Now, returning to the question about current density depletion in the middle of the channel, we see that the answer is directly coupled to the depletion of the oxygen concentration in the middle of the channel, as can be inferred from Figure 4. Clearly, the convective flow of oxygen driven by natural convection into the cathode channel is not high enough to penetrate deeper into the cathode flow field to produce electricity. This mass transport limitation can be reduced by shortening the cathode flow field, so that the oxygen still can reach to the middle, as can be seen in Figure 4a.

Orientation and Gravitational Effects

The flow arising from natural convection depends on the coupling between transport of mass, energy and momentum and the variation of the density. The orientation of the fuel cell/stack can therefore be expected to have an impact on the performance. To study if this is the case, let us return to case b and introduce three different orientations: vertical (90°, base-case); tilted (45°); horizontal (0°), as shown in Figure 5.

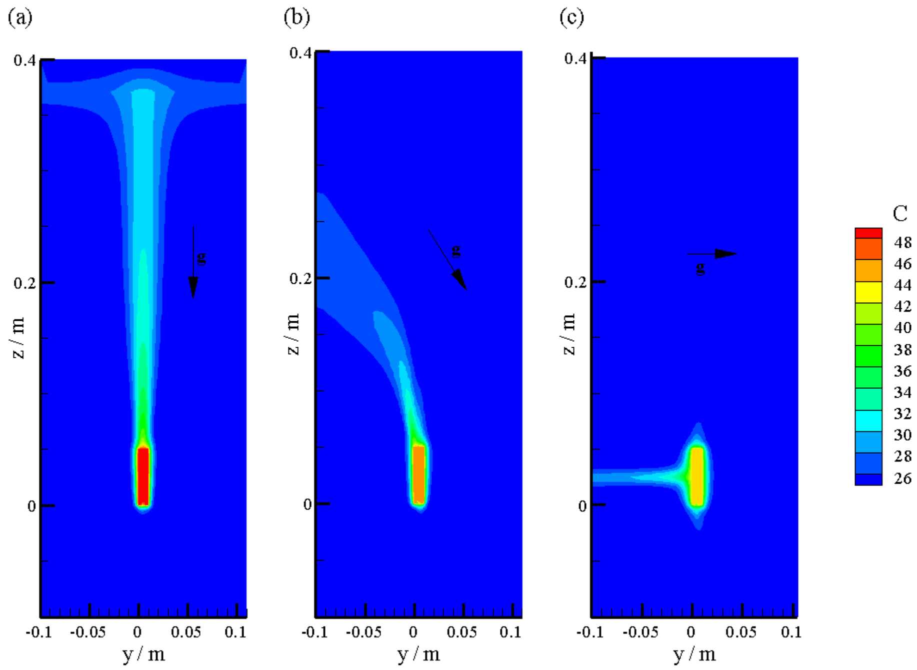

Figure 5. Temperature distribution (°C) for different gravitational orientations: a) vertical (90°); b) tilted (45°); c) horizontal (0°)

Before we look into cell performance, let us have a closer look at the temperature distribution, which is one of the driving forces for the density variations and buoyant flow. As shown in Figure 5, the temperature distribution is similar to the thermal plume that Fabian et al. [34] observed experimentally. Focusing on case a, and the immediate vicinity of the cell, as depicted in Figure 6, we find that the average velocity is around 2×10^{-2} m s^{-1} at the cathode inlets arising from buoyancy flowing from bottom to the top. For tilted case, a slightly lower velocity is observed flowing at the bottom of the cathode channel with the average velocity of around 8×10^{-3} m s^{-1}. In contrast, for the horizontal placement, the inlet velocity is around one order-of-magnitude lower with an average flow velocity of 3×10^{-3}. In addition, the maximum velocity due to natural convection in the surrounding is around 5×10^{-2} m s^{-1}, which is similar to the velocities predicted by Lister et al. [14].

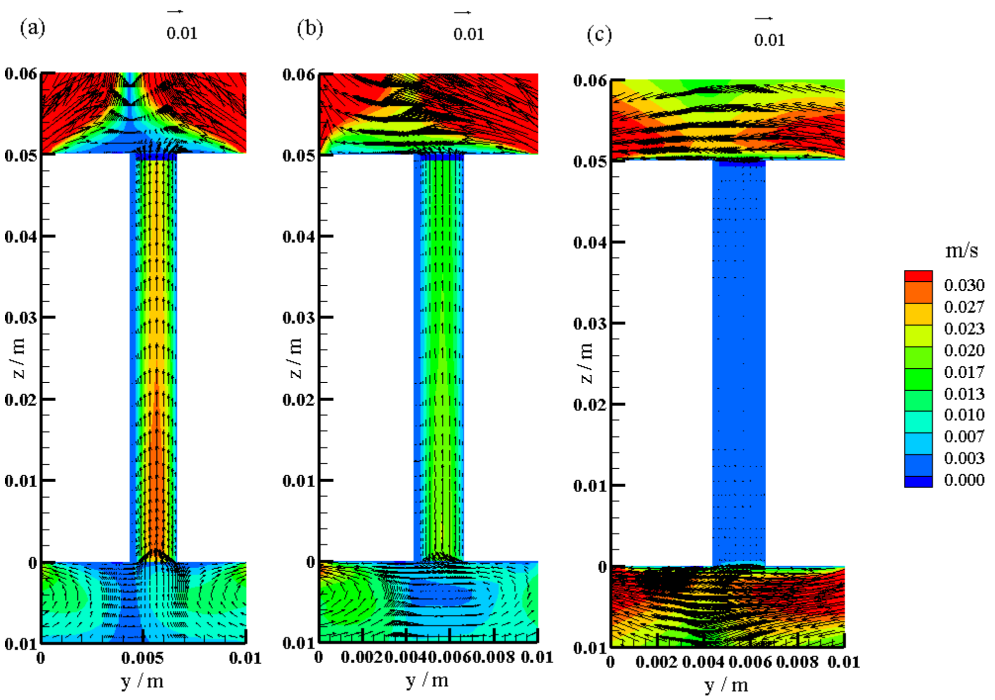

Figure 6. Velocity vector and contour (ms^{-1}) at the cathode and its immediate ambient for different gravitational orientations: a) vertical (90°); b) tilted (45°); c) horizontal (0°)

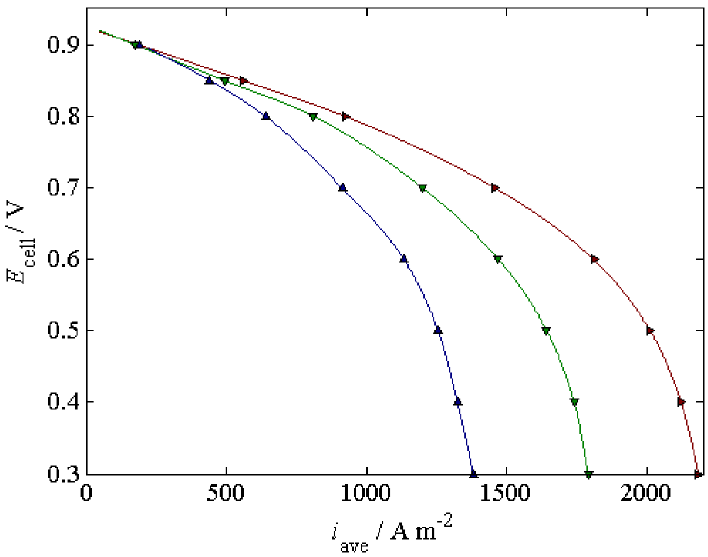

Figure 7. Polarization curves for different gravitational orientations: [►] vertical (90°); [▼] tilted (45°); and [▲] horizontal (0°)

In free-breathing fuel cell, the velocity is highly nonlinear as it is functions of buoyancy flow due to temperature gradient, flow channel geometry and orientations as well as mass transfer driving force due to oxygen consumption. Note that in this simulation, the air flow rate is not fixed; instead we prescribe ambient condition, i.e., constant ambient pressure, temperature and mass fraction, to allow for natural convection air flow due to the factors mentioned above. Moreover, the three-dimensional simulation is able to capture the effect of channel-rib geometry to the incoming air flow and species distribution in the catalyst layer. Closer inspection reveals that rib adds flow resistant to the incoming air to flow channel: small boundary layer is observed at the wall between rib-ambient. In the catalyst layer, the three-dimensionality effect of rib is also seen: oxygen concentration bellow rib area is slightly lower than that bellow channel; this is mirrored by no-uniform current generation and temperature distribution.

The impact of orientation on fuel cell performance is highlighted in Figure 7. The highest performance can be achieved by vertical alignment of the cell, followed by tilted case and finally the horizontal one for the operating conditions considered here. On closer inspection, we note that by changing gravitational orientation, the cell performance can improve by up to ~ 35%; that is by changing cell orientation from horizontal with limiting current of ~ 1300 A m^{-2} improves to around 2300 A m^{-2} as the cell is arranged vertically.

Thermal Management: Single Cell and Stack

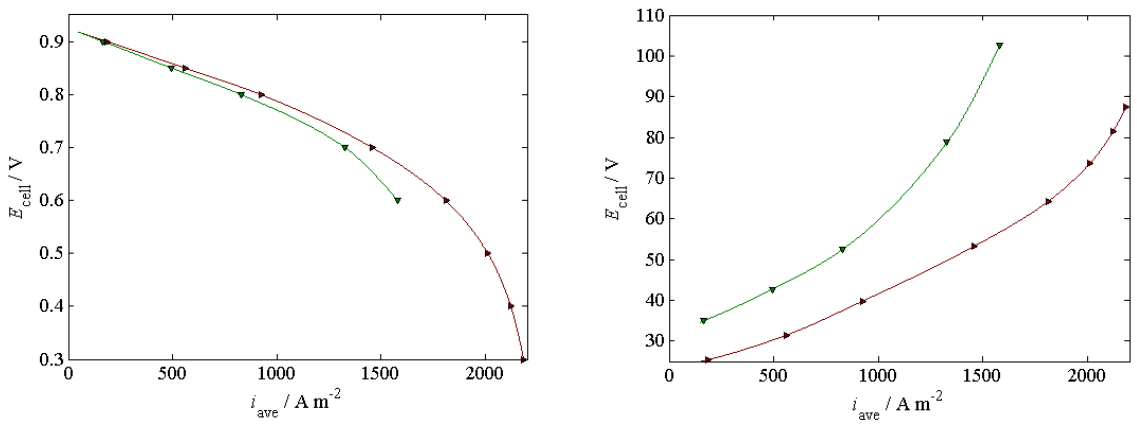

Figure 8. Comparison of (a) polarization curve and (b) average temperature for single cell [▶] and stack comprises of 12 cells [▼] with free air-breathing

One key component in control strategies of a fuel cell stack or single cell is thermal management. This is especially important for the former as every cell can generate a significant amount of heat, which needs to be removed from the stack. For the case of a fuel cell single cell or stack operating at natural convection conditions, the removal rate is limited by the natural convection to and from the cell/stack. Generally, this only allows for the operation of small stacks of a few cells. Here, we simulate the thermal envelope for both a single cell and a stack comprising of twelve cells, the results of which are shown in Figure 8.

The temperature increase for the stack is much higher than the single cell as expected. The overall temperature increase for the latter is around 23°C at operating cell voltage of 0.7 V (see Figure 9a), which is in agreement with experimental data from Fabian et al. [34]. For the former, the stack temperature is around 55°C higher than the ambient air (Figure 9b). The higher temperature inside each cell of the stack leads to a lower water content in the membranes and thus an increase in ohmic resistance, which in turn manifests itself in a lower performance. In this case, the overall current density that is generated by the stack is around 20% lower than that of the single cell. As we proceed to higher current densities, the single cell performance can sustain up to more than 2000 A m^{-2}; whereas for stack, the performance is only able to generate current density up to ~ 1600 A m^{-2}, after which the performance drops to zero as temperature inevitably rise to more than 100°C which indicates that membrane start to failure. To improve performance of the stack, one needs to carefully design it to maximize the buoyant flow and perhaps introduce additional cooling channels or add fan to forced more air flows to the cathode.

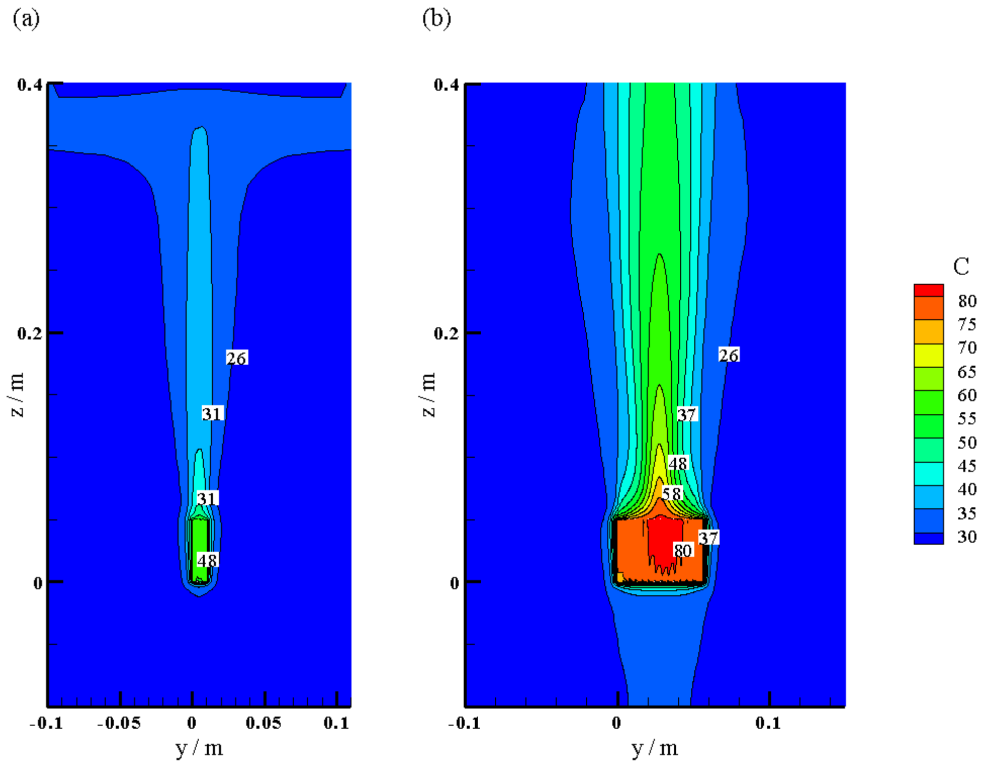

Figure 9. Temperature contours (°C) for a) single cell; b) stack comprising 12 cells with its immediate ambient

Concluding Remarks

A numerical study of a free air-breathing PEM fuel cell was carried out for both a single cell and a stack. It is shown that the cathode flow field design plays an important role in determining the mass transport limitations that arise along the cathode; a short length allows for more oxygen to be transported into the cathode. Furthermore, orientation of the cell/stack with respect to gravity also needs to be considered to ensure adequate airflow; for conditions considered here, a vertical alignment of the cell gave a better performance than tilting the cell at an angle or even positioning it horizontally. Finally, the simulation results indicate that stacks, even when only comprising of a few cells, can heat up significantly relative to the ambient conditions.

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