

Bipolar Plates

A Heinzl, F Mahlendorf, and C Jansen, University of Duisburg–Essen, Duisburg, Germany

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Introduction

Proton-exchange membrane fuel cells (PEMFCs) are energy converters suitable for various applications with differing requirements. Hence, the material combinations to be used in PEMFCs may also differ. The requirements for bipolar plates are as follows:

- good electrical conductivity ($>100 \text{ S cm}^{-1}$ bulk conductivity),
- high thermal conductivity ($>20 \text{ W cm}^{-1}$),
- high chemical and corrosion resistance,
- mechanical stability toward compression forces,
- low permeability for hydrogen,
- low-cost material being processable with mass production techniques,
- low weight and volume, and
- recyclable materials.

Two different kinds of materials have been used in the past: metallic and graphitic. For mobile applications of fuel cells, the requirement of high power densities at very low cost is difficult to fulfill, though the lifetime in terms of operational hours is limited to several thousands. Here, stainless steel seems to be the material of choice – the material already being a mass product, its forming processes are well established in the automotive industry. Thin metal sheets show sufficient mechanical strength. Two sheets of thin and structured metal plates can be combined into a bipolar plate with flow fields on both sides and cooling channels in between. For improving lifetime, a corrosion-protective coating is typically required.

For stationary applications, lifetime expectations are usually much higher; 40 000–80 000 h would be advantageous for residential power supply systems. Therefore, graphitic materials are preferred as bipolar plate materials for this purpose. Graphite itself is not sufficiently gas-tight to separate hydrogen and air from the cooling channels. Various methods to improve the properties of graphite have been investigated in the past: impregnation of graphite plates with a resin or composite materials with polymer binders. Here, forming processes have to be developed or at least adapted to the new material combinations. Both compression molding and injection molding have been investigated.

Flow field design is, to some extent, dependent on the materials used. But it is mainly influenced by the requirements of gas distribution and water management in the plane of larger electrode areas, low pressure drop mainly at the air electrode, and good electrical contact

over the cell. Particularly, multiple serpentine flow fields have been realized, which withstand a certain pressure drop and favor removal of condensing water droplets.

Metallic Bipolar Plate Materials

The first applications of PEMFCs were of high cost. One example is fuel cell submarines. Here, expensive, corrosion-resistant metals were used as bipolar plate materials. But for mobile applications, even stainless steels are a cost factor. Therefore, substrates and coatings have been investigated in order to find the optimal material combinations. But this work mainly remained unpublished, as it often is proprietary company know-how.

Corrosion also occurs the anode as it does on the cathode side of a PEMFC. Air and positive potentials at the cathode usually lead to the growth of metal oxide layers, causing an increase in the electrical resistance. The reducing environment at the anode of the fuel cell leads to a reduction of the oxide protective layer of metallic materials, hydride formation, and dissolution of the metal in product water or humid hydrogen feed gas as a consequence. The release of metal ions, therefore, can contaminate the polymer electrolyte membrane and reduce the activity of the electrode catalysts.

Bipolar plates made of stainless steel, titanium, aluminum, and several metal alloys have been subjected to different coatings to improve their corrosion resistance. Two classes of coatings can be distinguished: carbon-based and metal-based. Carbon-based coatings mainly comprise conducting polymers, e.g., polyaniline, polypyrrole, and diamond-like carbon. Metal-based coatings include noble metals, metal nitrides, and early transition metal elements such as molybdenum, vanadium, and niobium that form a thin oxide layer that passivates the underlying metal layer against corrosion.

The development of low-cost coatings for stainless steel has received most attention. Good corrosion resistance and low interfacial contact resistance have been reported for different nitrided and transition metal alloy-coated stainless-steel samples. Titanium is considered to be rather expensive, especially for automotive applications. Aluminum, on the contrary, requires a perfect coating; otherwise, galvanic pitting corrosion occurs.

The production process of bipolar plates out of steel is a forming method like stamping or hydroforming. Both processes are well known, but flow field geometries require a rather high aspect ratio (depth in relation to the

width of the gas channel) and quite fine structures in the millimeter range. These requirements pose some challenges to the forming process and to the coating process for corrosion-protective coating as well. Either the coating is applied prior to the forming process, in which case it has to withstand the occurring mechanical stress, or the coating is applied to the fine gas channel structures, covering vertical walls and the bottom of each channel. In both cases, the formation of microcracks in the coating layer has to be avoided.

A promising alternative to channel-type flow fields is the use of open-pore metal foams for distribution of the gaseous reactants and for water removal. Foams made of nickel, nickel–chromium, and stainless steel have been investigated. Size, shape, and distribution of the pores in the metal foam have to be tailored for each application. The published data often show improved initial cell performance when compared to conventional channel design flow fields. But with materials like nickel, a fast contamination of the polymer electrolyte membrane by metal ions has been observed. Finally, metal foams, for their successful application in PEMFCs, again require corrosion-protective coatings.

In conclusion, coated metal bipolar plates seem to have achieved corrosion stability for the relatively short operation times of automotive applications. Several car manufacturers are currently using metallic bipolar plates in their automotive PEMFC stacks.

Graphitic Bipolar Plate Materials

Much more emphasis has been placed on the development of graphitic materials for bipolar plates. Graphite was already known for its application in phosphoric acid fuel cell to be a suitable material. Pure graphite-based bipolar plates offer the advantages of excellent chemical resistance and good thermal and electrical conductivity combined with a lower density than metal plates. However, machining the flow fields into pure graphite plates is a complicated and time-consuming step that leads to high prices. Moreover, graphite plates are brittle and porous; they have to be coated to be made impermeable to the fuel and oxygen. Hence, graphite-based bipolar plates are nonviable candidates as low-cost PEMFC components.

Graphite composite materials with polymer binders are more suited to achieve the desired properties and to improve manufacturing technologies for bipolar plates including the flow fields and cooling channels. These composite materials are made of commercially available polymers as binders and a high loading of conductive carbon compounds (e.g., natural or synthetic graphite powder, carbon blacks, and carbon nanotubes), which increases the conductivity. The polymers are

either thermoplastics such as polyvinylidene fluoride, polyethylene, polypropylene, liquid crystal polymers, and polyphenylene sulfide, or thermosets, such as vinyl ester, phenolic resins, and epoxy resins.

The conducting particles form a percolation network within the polymer matrix. Owing to the polymer matrix, the composite material, at least partly, retains the processability of the polymer. To obtain a mechanically stable bipolar plate with low gas permeability, a good quality of dispersion of the conductive component particles within the polymer binder is required. This process can take place in a discontinuous way using a kneader or continuously using an extruder, although the most homogeneous material can be obtained using a twin screw extruder. The extruder generally is equipped with at least two gravimetric metering units for adding the polymer and the premixed filling materials. Mechanical properties of the composite material (e.g., tensile strength and flexural strength) are usually improved by the addition of graphite fibers.

The composite material granules that are obtained from the extruder can be used to manufacture bipolar plates complete with flow field structures by conventional production methods, such as compression molding or injection molding. For small and intermediate series of bipolar plates, compression molding still seems to be the most widely adopted production technology. Injection molding, on the contrary, is a true mass production technique for large series (>50 000) of bipolar plates (Figure 1). Injection molding of highly filled graphite composite materials is much more demanding than that of conventional plastics, as these materials exhibit high viscosity and high flow resistance. Injection pressure, injection velocity, and nozzle temperature have to be adapted to the specific composite material. Injection molding of bipolar plates, mostly with thermoplastic resins, has been demonstrated by a few companies and research institutes worldwide.

Injection molding of thermosets and thermoplastics is quite different. For thermoplastics, the composites are heated up beyond the melting point and the plasticized mixture is then injected into the mold, which is kept at a lower temperature. In the case of thermosets, the compounded composite mixture is injection molded at temperatures significantly below the melting point of the thermoset resin. Thermoset-bonded graphite composites are generally more complicated to process, as they have to be post-cured after injection molding in order to achieve sufficient stability. Following the injection molding of thermosets and thermoplastics, a thin polymer-rich skin layer has to be removed from the surface of the bipolar plates by processes like abrasive blasting in order to reduce the contact resistance to the gas diffusion layer (GDL). Cycle times below 20 s for the production of a single plate have been reported for

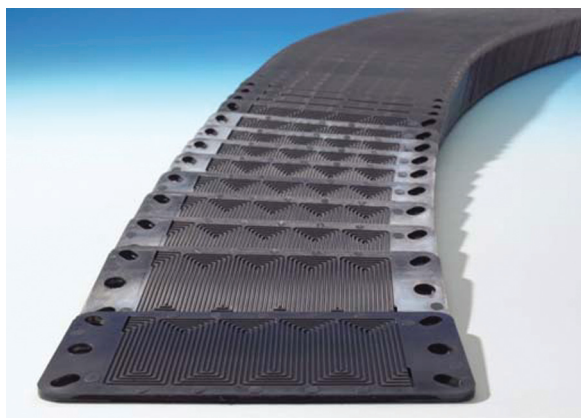


Figure 1 Injection molded bipolar plates made of graphite composite material (ZBT, Duisburg, Germany).

thermoplastic-bonded graphite composites. Given a cycle time of 20 s, the maximum annual capacity of one injection molding machine is significantly above 1 000 000 plates. High production volumes of a specific type of bipolar plate would lead to its low production cost.

An innovative approach to improve PEMFC water management is the use of porous bipolar plates, typically made of graphite composite materials. The pores of these water transport plates (WTPs) (as used, e.g., by UTC Power) are filled with liquid water, which communicates directly with the coolant stream. Water transport plates provide a way for removing liquid product water, which is produced in the cell reaction, so that it does not accumulate in the GDLs or block the gas channels. On the contrary, when the reactant gases are not properly humidified, the water transport plates allow water to evaporate into the gas channels in order to humidify them. The water removal property of the porous plates is determined by their porosity and wettability. However, the coolant stream has to be kept at a pressure lower than that of the reactant gases in order to provide a driving force for the product water removal.

Another promising candidate as the bipolar plate material is graphite foil. It is obtained from high-purity natural graphite flakes, which are processed into a continuous foil by acid and thermal treatment to produce expanded graphite crystals. These crystals are then formed into a foil through an extensive calendaring process without any resins or binders. Graphite foil shows good electric conductivity and high chemical resistance, but in order to be used for fuel cell applications, their gas tightness has to be improved, e.g., by impregnation with a resin. An important characteristic of graphite foil is its compressibility. Flow fields are incorporated into the foil by embossing.

Chemical stability is an important issue related to materials leaching out of the bipolar plate during long-term operation of the fuel cell. The quality and purity of

the conductive carbon materials as well as of the polymer resins determine their suitability for PEMFCs.

For stationary PEMFC applications, bipolar plates made of graphite composite materials are the only alternative, showing good long-term stability. As an aging mechanism, carbon oxidation at the positive potential at the air side of the fuel cell is known. The hardest operation condition is ‘standby’ at open-circuit voltage rendering the highest positive potential at the air electrode.

As PEMFCs can also use methanol as fuel (direct methanol fuel cell), material development must also consider leaching out of poisonous compounds in contact with methanol. Another challenge is the use of new membrane materials for operation at elevated temperature; membranes that withstand temperatures up to 180 °C are under development. Carbon corrosion will be accelerated under these operating conditions. This applies to the bipolar plate as well as to GDL and catalyst carrier materials, which usually consist of carbon.

Comparison of Metallic and Graphitic Bipolar Plates

As the electrical resistance of a bipolar plate may not contribute significantly to the total resistance of a fuel cell, this issue was investigated carefully. In the case of graphite composite materials, usually 80 wt% of carbon materials are mixed with 20 wt% of polymer binder to achieve conductivities between 50 and 100 S cm⁻¹. But the composition of the materials is not the only issue. In order to realize a cooling for the fuel cell, a channel structure for air or water coolants has to be realized. Typically, two bipolar half plates are manufactured with a cooling channel structure on the back side. These two half plates are pressed together, which leads to a significant inner contact resistance. The same construction principles are used for metallic bipolar plates, but in this case, laser welding or other joining techniques leading to low contact resistances are available.

Another cause for enhancement in resistivity is the reduction of contact area by the flow field design. The ribs of the flow field are in electrical contact with the adjacent GDLs, but the bottom of a channel is not. Last but not least, there is a contact resistance between the bipolar plate material and the GDL material, as for both graphite composite and metallic bipolar plates. Thus true resistance measurements must take all these influences into account, and the sum of all these resistances still has to be low compared to the ionic resistance of the membrane. Nevertheless, several groups have successfully developed materials and even manufacturing processes conforming to these requirements.

Weight and volume of PEMFC stacks are dominated by the bipolar plates, which account for almost 80% of

the stack weight. Metal sheets as thin as 200 μm have a sufficient mechanical stability; metallic bipolar plates can therefore be more or less as thin as twice the gas channel depth, thus facilitating the construction of compact and light-weight PEMFC stacks. Bipolar plates of graphite composites offer improved corrosion resistance and low-cost materials and manufacturing technologies. These are preferred for stationary and residential PEMFC applications where space and weight restrictions are less severe, but durability requirements are high.

Flow Field Design

For accurate flow field design, the fuel and oxidant composition and stoichiometry as well as typical operation conditions are essential. The task is to overcome diffusion limitations of fuel and oxidant and an excess or lack of humidity. As it is impossible to achieve completely homogeneous conditions over the entire active electrode area with respect to temperature, reactant concentrations, and humidity, always a compromise has to be made. Along a flow field channel from inlet to outlet, the duct gases (e.g., hydrogen and oxygen) are depleting due to the electrochemical reaction. Water is formed as a reaction product, and the amount of liquid and gaseous water is determined by the concentration and temperature distribution inside the cell (and the relative humidity of the gases). In addition, the membranes in PEMFCs show material-specific values for water transport owing to the electro-osmotic effect and diffusion, determining the product water distribution at the anode and cathode side of the fuel cell, and thus also setting the requirements for humidification of inlet gases. The electrochemical reaction itself is concentration dependent; thus high current densities occur at the inlet and lower values are observed toward the outlet of the gases. Therefore, inlet and outlet of fuel and oxidant usually are not on the same side of the cell. It is obvious that in addition to the flow field design, the choice of co-flow, counter-flow, or cross-flow conditions determines the performance of the cell.

There are, in principle, four different types of flow fields that have been investigated in the past:

- pin-type flow field,
- parallel channels flow field,
- serpentine flow field, and
- interdigitated flow field.

The pin-type flow field consists of an array of columnar pins arranged in a regular pattern, as shown schematically in **Figure 2**. The shape of the individual pins is generally cubical or circular. As the reactant gases flow through a network of series and parallel flow paths, only low pressure drops occur. Preferred flow path

according to the principle of least resistance can, however, lead to inhomogeneous reactant distribution and locally insufficient product water removal. The result of a typical simulation is shown in **Figure 3**; especially at the air side, inhomogeneous oxygen supply is evident from an exemplary simulation. For air stoichiometry, flow field geometry, and GDL porosity, typical values are assumed. This type of flow field is quite suitable for high reactant flows with low utilization levels of fuel and oxygen.

The parallel channels type of flow field, as shown in **Figure 4**, is typically used when no accumulation of water droplets is expected. If droplets form, they may block one or more of the parallel channels, while the remaining gas stream flows through the least blocked channels. This is possible due to the low pressure drop of multiple parallel channels. If fuel and oxidant are supplied in excess of what is stoichiometrically used by the electrochemical reaction, parallel flow fields are

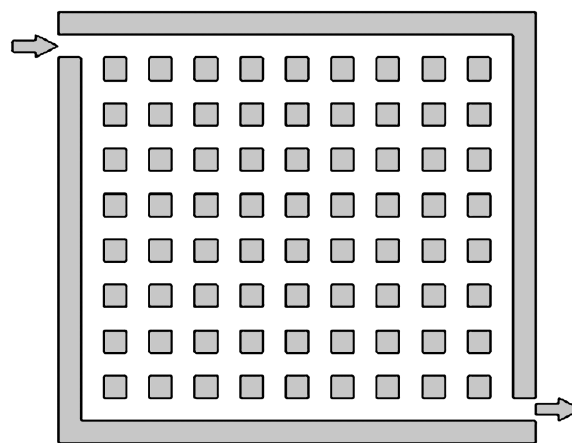


Figure 2 Schematic drawing of a pin-type flow field.

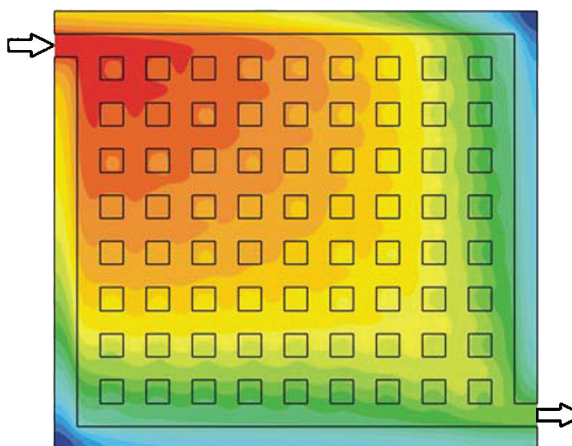


Figure 3 Oxygen concentration in the cathode gas diffusion layer (GDL) of a pin-type flow field (schematic). Red: high oxygen concentration; blue: low oxygen concentration.

applicable. The simulation results for parallel channels type flow field are depicted in **Figure 5**.

The danger of droplet accumulation can also be reduced to a large extent by recirculating part of the gases and condensing excess product water outside of the fuel cell stack. The same argument holds for pin-type flow fields.

As the pressure drop in the multiple parallel channels of each cell is small, attention has to be paid to the pressure drop in the gas distribution manifold of the stack. If it is larger than the single-cell pressure drop, this will lead to uneven reactant gas supply to the individual cells of a stack, favoring the cells that are close to the manifold inlet.

The interdigitated flow field consists of multiple dead-ended flow channels, as depicted schematically in **Figure 6**. Its main characteristic is a forced gas flow through the adjacent diffusion layer, which means active

transport of reactants in close vicinity to the electrode. If products are accumulating in the GDL, the forced flow represents a significant advantage, as can be seen from the simulation results depicted in **Figure 7**. A quite homogeneous oxygen concentration close to the electrode can be achieved. But pressure drop in this flow field is dependent on the properties – mainly porosity and hydrophobicity – of the GDL. As these properties are known to be subject to aging processes, this type of flow field is not very common.

Most fuel cell developers use any type of serpentine flow field (**Figure 8**), a compromise between pressure drop requirements and water removal aspects. In a single serpentine, oxygen depletes with the length of path (**Figure 9**), leading to a decrease in current density along the channel. Real flow fields, therefore, include multiple serpentine channels and, in addition, inlet and outlet parts of the channels can be placed close together, e.g.,

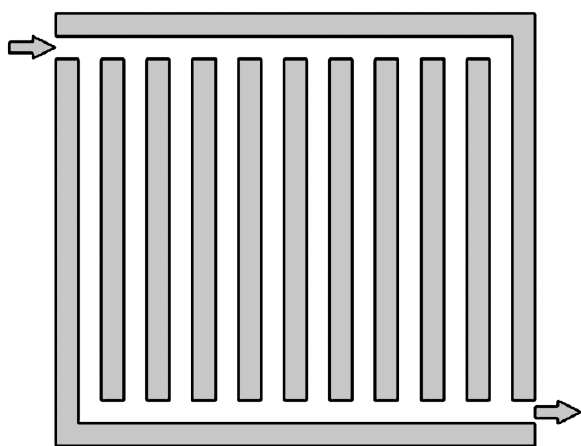


Figure 4 Schematic drawing of a parallel channels flow field.

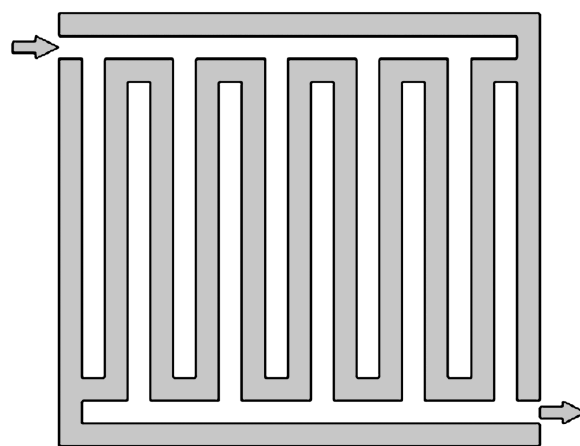


Figure 6 Schematic drawing of an interdigitated flow field.

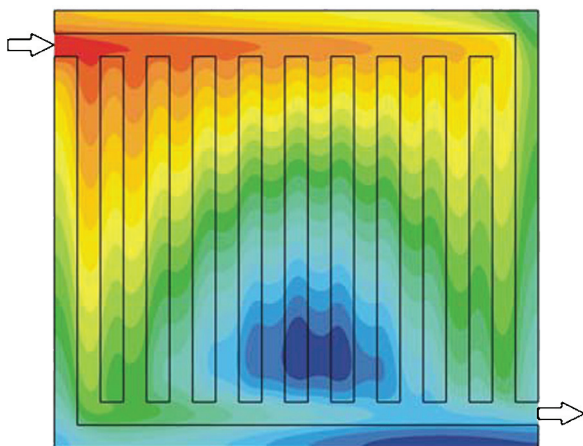


Figure 5 Oxygen concentration in the cathode gas diffusion layer (GDL) of a parallel channels flow field (schematic). Red: high oxygen concentration; blue: low oxygen concentration.

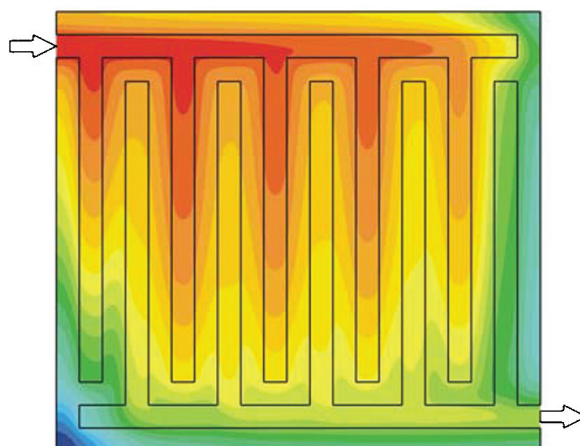


Figure 7 Oxygen concentration in the cathode gas diffusion layer (GDL) of an interdigitated flow field (schematic). Red: high oxygen concentration; blue: low oxygen concentration.

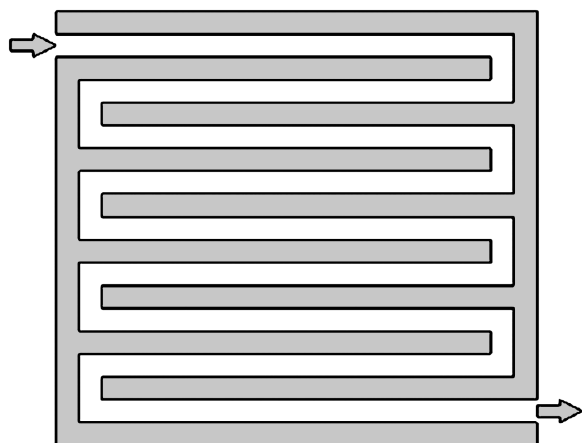


Figure 8 Schematic drawing of a single serpentine flow field.

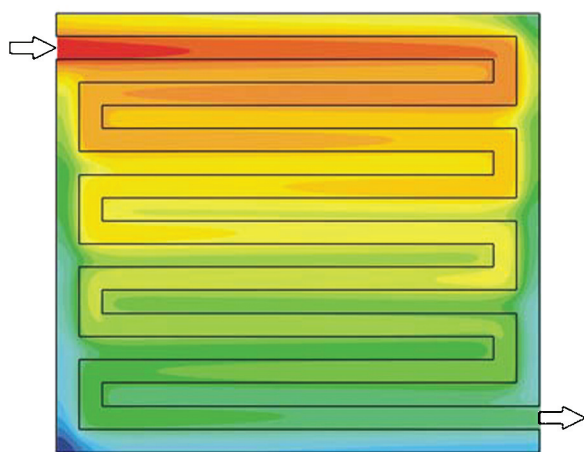
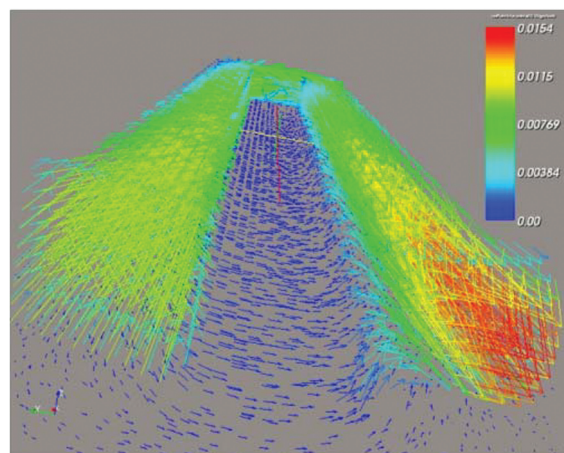


Figure 9 Oxygen concentration in the cathode gas diffusion layer (GDL) of a serpentine channel flow field (schematic). Red: high oxygen concentration; blue: low oxygen concentration.

leading to sites of high hydrogen concentration and low humidity (hydrogen inlet) and low hydrogen concentration and high humidity (hydrogen outlet) being close together. Thus, a certain equalization of conditions and performance is possible.

In all types of flow fields, hydrogen diffusion processes in the GDL and transport of water in the plane of the membrane are the main positive effects. The depletion of reactants and the formation of water and hence the humidity and water uptake of the membrane have been the subject of numerous simulation efforts, as the performance of fuel cells is strongly dependent on these profiles. Simulation has to consider the channel dimensions, pressure and flow profiles at edges and bends, as well as diffusion from channel to channel through the GDL.

Figure 10 shows the simulation results for gas flow through a bipolar plate channel with adjacent GDL. The cross flow through the GDL depends, to a large extent on the porosity and the thickness of the GDL.



Velocity magnitude

Figure 10 Simulation results of reactant gas flow through a channel with adjacent gas diffusion layer (GDL). The arrows depict the flow velocity through the channel and the cross-flow through the GDL.

Nomenclature

Abbreviations and Acronyms

GDL	gas diffusion layer
PEMFC	proton exchange membrane fuel cell
WTP	water transport plate

See also: **Fuel Cells – Overview: Modeling; Fuel Cells – Proton-Exchange Membrane Fuel Cells: Cells; Membranes; Gas Diffusion Layers; Overview Performance and Operational Conditions; Membrane–Electrode Assemblies; Modeling; Stacks.**

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