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A Numerical Study and Design of Multiple Jet Impingement in a PEMFC

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ABSTRACT

Impinging jets are widely used in applications where high rates of heat and mass transfer are required. Similarly, an efficient operation of the Proton Exchange Membrane Fuel Cell (PEMFC) relies on high heat and mass transfer rates to and from the catalyst layers on the anode and cathode side, which raises the question of whether jet impingement could be employed for a PEMFC as well. To answer this question, a laminar non-isothermal gas-phase model for a PEMFC equipped with a porous flow field is solved numerically for five different cases: (i) single jet (cathode); (ii) double jet (cathode); (iii) triple jet (cathode); (iv) single jets (anode, cathode); (v) ordinary flow without jets. It is found that the jets reduce the size of the concentration boundary layers in the net at the flow field/gas diffusion layer interface (GDL), but do not penetrate significantly into the GDL for low permeabilies of around 10^{-12} m^2. For macroporous layers with permeabilities of around 10^{-9} m^2, the jets are able to penetrate deeply. For multiple jets, the risk of entrainment with oxygen depletion between jets is demonstrated, with a resulting loss in cell performance. Overall, this initial study indicates that jets can enhance cell performance, but care must be taken so as to avoid entrainment effects when employing multiple jets in a PEMFC.

Keywords: PEMFC, laminar, jet impingement, design, mathematical modelling, simulation, CFD.

INTRODUCTION

The operation close to or at optimal conditions of a Proton Exchange Membrane Fuel Cell (PEMFC) requires careful control and management of the thermal and water envelope, as well as ensuring sufficiently high stoichiometric flow rates. Generally, the latter is provided by thin flow channels machined into the bipolar plate in various shapes such as serpentine, parallel, interdigitated or combinations of these [1]. One alternative to these traditional flow fields might be found in the technique of impinging jets, commonly employed in traditional engineering applications such as drying of paper and cooling of turbine blades. Impinging jets can be applied either in the form of single jets (circular or rectangular), as illustrated in Figure 1, or in the form of arrays [2, 3]. As a single jet impinges on the surface beneath it, the thickness of the hydrodynamic, thermal and concentration boundary layers are reduced within the impingement region. For multiple jets, further regions of fountain upwash flow formations [4] and entrainment can arise, depending on various conditions such as impinging jet velocity, spacing between jets and distance between jet inlet and impinging surface.

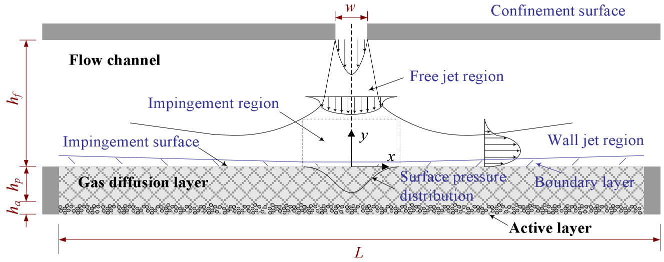

Figure 1. Schematic of single jet impinging on the GDL at the cathode of a PEMFC.

The main advantage with impinging jets can be found in their high heat and mass transfer rates, which we hypothesize, would be beneficial to the PEMFC cell performance as well if properly implemented. To ascertain the feasibility of incorporating jet impingement in a PEMFC, a numerical study is carried out for laminar single and multiple jets on the cathode and anode side. A single jet might suffice for small fuel cells, but larger ones would require multiple jets as the enhancement effect is localized. Furthermore, the surface the jet impinges on in a PEMFC is the gas diffusion layer, which is porous and not solid as in most applications with jet impingement. The jet might therefore (depending on the permeability) be able to penetrate into the GDL and thus enhance the gas transport within; one good candidate could be a macro-porous GDL [5].

For this study, a highly permeable porous flow field (net) is chosen [6, 7], which allows a reduction in dimensionality from three to two dimensions. While the net suppresses the jet to a certain extent due to its porous nature, it allows for charge and enhanced heat transfer to the current collector. Jeng and Tzeng [8] and Fu and Huang [9] have studied laminar jet impingement in a porous medium and found enhanced convective heat transfer, which we expect for jets applied to the PEMFC as well.

A laminar one-domain non-isothermal gas-phase model [10,11] that takes conservation of momentum, mass, species, energy and charge into account, as well as a phenomenological membrane model, is solved for five different cases (see Figure 2), *viz.* (i) single jet (cathode); (ii) double jet (cathode); (iii) triple jet (cathode); (iv) single jets (anode, cathode); (v) ordinary flow without jets. The latter provides a benchmark for a standard flow from the left to the right in the flow field, as shown in Figure 2e. The different configurations are then discussed and conclusions drawn.

MATHEMATICAL FORMULATION

A one-domain mathematical formulation comprising conservation of momentum, mass, species, energy and charge in all the layers of the PEMFC, i.e. flow field (porous net), GDLs, active layers, and membrane, is employed. For a typical PEMFC, the small length scales combined with average gas velocities of around 1 ms^{-1} (depending on stoichiometry) give rise to laminar flow conditions. While higher velocities would result in higher stoichiometry and generally improve cell performance, such high velocities would come at the cost of an increase in power requirements for the fans to maintain the flow (parasitic load). We will therefore vary the inlet velocity between 0.1 and 2 ms^{-1} in this study. The inlet gas flow comprises oxygen, nitrogen and water on the cathode side and hydrogen and water on the anode side.

$h_{f,p,}$	1.0×10^{-3} [5], 3.0×10^{-4} m [5]
$h_{a,m}$	1.0×10^{-5} [4], 1.8×10^{-5} m [4]
L	2.0×10^{-2} m
κ_f, κ_p	8×10^{-8} m^2, 1.0×10^{-12} m^2 [5]
$\varepsilon_{f,p,a,m}$	0.99, 0.6, 0.4, 0.28
D_{H2}	1.1028×10^{-4} m^2 s^{-1} [4,]
D_{O2}	3.2348×10^{-5} m^2 s^{-1} [4]
D_{H2O}	7.35×10^{-5} m^2 s^{-1} [4]
T_{in}, T_{cool}	80°C, 80°C
$J_a^{ref,0}$	1.0×10^{9} A m^{-3} [4]
$J_c^{ref,0}$	2.0×10^{4} A m^{-3} [4]
α_a, α_c	1, 1 [4]
γ_a, γ_c	0.5, 1 [4]
$C_{O2,ref}$, $C_{H2,ref}$	40.88 mol m^{-3} [4]
p_{op}	1 bar
$RH_{a,c}$	100%, 100%
R	8.314 J mol^{-1} K^{-1}
F	96487 A s mol^{-1}
$U_{in,cath}$	2.0, 1.0, 0.5, 0.1 m s^{-1}
$U_{in,anod}$	1.0 m s^{-1}
w_{jet}	1.0 x 10^{-3} m
E_{cell}	0.6 V

Table I. Main physical parameters and operating conditions.

The computational domains for the various jet impingement configurations are depicted in Figure 2. Note that the flow fields on both anode and cathode side are porous. The inlet width of each jet is taken to be 1.0×10^{-3} m.

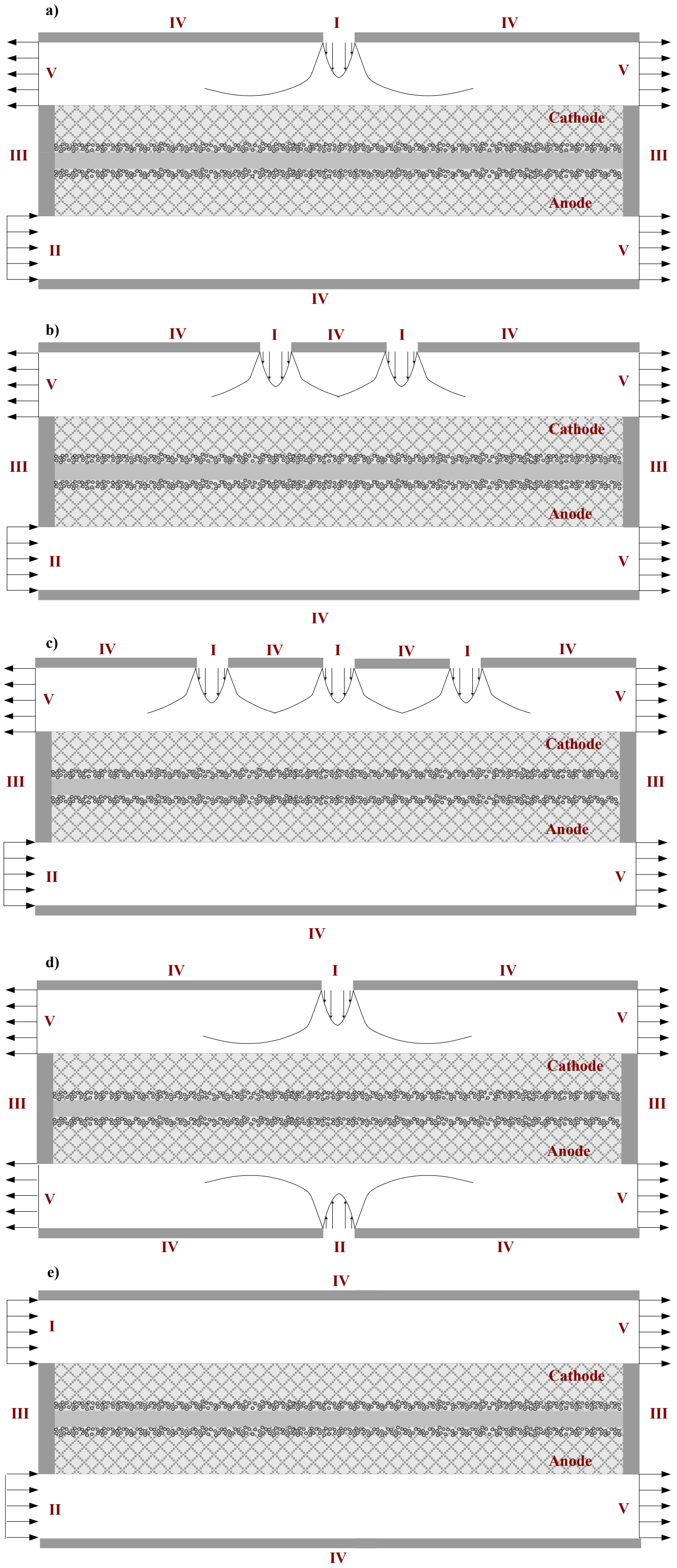

Figure 2. Computational domains for a) single jet; b) double jet; c) triple jet; d) jet at both cathode and anode; e) ordinary flow. The boundaries are marked with roman numerals: I cathode inlet; II anode inlet; III adiabatic wall; IV net/cooling plate; V outlet.

Furthermore, typical operating conditions are considered with 100% relative humidity on both anode and cathode side, at a temperature of 80°C. The remaining physical parameters and conditions can be found in Table I.

We do not present the mathematical formulation here for the sake of brevity, but refer to Wang and Wang [10] and Ju *et al*. [11] for more details. The latter also provides a detailed description of the validation of the model with experimental data for the case of traditional flow fields in the PEMFC.

NUMERICAL METHOD

The commercial finite element solver, COMSOL Multiphysics 3.4 (see [12] for details), was chosen to implement the mathematical model due to its versatility in handling general non-linear coupled partial differential equations. The various computational domains, as depicted in Figure 2, were resolved with around 1×10^4 - 2×10^4 elements for mesh independent solutions (accuracy of around 10^{-4}), and solved for with the segregated option and the Pardiso algorithm [12]. A typical run on a workstation with two dual core 3 GHz CPUs with 16 GB RAM required around 12 minutes.

RESULTS AND DISCUSSION

For each configuration, simulations were carried out for varying inlet velocities of the cathode jet(s) to study their impact on fuel cell performance.

The effect of the jets is clearly visible in Figure 3, which shows the velocity streamlines and temperature distribution ($T(x,y)$-T_{cool}) at the cathode side. Here, several features are apparent; foremost is that the jet does not penetrate into the GDL due to the low permeability (10^{-12} m^2). At higher permeabilities, e.g. for a macroporous gas diffusion layer with a permeability of 10^{-9} m^2 [5], the jet can be seen to penetrate into the porous layer (not shown here). In addition, the single and double jets impinge on the GDL, whereas only the middle jet in the triple configuration reaches all the way to the GDL. The temperature distribution is similar for all configurations with at most a temperature difference of around 1°C at the membrane between the cases, except for the double jet. For the latter, see Figure 3b, there is a zone between the jets where the temperature is lower and air is captured in two vortices (not shown). This gives rise to a depletion of oxygen, as can be inferred from Figure 4b, which is mirrored by a lower local current density (see Figure 5b) and hence less heat production. Clearly, this kind of entrainment can be detrimental to fuel cell performance, and should therefore be avoided/minimized when introducing multiple jets. The magnitude of the entrainment can be expected to depend on several factors, such as distance between jets, distance to impinging surface and jet velocities.

We further expect the jets to reduce the thickness of the boundary layers at the impinging surface; this is indeed the case as can be seen from Figure 4. In the impingement region for the single jet (Figure 4a, d), the boundary layer for the oxygen molar fraction is thin and grows as we move downstream of the jet on both sides. The same behaviour can be observed for the double and triple jet. In addition, for the double jet, there is a region of significant depletion of oxygen between the two jets. For the case of a single jet on the cathode or on both anode and cathode, the temperature (Figure 3a, d), oxygen concentration (Figure 4a, d) and current density (Figure 5a, d) distributions are very similar, indicating that a jet on the anode side has little to no effect for the operating conditions in this study.

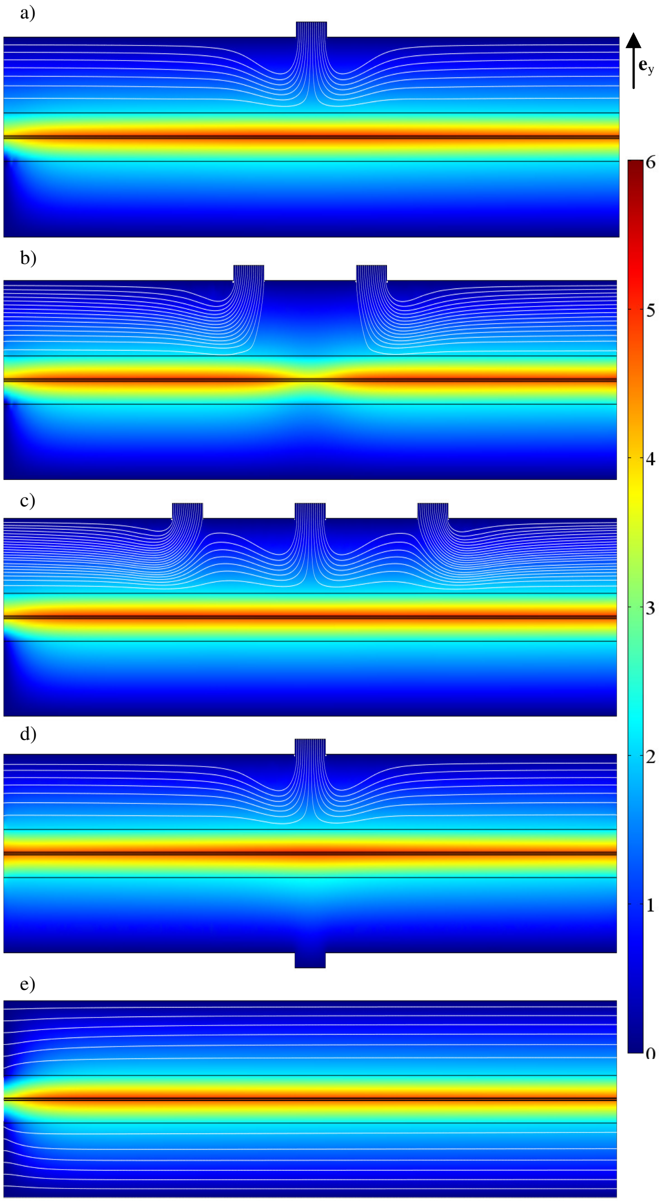

Figure 3. Velocity streamlines and temperature distributions (°C) above the cooling temperature (80°C) for 2 m/s inlet velocity at each cathode jet: (a) single jet; (b) double jet; (c) triple jet; (d) single jets; (e) ordinary flow without jets. (*N.B.* the geometry has been extended in the y-direction.)

In general, the anode side is not the limiting half-cell due to its fast reaction kinetics compared to the cathode. It might therefore not be advantageous to introduce jets at the anode side, as this also leads to a more complex design of the gas manifolds. Having jets on the cathode side, however, can be seen to enhance the mass transport of oxygen, which is mirrored by a more even current density distribution (Figure 5a, c) as compared to the ordinary flow case (Figure 5e).

The impact of the jets propagates all the way to the active layer as presented in Figure 5, which illustrates the normalized current density distribution at the cathode active layer/ membrane interface. We consider the normalized quantity here, i.e. current density divided by the average current density, as the inlet velocities, rather than the stoichoimetry for the various flow configurations were kept constant. For the ordinary flow without jets, see Figure 5e, the local current density is at its highest at the inlets to the left, after which it drops monotonically.

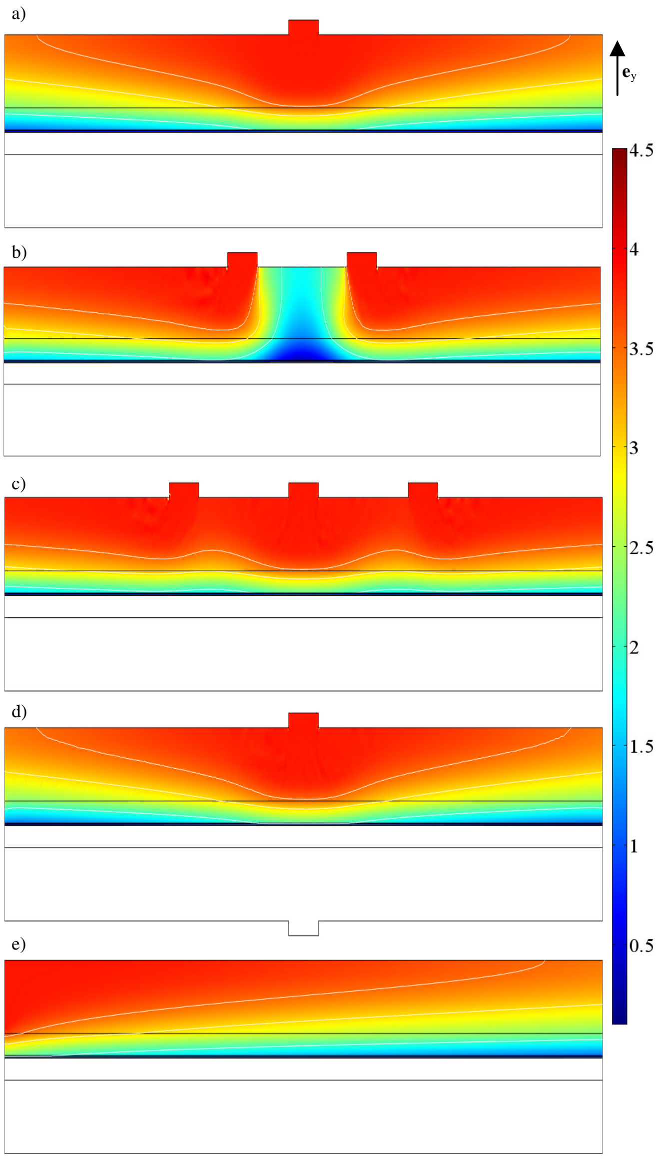

Figure 4. Molar concentration (mol m^{-3}) of oxygen in the cathode (2 ms^{-1} inlet velocity at each cathode jet): (a) single jet; (b) double jet; (c) triple jet; (d) single jets; (e) ordinary flow without jets. The contours correspond to 3.5, 3, 2 mol m^{-3}. (*N.B.* the geometry has been extended in the y-direction.)

For the single jet (Figure 5a, d), a maximum in current density occurs beneath the jet itself and can be seen to drop downstream in both directions of the jet. The enhancement brought about by the impinging jet is therefore limited to the vicinity of the jet and drops downstream. For the double jet, as already mentioned, the entrainment has a detrimental effect on the cell performance, with the local current density dropping to around 70% of its average value between the two jets. The triple jet sees the highest current underneath the middle jet, then drops and increases again under the two adjacent jets. This, in turn, would suggest that careful placement of the jet inlets could be employed to provide a more even current density distribution throughout the cell.

CONCLUSIONS

An initial study of the behavior of a single or multiple jets in a PEMFC has been carried out with a one-domain mathematical model. From the results, the following can be concluded:

- The jets reduce the boundary layers in the flow field, in this case a porous net, when the jet impinges on the GDL, giving rise to an increase heat and mass transfer.
- The enhancement is localized to the jet, and it diminishes downstream of the jet.
- Multiple jets can cause entrainment, which in turn leads to a local drop in current density and an overall loss of cell performance.
- When employed carefully, multiple jets could provide an even current density distribution.

Several factors that affect the jet impingement will be studied in future work, such as distance between jets, and spacing between jet inlet and GDL. In the end, whether multiple impinging jets are feasible from a cell performance as well as cost point of view, will require an optimization of several parameters, one of which is the added complexity/cost of the gas manifolds.

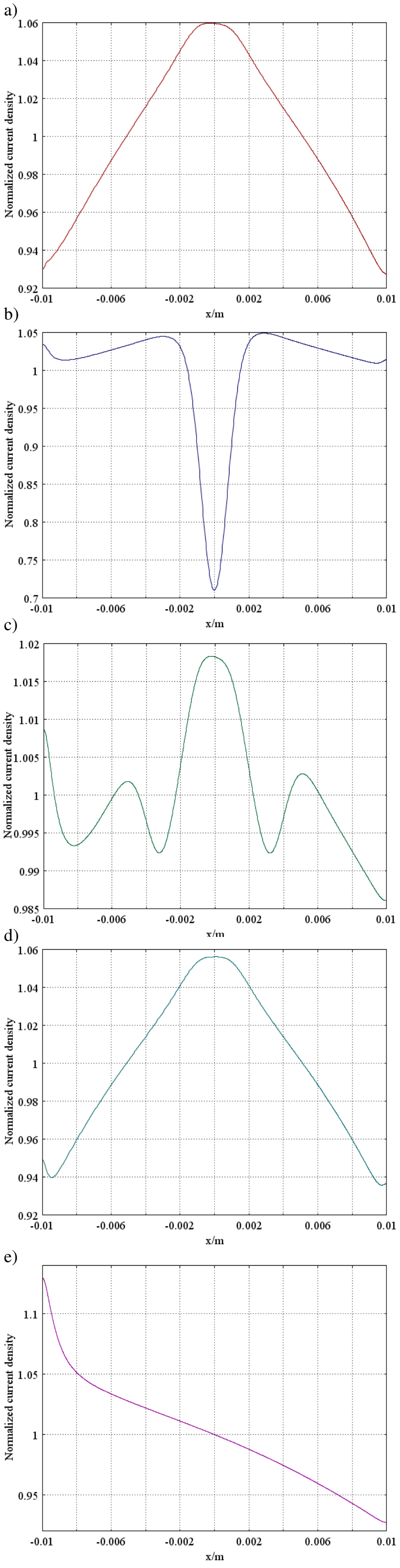

Figure 5 to the left. Normalized current density along the cathode active layer/membrane interface (1 m/s inlet velocity at each cathode jet): (a) single jet; (b) double jet; (c) triple jet; (d) single jets; (e) ordinary flow without jets.

NOMENCLATURE

C	[mol]	Concentration
D	[m^2 s^{-1}]	Diffusion coefficient
E	[V]	Cell potential
F	[A s mol^{-1}]	Faraday's constant
h	[m]	Height
$J^{ref,0}$	[A m^{-3}]	Exchange current density × specific area to volume ratio
L	[m]	Length
p	[N m^{-2}]	Pressure
R	[J mol^{-1} K^{-1}]	Gas constant
RH	[%]	Relative humidity
T	[°C]	Temperature
U	[m s^{-1}]	Velocity
w	[m]	Width
Special characters		
α	[-]	Transfer coefficient
γ	[-]	Concentration dependence
ε	[-]	Porosity
κ	[m^2]	Permeability
Subscripts		
a		Anode, active layer
c		Cathode
$cool$		Cooling water
f		Flow field (net)
H_2		Hydrogen
H_2O		Water
in		In
jet		Jet
m		Membrane
O_2		Oxygen
p		Porous backing (gas diffusion layer)

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