carbonate fuel cells (MCFCs), phosphoric acid fuel cells (PAFCs),

and solid oxide fuel cells (SOFCs) [8]. Fuel cells are categorized based on the type of electrolyte that is in contact with the anode and cathode. The electrolyte is selected according to the operating temperature of the fuel cell and the type and purity of the reactant used. Among the six types of fuel cells, PEMFCs and SOFCs have attracted the most attention and investment because SOFCs that operate at high temperatures (800–1000 °C) exhibit higher electrical efficiencies, their low heat output is more suitable for stationary power generation, and smaller units can be developed for portable power applications. However, PEMFCs that operate at low temperatures (60–80 °C) are suitable for both automotive applications and portable power applications. PEMFCs are characterized by high-energy conversion efficiencies, rapid startup, easy scale up, low noise, and zero emissions. The zero emissions property makes PEMFCs an ideal alternative solution for automotive applications.

Fundamentals of PEMFCs

PEMFC stacks that convert chemical energy to electrical energy, producing only water and heat as waste, are a reliable alternative solution. The low operating temperature, high power density, rapid startup, and low emissions of PEMFC stacks make them suitable for use in the automotive industry [9]. However, the performance and durability of PEMFCs are a major barrier to their commercialization [10].

In PEMFCs, the membrane electrode assembly (MEA) consists of a gas diffusion layer, catalyst layers, and a membrane. The gas flow channels on the bipolar plates are a key component that affects the performance of PEMFCs. The electrochemical conversion of chemical energy to electrical energy in PEMFCs is illustrated in Fig. 1:

- Hydrogen and oxygen are pumped into the anode and cathode channels, respectively.
- The reactant flow through the gas diffusion layer on the anode and cathode sides diffuses into the catalyst layer.
- Hydrogen is oxidized at the anode catalyst layer into protons and electrons.
- Protons then diffuse through the membrane to the cathode.
- The electrons that are produced from the oxidation of hydrogen flow through an external circuit from the anode to cathode, which produces electrical energy.
- On the opposite side, oxygen reduces the proton and electron in the cathode catalyst layer, and water is formed.
- The water that was produced in the cathode is forced out from the membrane to the cathode channel and out of the fuel cell.
- Heat is another byproduct that is produced during the oxygen reduction reaction in the cathode.
- The cycle is repeated to continuously convert chemical energy into electrical energy.
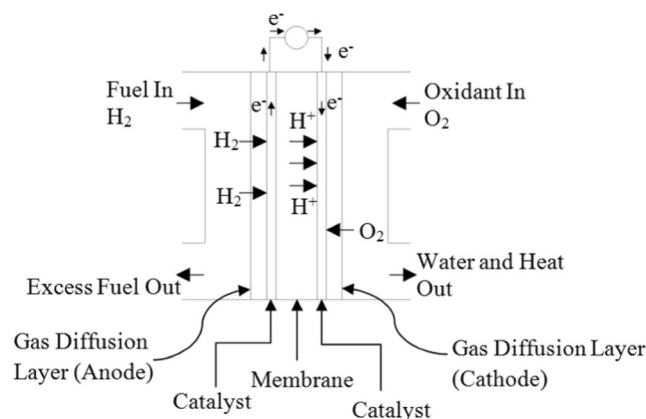

Fig. 1 Schematic diagram of a proton exchange membrane fuel cell

Recent improvements in PEMFC stack performance have primarily focused on water management in the channel of the bipolar plate because the water content in the fuel cell greatly affects its performance [11]. Several studies on the effects of different flow field designs on fuel cell performance have been reported [12–14], and they suggest that a serpentine flow field with optimized water management would produce a high and uniform current distribution [12]. Moreover, studies have also been conducted to optimize the channel dimensions for improving water management in fuel cells. Qin, Li, Jiao, Du, and Yin [15] reported that the dimensions of the channel on the bipolar plate greatly affect the water content in fuel cells. Baschuk and Li [16] and Shimpalee, Greenway, and Van Zee [17] claimed that shorter channel paths result in less condensed water compared to long channel paths. Consequently, multiple studies have shown that the design of the flow field greatly affects water management in fuel cells. The life span or durability of fuel cells is another major issue. In 2009, it was reported that a life span of approximately 2500 h was achievable for PEMFC stacks for use in transportation applications, which is far from the DOE target of 5000 h by 2015 [18].

The flow field design affects not only water management but also the distribution of reactants in fuel cells. The maldistribution of reactants in PEMFC stacks causes a non-uniform distribution of current density, localized hot spots, and performance degradation [19]. The distribution of reactants can be divided into two categories, namely, the distribution of reactant to each bipolar plate (manifold design) and the distribution of reactant among the channels on the bipolar plate (flow field design). Studies have investigated the effect of the manifold dimensions on the uniform reactant distribution to each bipolar plate [20, 21]. The proper design and dimensions of the manifold would improve the reactant distribution. The flow field design on bipolar plates is the key component for determining the uniform distribution of reactant for electrochemical reactions. Studies on the effects of the flow field on a uniform distribution have reported that serpentine and

interdigitated flow fields with strong convection may improve the cell performance [22, 23].

Objectives and scope

This review discusses the effects of PEMFC stack designs on water management and reactant distribution. The PEMFC stack designs that are discussed in this review include flow field designs and manifold designs of the cathode and anode plates. Moreover, the effects of the operating parameters are also discussed.

PEMFC stack flow field designs

The bipolar plates are crucial components of PEMFCs that must perform multiple functions to achieve effective performance and long lifetimes. Although the performance of PEMFCs is related to the fluid, mass, and diffusion transfer of molecules, the performance is also directly related to the bipolar plate, particularly the flow field. Bipolar plates also provide mechanical support to the MEA, isolate the reactants, and enhance the diffusion of reactant into the catalyst layer [24]. Moreover, the flow field design on the bipolar plates can facilitate water and heat management in fuel cells. Thus, the optimal flow field design must be achieved to enhance water management in fuel cells.

Over the years, various types of flow field designs have been investigated. Each flow field design has advantages and disadvantages that are dependent on the application of the fuel cell. The most common flow field designs that have been investigated are shown in Fig. 2 [25–28].

Parallel flow fields

The parallel flow field is the simplest design, and it consists of multiple parallel path channels that are directly connected to the channel inlet and outlet. Theoretically, a parallel flow field supplies identical reactant streams to each channel or cell, which simplifies conditioning of the input reactant [29]. During low flow rate operating condition, insufficient flow resistance in parallel flow fields causes a low pressure drop, which reduces the amount of gas that diffuses into the gas diffusion layer and leads to low PEMFC stack performance. However, the performance of parallel flow field could be improved by having higher flow rate [30]. By operating at higher flow rate, it would increase the pressure drop in channel and improves the gas diffusion. During lower flow rate operating condition, low pressure drop occurs in the channel and it does not help to purge the water that was produced from the electrochemical reaction from the fuel cell. Thus, water accumulates along the channel and causes reactant starvation that further reduces the fuel cell performance.

Serpentine flow fields

The serpentine flow field was introduced to improve the non-uniform distribution of reactants and water management in PEMFCs. Reactant gas is forced to flow through a single or multiple channel paths that are skewed to the edge of the entire active area. A serpentine flow field has a higher pressure drop than parallel channels due to the friction of the wall and the turning channel, and the increased pressure drop enhances the purging of accumulated water from the channel. This enhances the uniform distribution of the reactant over the entire active area, leading to uniform distributions of current density and water [31]. Consequently, PEMFCs have longer life spans due to decreased mechanical stress on the MEA.

Interdigitated flow fields

Another common type of flow field design that could enhance flow distribution and water management in fuel cells is the interdigitated flow field. In contrast to serpentine and parallel flow fields, the channel design of interdigitated flow fields is not continuous. The interdigitated design is based on dead-end channels that can enhance the convection flow, thereby leading to improved reactant utilization and an enhanced water removal rate [32]. The reactants are forced to diffuse through the dead-end channel into the gas diffusion layer, thus increasing the amount of gas in the catalyst layer for the electrochemical reaction. Thus, the performance of the PEMFC improves.

Bio-inspired flow fields

Recently, bio-inspired flow fields for PEMFCs have been investigated [33–35]. These flow fields were designed based on existing examples from nature, such as the veins of plants and leaves. Fuel cells employing bio-inspired flow fields exhibit a 26 % higher maximum power density than those with serpentine flow fields [36]. However, bio-inspired flow fields receive less attention due to material costs and manufacturing complexity [37].

Discussion

Among the four flow fields mentioned (parallel, serpentine, interdigitated, and bio-inspired), serpentine and interdigitated flow fields exhibit better performance than parallel flow fields because of their design that enhances forced convection, which increases the amount of reactant in the gas diffusion layer. Bio-inspired flow fields exhibit better performance compared to serpentine and interdigitated flow fields due to the uniform distribution of reactants and the optimal pressure drop. However, parallel flow fields represent the simplest design among the four flow fields discussed. For automotive applications, parallel flow fields are the most suitable due to

Fig. 2 Schematic diagram of various reactant flow fields [28]: **a** single serpentine flow field, **b** Z-parallel or single parallel flow field, and **c** interdigitated flow field
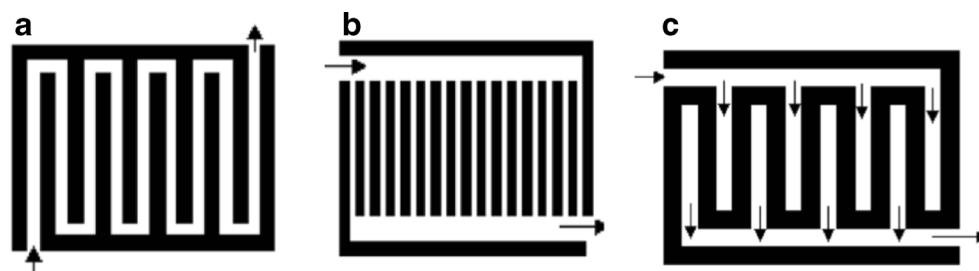
their compact design. The lower pressure drop and simple design may reduce manufacturing costs and reduce the operating pressure in fuel cells, which would effectively increase the overall power yield. Therefore, a modified parallel flow fields designed to improve the temperature and current density distribution could be an excellent choice for automotive applications [38].

Effects of flow field design on water management

Water management is an important area of research because it greatly influences the performance and durability of fuel cells. Several recent reviews have focused on water balance, transport, formation, accumulation, and flooding in fuel cells [39–41]. Water produced from electrochemical reactions in the cathode diffuses to the anode for membrane hydration. Electro-osmotic effects occur in which water is transferred from the anode to the cathode when protons diffuse through the membrane. Consequently, flooding occurs, during which water accumulates in channels and blocks the passage of reactant. In fuel cells, excess water causes flooding, and too little water causes membrane dehydration. Reactants that are blocked from flowing through the channel lead to non-uniform current distributions and performance degradation in the fuel cell. Li and Sabir [42] provided a compressive review on flow field designs.

The effects of flow field designs

The influence of the flow field design on the water management and performance of PEMFCs has been investigated by many researchers. Investigations have been performed by varying the operating and geometric parameters, such as the operating voltage, the pressure of reactants, and the active area. Wang, Zhang, Yan, Lee, and Su [43] investigated numerically the influence of parallel, interdigitated, and single serpentine flow fields on the water removal rate in PEMFCs by altering the active areas from 11×11 to 41×41 mm^2. They reported that interdigitated flow fields were less affected by altering the active area compared to serpentine and parallel flow fields. In contrast, interdigitated and serpentine flow fields exhibited better liquid water distribution compared to

parallel flow fields. Parallel flow fields exhibited poor water removal due to the low hydrodynamic stress force under the rib. Similar results were also reported by Jang, Yan, Li, and Tsai [44]: parallel flow fields exhibited the worst liquid water removal rate compared to serpentine flow fields. Another study in which the water distributions were analyzed in parallel, serpentine, and mixed flow fields (Fig. 3) also reported that the parallel flow field exhibited the worst liquid water removal rate and that the serpentine flow field exhibited better liquid water removal [13]. This result also demonstrates that the membrane was not uniformly hydrated for the serpentine flow field. In the same study, the mixed flow field exhibited the best liquid water removal rate, the water in the cathode was uniformly distributed, and the membrane was uniformly hydrated. Additionally, the flooding effect and reactant consumption can be improved with a serpentine flow field by increasing the channel length without changing its active area size because rectangular active areas perform better than square active areas [45].

Serpentine flow fields are commonly used in PEMFC stacks because of their configuration that enhances water management and performance. A study was conducted to examine the effects of different configurations of serpentine flow fields by comparing a single channel, a double channel, a cyclic-single channel, and a symmetric single channel in serpentine flow fields (Fig. 4) with an active area of 10 cm^2 [46]. A computational fluid dynamics (CFD) analysis was used to investigate the influence of inlet humidity. At high inlet humidity, the double-channel flow field exhibited the most uniform membrane water distribution, and the cyclic single- and symmetric single-channel flow fields had low water contents due to their excessively short channel lengths. The authors reported that the cyclic single and the symmetric single channel flow fields had better performance and membrane water distribution at low inlet humidity.

Lee, Kim, and Park [47] also analyzed the effect of relative humidity on net water production in multi-inlet and single-inlet serpentine flow fields (Fig. 5). These authors reported that for serpentine designs, as the relative humidity increased from 10 to 70 %, the PEMFC power density also increased from 0.074 to 0.139 W/cm^2. A similar trend was observed for multi-inlet flow fields, where the power density increased from 0.156 to 0.296 W/cm^2 as the relative humidity increased.

Fig. 3 Flow configurations of **a** parallel, **b** serpentine, and **c** mixed flow fields [13]
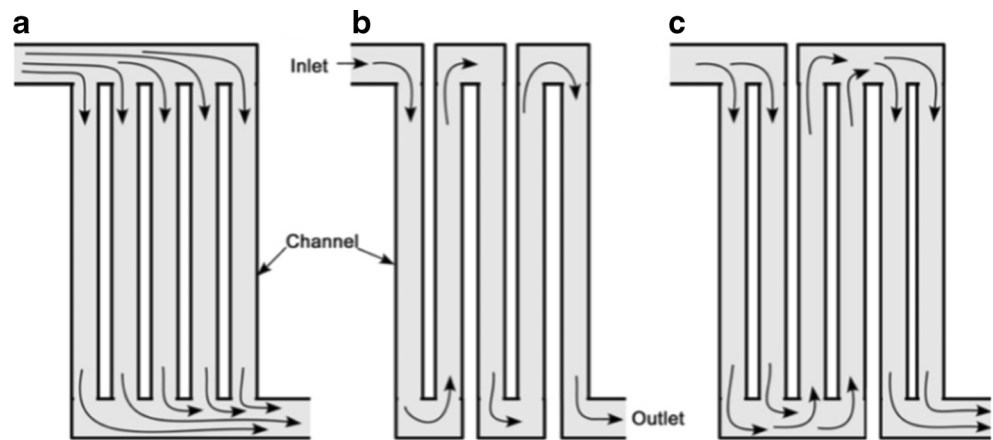
The recorded power density value clearly demonstrated that the multi-inlet flow field exhibited higher power generation than the serpentine flow field. Thus, this study demonstrated that multiple inlets for the cathode reactant reduce the water accumulation while maintaining the reactant flow rate. Both studies which were conducted numerically [46, 47] also showed that the water distribution in fuel cells is improved at high inlet humidity, although water accumulation in the channels was also promoted. Therefore, the proper design of the flow field and the optimal inlet humidity could promote uniform water distribution and enhance fuel cell performance.

Boddu, Marupakula, Summers, and Majumdar [48] analyzed numerically the influence of the pressure drop on five different serpentine flow fields and channel contact surface configurations. The different serpentine flow fields included single serpentine channels with curvilinear bends, single serpentine channels with square bends, multiple serpentine channels with square bends, and dual serpentine channels with 1.2-mm and 1-mm square bend widths, as shown in Fig. 6. It was

reported that the serpentine channels with curvilinear bends have a higher pressure drop than those with square bends due to the increased flow lengths with rounded corners. Comparison of the five configurations revealed that an increased number of channels and a decrease in the channel width resulted in a lower pressure drop compared to the single serpentine channel. However, increasing the number of channels induced more uniform reactant and water distributions. Shimpalee, Greenway, and Van Zee [17] reported that a uniform current distribution can be achieved with shorter channel lengths or by increasing the number of channels.

Compared to serpentine flow fields, interdigitated flow field designs exhibit better water removal rates due to their dead-end channel design that induces a higher pressure drop. However, interdigitated flow fields are not commonly used compared to serpentine flow fields due to their strong ability to remove water from PEMFCs, which leads to membrane dehydration and performance degradation. A previous study that compared the interdigitated and serpentine flow fields

Fig. 4 Serpentine flow fields on a 10-cm² area: **a** single-channel flow field, **b** double-channel flow field, **c** cyclic single-channel flow field, **d** symmetric single-channel flow field [46]
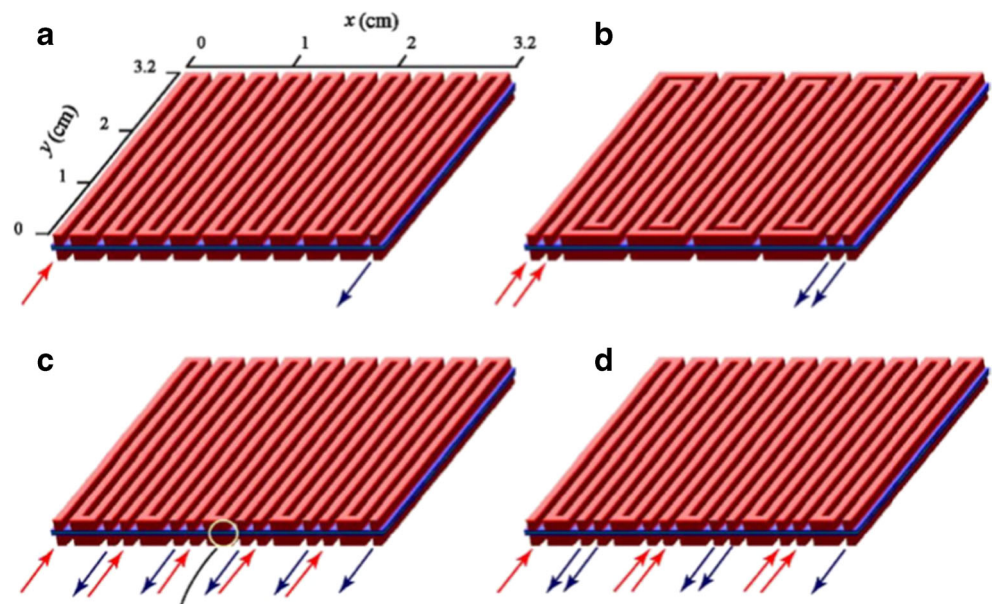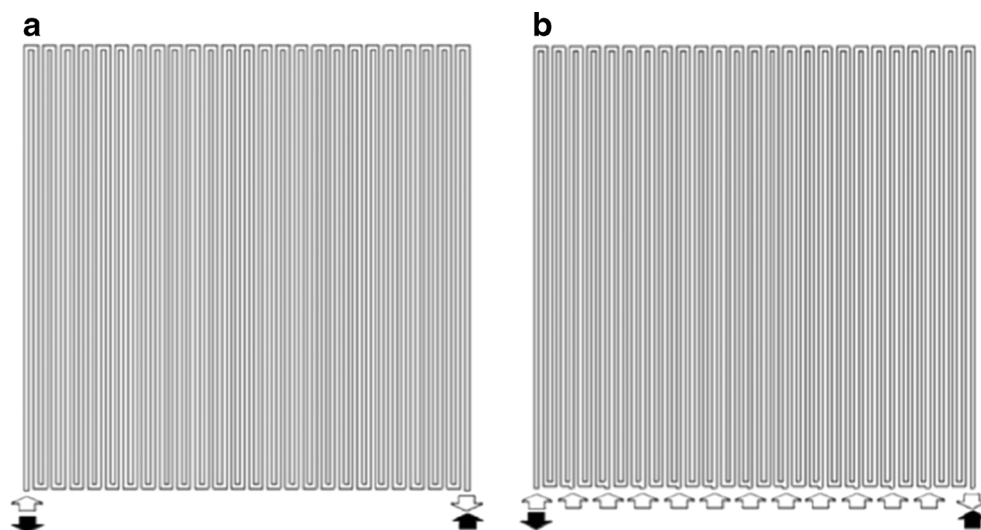
Fig. 5 Serpentine channel designs: **a** a single channel and **b** a multi-inlet channel; the *black arrows* indicate inlets in the anode channel, and the *white arrows* indicate inlets in the cathode channel [47]

reported that at low reactant flow rates and non-humidified reactants, interdigitated flow fields have a more uniform current distribution than serpentine flow fields [49]. Hu, Fan, Chen, Liu, and Cen [50] and Birgersson and Vynnycky [51] numerically compared interdigitated flow fields with other types of flow fields, such as conventional, parallel, and foam fields. Their results indicated that interdigitated flow fields induce strong forced convection, which forces the reactant to diffuse into the catalyst layer for the electrochemical reaction. Thus, the dead-end channel of the interdigitated flow field can increase the reactant transfer rate, which increases the current density of the fuel cell. However, the humidification of the fuel cell is accounted for in the interdigitated flow field due to its strong water removal ability.

Table 1 Configuration of the anode and cathode channel flow fields [52]

To improve water management in fuel cells, a 20° slanted channel design has also been considered, for which analyses were performed in increments of 3 A from zero to the maximum current density [52]. Table 1 shows the orientations of a slanted channel and a square channel with membrane electrode assembly (MEA). These orientations were considered in the analysis, incorporating seven parallel serpentine channels with four primary channels on each side of the channel plate. The down-slanted channel plate on the anode side exhibited improved cell performance by retaining the excess water in the bottom of channels away from the anode gas

diffusion layer. This configuration effectively removes the excess water from the anode and enhances back diffusion from the cathode to prevent membrane dehydration. The removal of water from the cathode gas diffusion layer was enhanced by the down-slanted design of the cathode channel. However, the water that was produced from the electrochemical reaction at the cathode was used to maintain membrane hydration for proton conductivity. Enhanced water removal from cathode diffusion layer leads to membrane dehydration, which degrades the performance and durability of fuel cells.

The effect of flow channel geometric parameters

Channels are designed to allow reactants to diffuse uniformly into the catalyst layers for reactions [53]. The channel geometry, such as its width, depth, angle, and shape, affects the water management and the performance of the fuel cell. Therefore, proper design of the channel geometry improves water removal to prevent channel flooding. Huang, Chen, and Kim [53] numerically study the inverse design method to optimize the gas channel geometry. Study was conducted at high voltage 0.7 V and low voltage 0.4 V of operating condition by using B-spline curves technique and Levenberg-Marquardt method. It is reported that the time and cost to optimize gas channel for channel design are reduced and desired current density is achieved by using the developed method. The other objective of this numerical work is to increase the current

Fig. 6 Serpentine flow fields: **a** single channel with curvilinear bends, **b** single channel with square bends, and **c** dual channels with widths of 2, 1.2, and 1 mm [48]
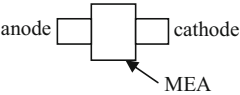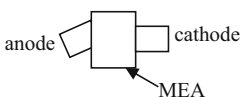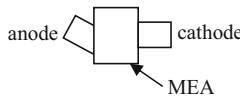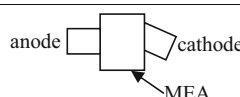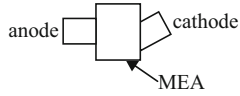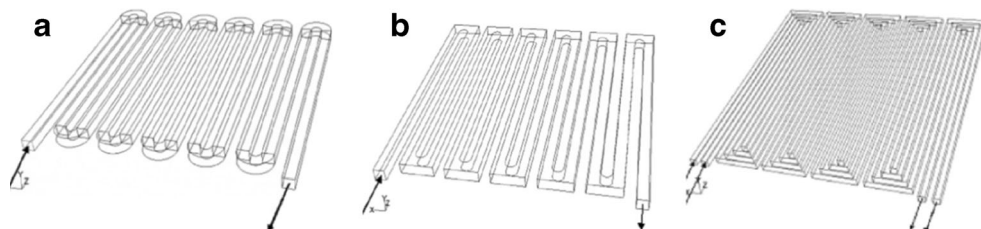
Table 1 Configuration of the anode and cathode channel flow fields [52]

Anode flow field	Cathode flow field	Orientation of anode/cathode
Square plate	Square plate	anode / cathode / MEA
Down-slanted plate	Square plate	anode / cathode / MEA
Up-slanted plate	Square plate	anode / cathode / MEA
Square plate	Down-slanted plate	anode / cathode / MEA
Square plate	Up-slanted plate	anode / cathode / MEA

density by 20 % from the existing channel design. They reported that at 0.4 V, the longer redesigned channel has better water removal rate and higher current density. This is because the longer channel has higher pressure drop which assist the water purging. Wang, Duan, Yan, and Peng [54] numerically investigated the effects of the channel width ratio (the total flow channel width to the total cell width ratio) for serpentine and parallel flow fields. Their analysis demonstrated that parallel flow fields have a greater impact on performance compared to serpentine flow fields when the channel width ratio is increased. As the parallel flow field channel width increases, the diffusion effect of the reactant into the gas diffusion layer and the catalyst layer increases due to the contact area between the gas diffusion layer and the reactants. In contrast, the channel width ratio induces a reduced effect in serpentine flow fields due to their under-rib convection or forced convection capability. This capability enhances reactant diffusion and the water removal rate in PEMFCs. Higier and Liu [55] experimentally studied the effects of the channel and rib widths on PEMFCs incorporating a serpentine flow field. Their study demonstrated that larger rib widths exert additional compression forces that decrease the capability of the gas diffusion layer to diffuse reactants. In addition, when the rib width is reduced with a narrower channel, performance of the PEMFC increases due to the reduction in reactant concentration losses. They also reported that the effect of the rib width was significant at low operating cell voltages. Shimpalee and Van Zee [56] studied numerically the impact of the channel and rib widths on serpentine flow fields with active areas of 25 cm^2. Stationary and automotive applications were considered to examine the effects of the channel-to-rib ratio. Wider channels with narrow ribs exhibited better performance for automotive applications because the electro-osmotic effect that diffuses water from the cathode to the anode kept the membrane hydrated and increased the PEMFC performance. However, it was reported that a larger rib area enhanced heat removal because the heat from the membrane could be transferred to a bipolar plate due to the large contact surface. Consequently, poor heat management was observed for the best-performing channel-to-rib ratio for automotive applications. Thus, for a parallel flow field, larger channel widths enhanced the reactant distribution, and for serpentine flow fields, narrower widths produced better performance by reducing the reactant concentration losses.

Experimental studies on serpentine and interdigitated flow fields with rib-to-channel ratios of 1:1 and 2:2 were conducted by Karthikeyan, Velmurugan, George, Ram Kumar, and Vasanth [57]. It is known that interdigitated flow fields exhibit higher performances compared to serpentine flow fields due to their ability to force the reactant into the catalyst layer by having dead-end channels. Studies on variations in the rib-to-channel ratio have reported that an interdigitated flow field provides higher performance than a serpentine flow field and that at ratio of 1:1, where the number of ribs increased, improved the reactant distribution, and avoided the occurrence of hotspots for the interdigitated flow field.

Larger channel widths enhance reactant diffusion into the gas diffusion layer, and electrical conductivity can be improved by increasing the rib width [58]. A 50 cm^2 active area was used to experimentally determine the effect of the rib width [59]. Variations in the rib-to-channel width (0.25, 0.5 and 1 mm) were studied using multiple cell voltages to evaluate the cell current density performance. The study showed that the rib width had a greater impact on the PEMFC performance at higher current densities. Thus, the 0.25-mm rib width exhibited improved performance when the channel width was large. However, small rib widths and large channel widths enhance the contact resistance, which in turn reduces the cell performance. To compensate for this phenomenon, a smaller channel width is required to increase the number of ribs in the active area to reduce the contact resistance. Sun, Peppley, and Karan [60] analyzed numerically a two-dimensional cross-channel model to determine the effect of the channel rib ratio on water transport in PEMFCs using channel-to-rib ratios of 1:1, 2:1, and 4:1. They reported that water production was reduced under the rib as the channel-to-rib width increased. For the ratio of 1:1, a poor water removal rate was observed relative to the other ratios. Therefore, a high channel-to-rib ratio enhanced the removal of water from the catalyst layer. Thus, the channel width should be larger than the rib width to improve water management and the performance of the fuel cell.

The effect of the channel path length was numerically investigated by Shimpalee, Greenway, and Van Zee [17] for a serpentine flow field with an active area of 200 cm^2. The variations in the channel length were obtained by increasing the number of channel paths; 3-channel flow field, 6-channel flow field, 13-channel flow field, 26-channel flow field, and 26-channel complex flow field were studied (Fig. 7). The authors showed that the channel path length affects the water content in the channel, whereas the channel length proportionally increases with the channel water content. Therefore, shorter path lengths yield less condensed water and a more uniform current density distribution.

The effects of channel path length have also been investigated in interdigitated flow fields by Santamaria, Cooper, Becton, and Park [61]. The study was performed numerically and verified experimentally using channel lengths of 5 and 25 cm. The results of this study again showed that the shorter path length led to improved reactant distributions and water management compared to the longer channel path. The maximum power density was recorded for the short path length, which was 12.7 % higher than the short path length power density. However, the analysis performed by Bachman, Charvet, Santamaria, Tang, Park, and Walker [62] showed that for a parallel flow field, the longer channel path exhibited better performance compared to the shorter length. This experimental study was performed using a parallel flow field with 5, 15, and 25 cm lengths. The study showed that with a 5-cm path length, unstable performance was obtained and water accumulated in the channel, causing pressure and voltage drops. The maximum power was observed for the 25-cm channel length, which was 87 % higher than that of the 5-cm channel length. Therefore, due to the smaller pressure drop and no forced convection capabilities exhibited in the parallel channel, the longer channel path length enhanced water management and PEMFC performance. Thus, the effects of the channel geometric parameters are dependent on the flow field design.

In addition to varying the geometrical dimensions of the channel to improve water management, the cross-section of a channel may also affect the water removal rate. Square or rectangular channel cross-sections are commonly used in channel designs in which the height of the channel remains constant throughout the active area. Ahmed and Sung [63] studied a three-dimensional model of a single straight channel geometry with rectangular, trapezoidal, and parallelogram channel cross-sections (Fig. 8). Their study revealed that the trapezoidal channel geometry led to a more uniform reactant distribution compared to the other channel geometries because the larger channel width on the surface near the gas diffusion layer enhanced the diffusion rate of the reactant into the gas diffusion layer. Zhu, Liao, Sui, and Djilali [64] also analyzed a three-dimensional model to evaluate the liquid water removal rates of rectangular, trapezoidal, upside-down trapezoidal, triangular, rectangular with a curved bottom wall, and semi-circle cathode channel geometries. It was reported that the triangular and trapezoidal channel cross-sections were associated with the shortest water removal times.

Fontana, Mancusi, da Silva, Mariani, Ulson de Souza, and Ulson de Souza [66] numerically investigated the influence of tapered flow channels (0°, 0.5° and 0.75°) on PEMFC performance. Uniform oxygen distribution was observed as the inclination angle increased. Oxygen was forced to diffuse into the catalyst layer as the area of the channel decreased, thus enhancing the cell performance and reducing membrane flooding. However, the inclination of the channel increased the pressure drop in the channel, where a pressure drop of approximately 3.5 times higher was recorded compared to that in the rectangular channel. Mancusi, Fontana, Ulson de Souza, and Guelli Ulson de Souza [65] continued the investigation of tapered channel flows (Fig. 9), focusing on two-phase flows in the channel. At low temperatures, the performance differences were insignificant, and as the temperature increased, the performance of PEMFCs increased with the tapered angle. The authors also showed that the water removal rate increased as the inclination angle increased due to the increased reactant velocity in the channel with increasing inclinations. The water that formed in the steep channel was easily removed due to the minimal size of the water droplet. In contrast, water slug was observed to accumulate the in square channel. Thus, the channel cross-section does affect the water removal rate in fuel cells.

Fig. 7 Serpentine flow fields: **a** three channels, **b** six channels, **c** 13 channels, **d** 26 channels, and **e** complex 26 channels [17]
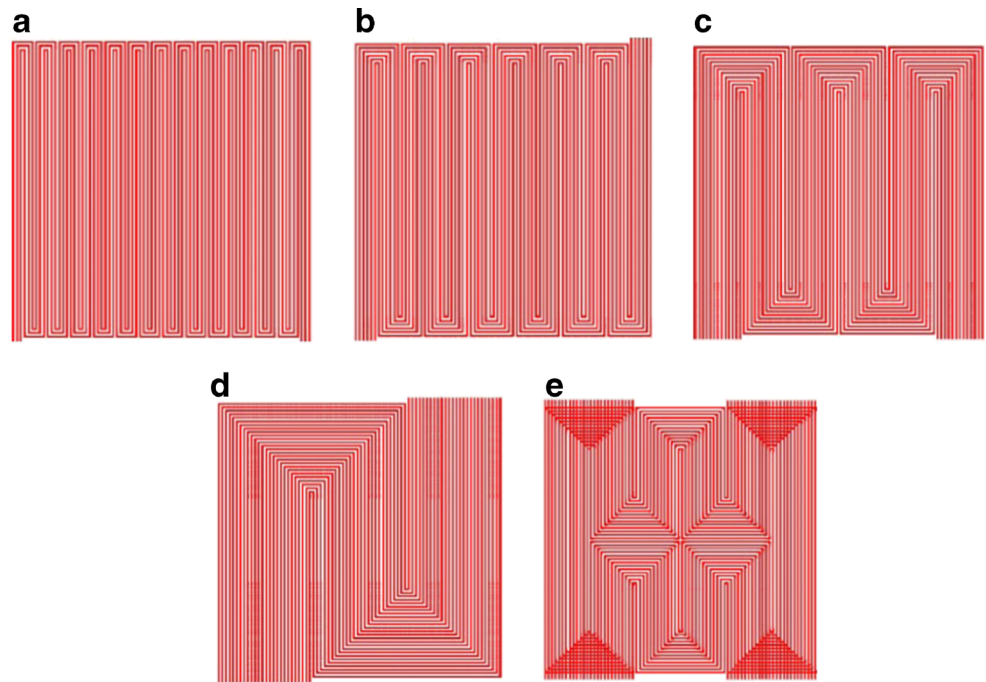
Flooding

The flooding effect is a phenomenon in which a water slug is formed in the cell channel that prevents the reactant from entering the channel or the catalyst layer for the electrochemical reaction [67]. Many researchers have investigated the effect of flooding on PEMFC performance [68–70]. These studies have concluded that the fuel cell voltage is affected by flooding, which causes an unstable or sudden voltage drop in PEMFCs. The confirmation of water formation in the channel is performed using a polarization curve. To better visualize the formation of water, researchers have also used neutron imaging to observe the formation of the water distribution in the channel [71–73]. The formation of a water slug that leads to flooding typically occurs during the generation of a high current density when the water generation rate in the channel is higher than the purging rate. To overcome this problem, the impact of the two-phase flow maldistribution in PEMFCs was studied by Ding, Bi, and Wilkinson [74]. In this study, two parallel square channels of 1 × 1 and 50 mm in length were

considered with different amounts of water injected into the channels to introduce channel flooding. Three different flooding scenarios were considered: 50/50, 25/75, and 0/100. Variations in gas stoichiometry to improve the cell performance during flooding were reported to be insignificant, where the 0/100 flooding effect showed no performance improvement. However, adding an inlet resistance could improve the fuel cell performance during flooding of the channel.

Han, Choi, and Choi [75] numerically and experimentally studied the flooding phenomenon by adding the Concus-Finn condition to enhance water removal from the cathode channel. The Concus-Finn condition (Fig. 10) was met when the addition of the contact angle on the channel wall surface and half opening angle of the tapered channel was less than $\pi/2$. They reported that when the Concus-Finn condition was met, the flooding phenomenon was improved by moving the water droplet that accumulates in the channel to a narrower channel. However, gravity in the channel should be considered because it could prevent movement of the water droplet. Qin, Li, Jiao,

Fig. 8 Channel cross-section: **a** rectangular, **b** trapezoidal, and **c** parallelogram [19, 63]
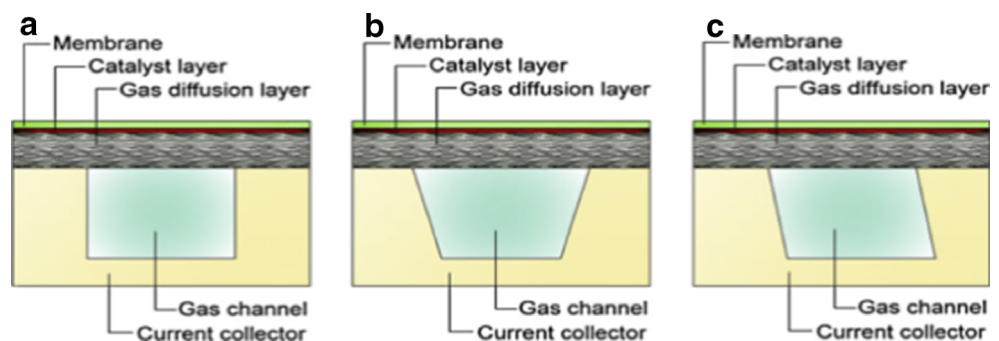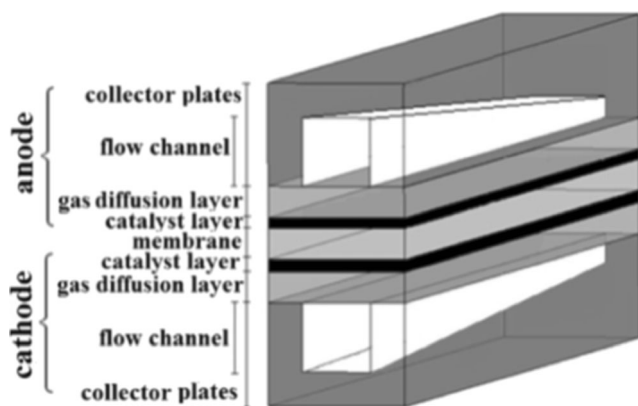
Fig. 9 Three-dimensional tapered channel [65]

Du, and Yin [15] numerically investigated the water removal rate from the channel through the use of a hydrophilic plate in the middle of the channel. The study was conducted using a 50 mm length of 1 × 1 mm square flow channel with a hydrophilic plate fixed at the bottom surface of the channel located at the middle of the flow channel. They reported that adding the hydrophilic plate to the channel facilitated the removal of the water droplet from the MEA surface and the channel. The increased pressure drop in the channel due to the presence of the hydrophilic plate gradually reduced during the water removal and transport processes. Therefore, flooding in fuel cells is influenced by the channel cross-section.

Discussion

The flow field design and geometric parameters greatly affect water management in PEMFC stacks. Serpentine and interdigitated flow fields are effective in removing water due to their forced convection designs. However, the effective removal of water causes the membrane to lose humidity, which causes the membrane to lose its proton conductivity, thereby leading to
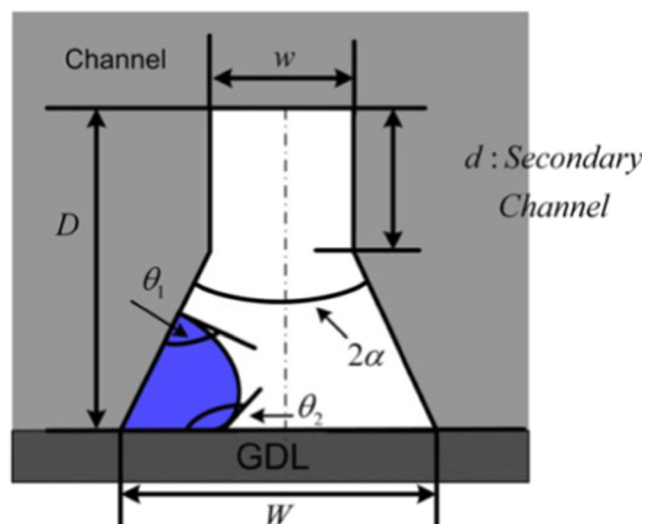

Fig. 10 The Concus-Finn channel design [75]

performance degradation and a shorter life span. Therefore, a proper flow field design with an intermediate water removal rate is desired. As reported by Shimpalee and Van Zee [56], for automotive applications, the performance of a PEMFC can be enhanced by utilizing a larger channel width. This would increase the amount of reactant that diffuses into the gas diffusion layer due to the larger contact surface between the reactant and the gas diffusion layer. Although a trapezoidal cross-section channel geometry enhances the performance of the PEMFC, such channel geometry is not feasible for automotive applications due to high manufacturing costs. Therefore, the optimal channel dimension and flow field design suitable for automotive applications are a flow field with a large channel width, which could improve water management and enhance the performance of PEMFCs.

Effects of flow field design on reactant distribution

For PEMFC stacks, a uniform distribution of reactant gasses is a major criterion for improving the performance. Stack designs that consist of a manifold and a flow field are important for reactant distributions. PEMFC stack failure is generally dictated by the weakest cell, where the current limit is determined by the lowest reactant supply cell [76]. Thus, a uniform flow distribution throughout the fuel cell stack would provide better fuel cell performance [77]. The effects of the reactant distribution are not solely dependent on the fuel cell stack design; the operating conditions in the fuel cell stack, such as the flow rates, pressure, temperature, and humidity, can also affect the reactant distribution.

Effects of cell distribution in the stacks

The reactant cell distribution is an important factor for improving the performance and durability of PEMFCs. Recent studies have shown that a uniform flow distribution in fuel cells is critical for maximizing cell performance [78, 79].

Parallel flow field designs are known to exhibit a non-uniform reactant distribution as a result of the low pressure drop. To overcome the non-uniform reactant distribution in parallel flow fields, Zhang, Hu, Lai, and Peng [80] investigated the geometry of parallel flow fields to improve the reactant distribution. They optimized the parallel flow field by varying the header and channel cross-section. It was reported that increasing the header cross-section improved the reactant distribution. However, this modification is not feasible in practice because it would either reduce the active area or increase the overall fuel cell dimensions. In addition, the authors varied the channel width to improve the reactant distribution, but insignificant improvements were reported. Another study [81] introduced a gas flow restrictor/distributor placed at the header of the parallel flow field to improve the reactant distribution.

The authors experimentally investigated the effect of the inlet flow restrictor/distributor using two flow field plate designs, as shown in Fig. 11. It was reported that by adding an inlet flow restrictor, the channels on the cathode plate exhibited almost no water staining. However, a uniformly distributed water stain was observed on the anode plate. A completely reverse phenomenon occurred on the plate without the inlet flow restrictor, where non-uniform water stains were observed on the cathode and anode plates. It was shown that the gas flow distributor improved the reactant distribution on the parallel flow field by altering the pressure drop in the channel.

Ramos-Alvarado, Hernandez-Guerrero, Juarez-Robles, and Li [82] studied the flow distribution in parallel flow fields with a bifurcated structure at the inlet. Two different bifurcated structures with parallel flow fields (distributor A and distributor B) were compared with a serpentine flow field (Fig. 12). The performances of distributor A and distributor B were lower than that of the serpentine flow field. Thus, optimization was performed using distributor C and distributor D, as shown in Fig. 13, and the authors found that distributor D resulted in higher power generation than did the serpentine flow field. It was concluded that distributor D has better performance than serpentine flow field and it also uses lesser pumping power and manufacturing cost due to its simple design.

Operating parameters

The operating parameters, including the reactant flow rates, reactant humidity, cell operating pressure, and cell temperature, are crucial in determining the fuel cell performance. These operating parameters directly affect the thermal, water, and reactant distributions, which are key for the efficient operation of PEMFCs [83, 84]. Recently, the importance of the operating parameters that affect the fuel cell performance has motivated research on the influence of various operating parameters on the performance of PEMFCs. Studies on the effects of temperature and relative humidity [85, 86], the cathode inlet gas flow rates [30, 87, 88], and operating fuel cell pressure [89, 90] on fuel cell performance have been reported.

The performance of PEMFCs can be affected in two ways if liquid water exists in a channel. The first is reduced reactant flow in the channel, which leads to maldistribution, and the second is reduced contact area between the reactant and the gas diffusion layer, which reduces the electrochemical reaction [91]. Therefore, water management is critical in PEMFCs because it can cause maldistribution of the reactant and lead to reduced fuel cell performance. For efficient fuel cell operation, the humidity in the cell must be carefully considered. The appropriate humidity in fuel cells not only improves its performance and efficiency but also maintains the function of the membrane and the catalyst for a longer life span [92]. Jian, Ma, and Qiu [93] investigated the effects of humidification of the anode and cathode reactants on changes in the current density and temperature. A three-dimensional model of the interdigitated flow field was considered in their study by varying the humidification percent for both the anode and the cathode. Increasing the humidification of the cathode and anode increased the temperature difference and the current density. However, a sharp decrease was observed during the fully humidified condition of the cathode and anode due to worsened concentration polarization.

Freire, Antolini, Linardi, Santiago, and Passos [94] studied the effects of the humidification temperature on fuel cell performance using trapezoidal cross-sectional serpentine flow fields/square serpentine flow fields at the cathode and normal square cross-section serpentine flow fields at the anode. The study was conducted by varying the reactant humidification temperature from 80 to 100 °C. It was reported that at lower humidification temperatures, the performances of the cell were poor for the trapezoidal cross-section compared to the square cross-section due to the greater water removal rate, which leads to improper membrane hydration. Thus, both studies showed that optimal humidification of the reactant improves the performance of fuel cells, and vice versa, improper humidification leads to membrane dehydration and causes performance degradation.

Reactant starvation

Reactant starvation often occurs due to liquid water blockage in channels or an undersupply of reactant [95, 96]. The excess liquid water in the channel tends to prevent the reactant from accessing the catalyst layer for the electrochemical reaction. An insufficient supply of reactant into the channel causes an uneven reactant distribution that leads to starvation and that increases the local potential of the fuel cell, thus enhancing carbon corrosion and loss of the platinum catalyst layer [10]. Therefore, investigating the effects of reactant starvation and taking the necessary measures will improve the performance and durability of PEMFCs in the future.

Cathode reactant starvation

Water flooding tends to occur in the cathode channel due to the generation of water from the cathode reaction, water that is transported by the humidified reactant, and the electro-osmotic effect that transports water during proton diffusion through the membrane. Cathode reactant starvation occurs during a sudden change in the reactant demand, such as during the startup process and load change and during water blockage in the channel. During cathode reactant starvation in fuel cells, protons that diffuse through the membrane recombine with electrons in the cathode and form hydrogen. This phenomenon causes the cathode potential to suddenly drop and reverses the cell voltage [97].
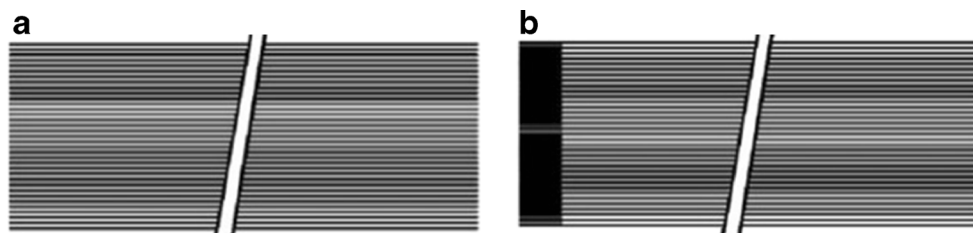
Taniguchi, Akita, Yasuda, and Miyazaki [98] studied experimentally the effect of air starvation and reported that air starvation accelerates the degradation of the electro-catalyst and performance. Comparison of normal and air starvation operation showed that during air starvation, the generation of heat was higher. Liu, Yang, Mao, Zhuge, Zhang, and Wang [99] investigated the starvation behavior in a single-cell PEMFC by measuring the current distribution. When the oxygen concentration decreases, the entire fuel cell suffers from concentration loss and a decrease in the local current was observed. However, a non-zero current density region was observed during cathode starvation, although a zero current density region may exist if a poor flow field or water flooding occurs in the channel. Zhang, Shen, Guo, and Liu [100] experimentally analyzed the starvation characteristics via dynamic variations in local current densities and temperature using a single serpentine flow field. The analysis revealed that during the current-controlled mode, a reversal of the cell voltage occurred, and the current density was increased near the inlet. In the voltage-controlled mode, the effect of starvation was less observed because the current in the PEMFC decreased with lower flow rates. Therefore, the investigations of various researchers revealed that air starvation should be avoided because it affects the performance and durability of PEMFCs.

Anode reactant starvation

During anode reactant starvation, an insufficient amount of hydrogen reactant for maintaining the current in the PEMFC leads to an increase in the anode potential, and water is oxidized in the anode while oxygen is produced. An oxygen reduction reaction simultaneously occurs at the cathode, which leads to a bilateral selective pump where oxygen is pumped from the cathode to the anode and water diffuses from the anode to the cathode [99]. Mixing anode and cathode reactants in fuel cells causes explosions. Moreover, increasing the anode potential enhances carbon corrosion in the anode catalyst layer due to the presence of platinum. Several researchers have studied the degradation behavior in the anode during reactant starvation conditions [101–104]. They concluded that anode reactant starvation causes an increase in the anode potential and promotes carbon corrosion due to the presence of platinum in the anode catalyst layer. Thus, starvation of the reactant should be avoided in PEMFCs because an irreversible degradation of the membrane and explosion may occur, which would lead to a shorter life span and poor performance of PEMFCs.

As previously mentioned, liquid water in the channel causes reactant starvation. In the anode channel, water also accumulates due to the diffusion of water from the cathode to the anode and the humidified reactant. In practice, the access of water in the channel can be removed by supplying hydrogen at a higher stoichiometric flow rate than required [105]. However, this method leads to wasted hydrogen because the fuel utilization of fuel cells ranges from 80 to 90 % depending on the design [106]. Liang, Dou, Hou, Shen, Shao, and Yi [107] evaluated the effects of fuel cell stacks on different degrees of fuel starvation at the anode by varying the hydrogen stoichiometries from 1.1 to 0.2. They reported that as the hydrogen stoichiometry was reduced, the highest current distribution gradually shifted to the outlet of the channel. The results were reversed, where the current density should decreased from the inlet to the outlet as the hydrogen was consumed along the anode channel, under normal operating conditions of the fuel cell. When inadequate hydrogen was fed to the anode channel, a phenomenon known as the "vacuum effect" occurred, where hydrogen was drawn back from the exit manifold into the anode. Consequently,

Fig. 12 Three-dimensional flow fields: **a** distributor A (parallel flow field), **b** distributor B (parallel flow field), and **c** serpentine flow field [82]
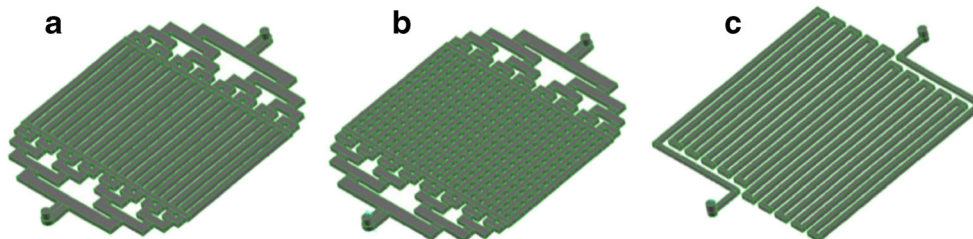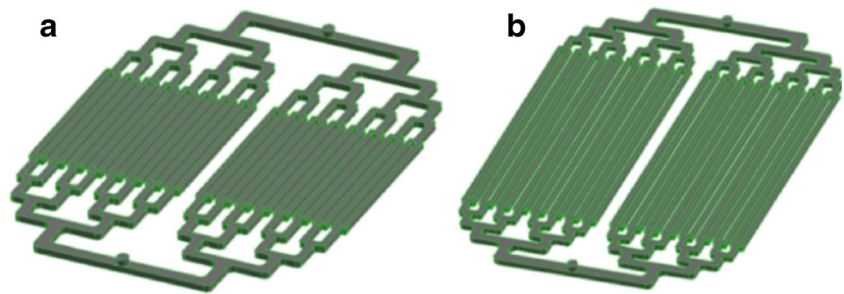
Fig. 13 Parallel flow fields: **a** distributor C and **b** distributor D [82]

reactant starvation occurred near the anode inlet and the highest current density was near the outlet.

Discussion

The reactant distribution in a PEMFC stack is crucial because it can lead to performance degradation and a decrease in the life span of the stack. It is well known that parallel flow fields have less flow resistance and smaller pressure drops, which lead to a non-uniform distribution of the reactant in the channel. Therefore, to fully enhance the simple flow field design, an inlet flow distributor [81] and a distributor D design [82] were added to the parallel flow field design to achieve a uniform reactant distribution. The distributor D design is not feasible for automotive applications due to the increased fuel cell dimensions. The bifurcated structure connected to the inlet includes an additional area compared to the inlet flow distributor. In addition, flow uniformity was enhanced by increasing the ratio of the pressure drop in the channel to the pressure drop in the manifold [108]. Therefore, an inlet flow distributor that increases the pressure drop in the channel would improve the flow uniformity and reduce flooding in the fuel cell.

Regarding the operating conditions, humidification of the reactant plays an important role in fuel cell performance. Either improper reactant humidification leads to a non-uniform reactant distribution due to channel flooding or to membrane hydration when there is insufficient water in the PEMFC. Hydrogen and air starvation in a PEMFC stack affect the performance and durability of the PEMFC. In anode starvation, insufficient of hydrogen supply to the PEMFC stack causes an explosion because the oxygen is drawn to the anode and mixes with the reactant in the fuel cell. Therefore, proper management of the operating conditions and the reactant supply would improve the performance and durability of PEMFC stacks.

### Effects of the manifolds on reactant distributions

The flow distributions in the manifold are another important component in determining the performance and durability of fuel cells. The manifold is the path that supplies the reactant from the source to each single cell of a fuel cell stack. As shown in Fig. 14, consecutive and bifurcation manifolds are two common manifolds used for flow distributions [109]. The bifurcation structure is commonly used in many industries because the flow rates in a bifurcation manifold do not change due to the distribution. The design of the bifurcation manifold is similar to a tree branch structure, where the diameter of the distribution gradually reduces to a final level. However, the consecutive structure is a much simpler design compared to the bifurcation structure because it distributes the flow equally to each parallel path, and a smaller pressure drop occurs in the design. However, severe non-uniform distribution of the reactant may occur if the flow resistance of each parallel path is not equal.

An experiment was conducted to study the uniformity of the reactant gas in each cell by constructing a four-cell stack with a cascade bifurcation and a Tee-channel manifold [110]. The experiment revealed that the cascade bifurcation manifold provided a nearly uniform distribution of the reactant to each single cell. However, the bifurcation manifold for the reactant gas distribution was externally constructed, thus increasing the dimensions of the fuel cell stack, which directly increases the manufacturing cost. Moreover, a fuel cell should have a compact design for portable and automotive applications.

Another experimental study investigated the non-uniform distribution of a fuel cell stack [111]. The number of feed channels was varied with two different types of cathode flow fields. It was reported that increasing the number of feed channels and the cross-sectional area of the manifold reduced the maldistribution. Chen, Jung, and Yen [112] also numerically analyzed the effects of the low distribution by varying the manifold width. In this study, the number of feed channels was maintained constant, and the air feeding rate was varied. The authors reported that an improved flow distribution was observed for the larger manifold. Consequently, the manifold width does affect the reactant distribution to each cell. However, Wang [113] investigated the influence of the flow and pressure manifold distribution in U-type fuel cell stacks. The friction and momentum of the fluid make up the static pressure that arises in the distribution manifold. The study concluded that the friction and momentum exert effects in opposite directions, and the balance of both could reduce the non-uniform distribution.
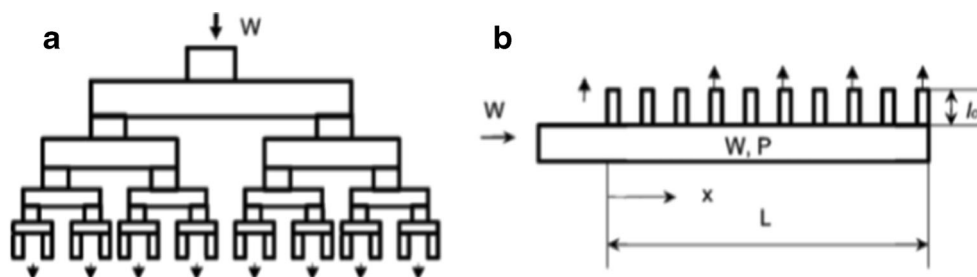
Discussion

A uniform reactant distribution in a manifold can be achieved by increasing the manifold dimensions and the number of feed cells. Increasing the manifold dimensions could reduce the pressure drop in fuel cells, thus inducing stable, high-operating performance in fuel cell stacks [112]. However, to enhance the uniform distribution in a cell, a higher flow resistance is needed between the manifold and the cell. Consequently, an ideal fuel cell stack design should include a higher pressure drop in the cell and a lower pressure drop in the manifold area.

Future research opportunities

Water management and reactant distributions are affected by the flow field design and by the operating and geometric parameters. Further research on PEMFC stacks for automotive applications is required to identify and develop the ideal design for PEMFC stacks. Current studies have focused on investigating the flow field, the geometric parameters, and the operating parameters. Fewer studies have investigated the effects of the manifold design. The manifold design plays an important role in the reactant distribution and the overall pressure drop in PEMFC stacks. Optimization of the manifold design is required to ensure a uniform distribution of the reactant during the first stage of distribution before entering the channel in the fuel cell. In addition, further research is required regarding parallel flow field designs, which is the simplest flow field design among the most common designs, such as serpentine and interdigitated flow field designs. However, parallel flow field designs receive less attention due to their non-uniform reactant distributions. Parallel flow field designs should be further studied due to their simple and compact design, which is more suitable for automotive applications. The fundamental understanding of liquid water behavior and reactant distribution in parallel flow fields is required to further optimize their design. The optimization of parallel flow fields would enhance their performance to ensure a uniform reactant supply and efficient water removal and to prevent reactant starvation, thus maintaining high fuel cell performance and durability.

Conclusions

This review reports that water management and the reactant distribution greatly affect the performance and life span of fuel cells. Flooding is a crucial phenomenon that occurs in fuel cells, which leads to a degradation in their performance and life span. Flooding occurs during the generation of high current density when water generation is high due to the electrochemical reaction. The generated water accumulates and blocks reactants from flowing into the channel, reducing the contact area of the reactant for diffusing into the catalyst layer for the electrochemical reaction. Thus, the proper selection of a flow field design could improve water management in fuel cells. Among the flow field design, serpentine and interdigitated flow fields exhibit the best liquid water removal rates compared to parallel flow fields. For interdigitated flow fields, the dead-end channel exerts strong force convection, which enhances the diffusion of the reactant into the catalyst layer and the removal of water from the gas diffusion layer. However, the membrane is not well hydrated due to the enhanced removal of water in gas diffusion layer and causing performance degradation. On the other hand, multiple channel serpentine flow fields with narrow channels and rib exhibit uniform membrane hydration and water distribution as compared to interdigitated flow fields. However, both flow fields required higher manufacturing cost and pumping power to supply the reactant. As for the simplest design parallel flow field which is lower in manufacturing cost, it was not commonly used in the industry due to its poor water removal and maldistribution. The performance of parallel flow field was enhanced by changing the design of the manifold, and inserting inlet resistance to the flow field design has improved the flow resistance and achieved a better performance that is comparable with serpentine flow field. Moreover, the performance of parallel flow field could exceed the interdigitated flow field by having a higher flow rate.

Uniform reactant distributions in fuel cells could yield better fuel cell performance because the lowest reactant supply cell determines the current limit. The manifold and the cell distribution play important roles for a uniform reactant distribution. During the non-uniform distribution of a reactant, starvation occurs in fuel cells, which leads to an increase in the fuel cell potential and promotes carbon corrosion and the loss

of the platinum catalyst layer. This causes the performance of the fuel cell to irreversibly decline and its life span to degrade. Consequently, starvation conditions should be avoided in fuel cells by ensuring optimal operating and geometric parameters to promote uniform water and reactant distributions. To reduce reactant starvation in a fuel cell stack, larger manifold widths can enhance the reactant distribution because a higher pressure drop in the channel and a lower pressure drop in the manifold improve reactant distributions among cells. Moreover, the reactant supply to the fuel cell shall not be fully humidified as it could provide excess water in fuel cell that enhanced flooding in channel.

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