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CFD to predict temperature profile for scale up of micro-tubular SOFC stacks

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Abstract

Thermal management is an important issue in the development of micro-tubular stacks. Computational fluid dynamics (CFD) has the potential to assist in the specification of operating conditions and designs that minimise temperature gradients and maximise the use of heat produced in the SOFC stacks. This paper reports the construction of a 20-cell micro-tubular SOFC stack and a CFD model of this system using the commercial code, Fluent 6.0. Model results for a single cell are reported.

Keywords: Modelling micro-tubular SOFC; Fluent computational fluid dynamics; Temperature profile; Flow distribution

1. Introduction

Micro-tubular SOFCs show significant advantages over competing fuel cell technologies. The tubular design reduces the sealing problems associated with ceramic fuel cells and the 2 mm diameter minimises thermal gradients, which can lead to failure or dictate slow start up times in larger diameter designs. There is great potential for micro-tubular SOFCs to form rapid-starting modular stacks. In order to transfer the good single cell test performance of micro-tubular SOFC technology to a multi-cell stack, a model is needed to configure and operate the system with acceptable temperature distribution.

The first objective of this project is to characterise heat transfer in micro-tubular cells and stacks to identify stack designs and operating conditions that will lead to optimal performance and efficient thermal management. Computer modelling using commercial Computational Fluid Dynamics (CFD) packages, such as Fluent [1] can generate temperature and flow data which are then tested experimentally in a small stack.

This paper describes a 20-cell test system which has been modelled using Fluent 6.0. Several authors have reported the use of CFD for other geometrical designs of SOFC [2–5]. No previous CFD modelling of micro-tubular stacks has been reported. This is the first CFD study of a rapid heating micro-tubular stack.

2. Background and motivation for the study

2.1. Micro-tubular SOFC

The micro-tubular cells were supplied by Adelan Ltd. The dimensions were 2 mm external diameter, length 55 mm with an active length of 25 mm. The electrolyte was 8 mol% yttria stabilised zirconia (8YSZ) formed into a tube by an extrusion process. The anode was made by injection of nickel cermet and the cathode was formed from a lanthanum strontium manganite coating. Current collection was via a nickel mesh at the anode and silver wire at the cathode. Silver ink was used to improve the electrical connection between the cathode and the silver wire interconnect.

The advantages of micro-tubular SOFC over competing fuel cell technologies have been demonstrated in single cell reactors [6]. Micro-tubular cells have been heated from room temperature to 850 °C within 1 min without failure and survived thermal cycling [7]. They have also demonstrated capacity to run on a variety of fuels [8]. These advantages coupled with a good power density mean micro-tubular cells have the potential to generate power for portable domestic and leisure applications.

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2.2. Importance of thermal and flow modelling

The temperature of the cells is important and needs to be understood because too high temperature degrades the materials and too low temperature impairs power output.

Temperature is dictated by flow rate and direction, electrical power output and heat losses from the stack. The temperature distribution in a micro-tubular stack has not previously been modelled, especially the possibility to form hot spots, which depends critically on the flow pattern and the heat losses. The end product of this research is a temperature and flow theory which allows improved designs of stack and system components. In summary effective thermal management of the micro-tubular stack through design and system controls is important to performance and reliability of the stack.

2.3. Size of the model

With power output in the region of 0.4–0.6 W per cell thousands of cells are needed to build significant power generators. A 20-cell unit was selected for this model because this was small enough to be readily constructed and modified, yet large enough to provide a reasonable picture of flow and heat distributions.

3. Twenty cell experimental system

The initial CFD model has been developed to simulate a 20-cell test stack shown schematically in Fig. 1 and photographed in Fig. 2. The cells were fed with fuel via a steel inlet manifold. The exhausted fuel was collected in a ceramic outlet manifold.

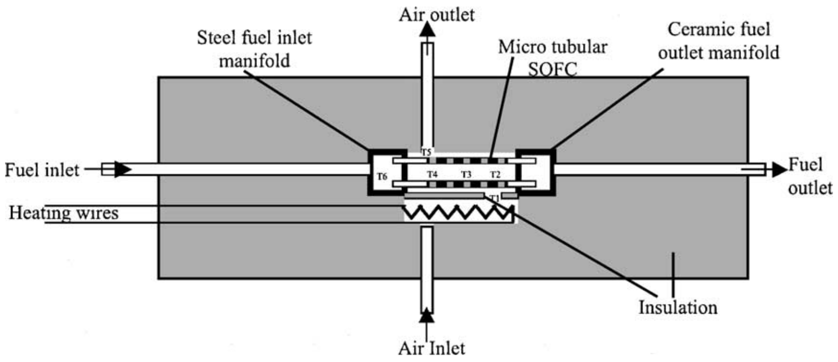

Fig. 1. Diagram of cross-section of experimental test stack.

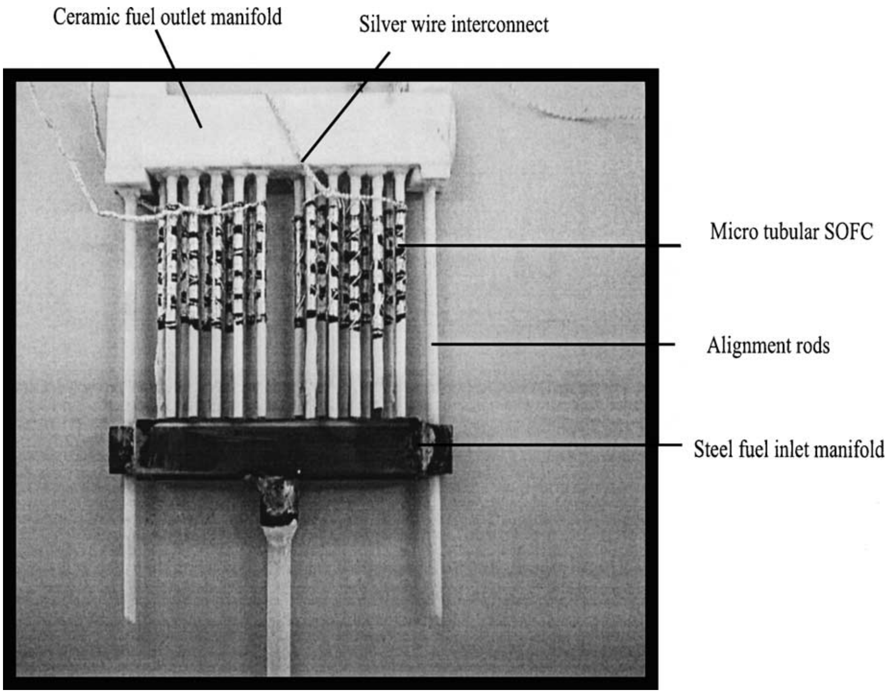

Fig. 2. Photograph of 20-cell test rig.

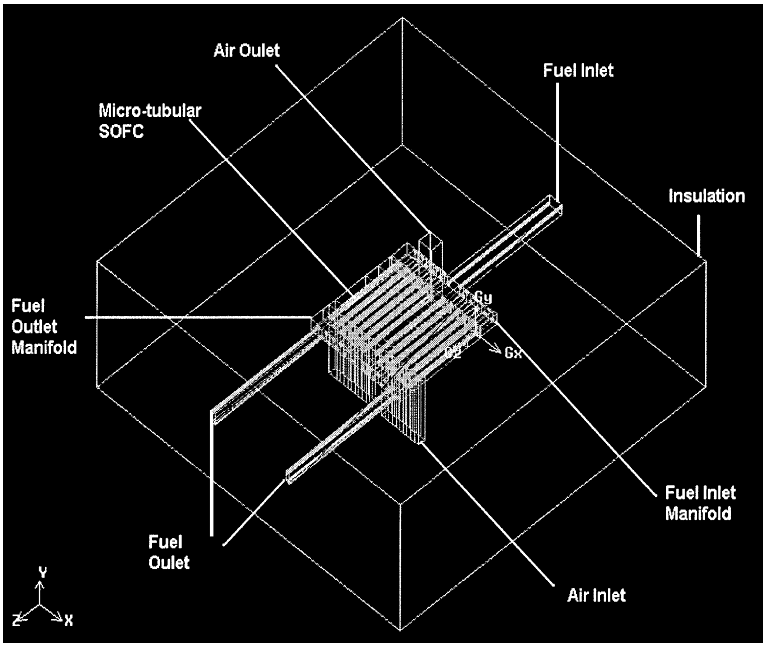

Fig. 3. CFD model of experimental test rig.

The temperature of the air feed to the cells was controlled using electrical heating elements and regulated using a thermocouple shown in Fig. 1. as T1. The temperature at various points through the stack was measured using thermocouples T2–T6.

4. CFD model

The first objective of the work was to input the coordinates of the experimental stack into the Fluent model as shown in Fig. 3. The geometry included the 20 micro-tubular cells, the steel fuel inlet manifold and injectors, the ceramic fuel outlet manifold, and the simplified inlet and outlet pipes to the manifolds. All this was surrounded by thermal insulation with dimensions and properties specified to match those of the micro porous insulation used in the experimental system. The mesh was generated using the structured meshing tools in the Fluent pre-processor.

Hydrogen was specified as the fluid flowing inside the tubular cells. The 'mass flow' boundary condition was used for the entrance to the air and fuel inlet pipes. The mass flow rates corresponded to an average of 20 std ml/min hydrogen per tube. The 'pressure outlet' condition was used at the air and fuel exits.

Each fuel cell tube was assumed to consist of a single material with the heat transfer properties of zirconia since the anode and cathode were thin relative to the electrolyte. The tube was split into three sections along its length. This was to distinguish the active area of the cell from the uncoated

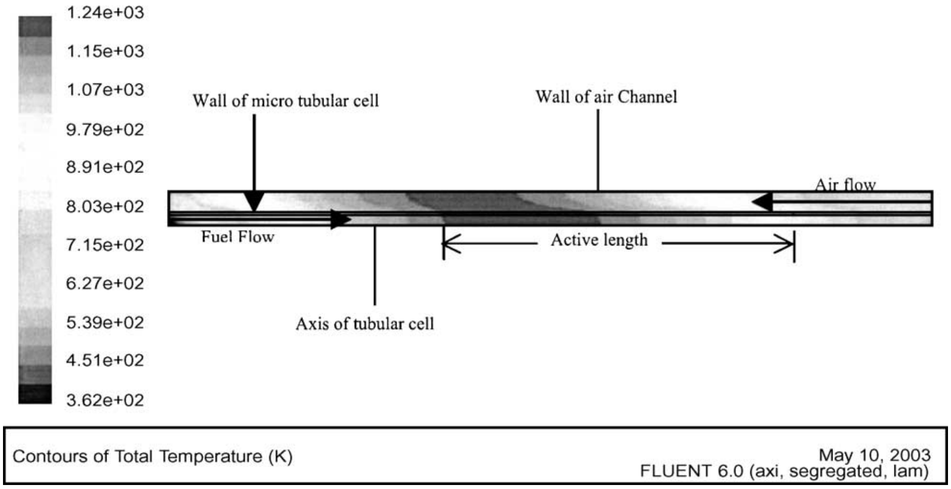

Fig. 4. Temperature contours for single tube.

sections of the 8YSZ tube at the inlet and outlet end of the cell.

A constant energy source term was added through the active section of the tube to account for heat production due to polarisation losses within the cell. The heat source term, defined per unit volume, was specified as 0.5 W as derived from previous experimental data on single tubes at 850 °C. This heat source term was varied according to the cell temperature. No diffusion or species source and sink terms were accounted for in this initial model. Subsequent models will consider chemical gradients in the cell.

Fig. 4 shows the temperature contours predicted for a single tube. For the single cell model the ‘axis’ boundary condition was used to simplify the geometry by utilising the symmetry around the axis of the fuel cell tube. The boundary at the outer edge of the air channel was assumed to be adiabatic. The ‘mass flow’ boundary condition was used at the air and fuel inlets. The mass flow rates corresponded to 20 std ml/min hydrogen and a stoichiometric ratio of air in relation to the hydrogen input. The ‘pressure outlet’ condition was used at the air and fuel exits. For stability the gases were initially specified as constant density and the simulation was run until the convergence conditions were satisfied for the mass, momentum and energy. The gas properties were then changed to ideal gas behaviour and the solver was run until convergence conditions were satisfied and the inlet and outlet mass fluxes balanced.

The air inlet temperature in the model was varied to find the conditions that would result in cell temperatures around 850 °C. With the air in counter current flow to the fuel, the optimum air temperature was found to be 400 °C. The resultant temperature profile is shown in Fig. 4.

The initial simulation also highlights a potential problem that temperature varies from the optimum even along the relatively short active length. There are several effects that have been neglected at this stage that may alter the temperature gradient. The assumption of adiabatic conditions at the outer boundary of the air channel neglects the heat loss to the atmosphere, which may help to even out the temperature distribution.

5. Conclusions

A 20-cell micro-tubular experimental stack has been built.

The CFD model of this stack has been constructed and simulation results on single microtubes have been obtained.

The next stage is to compare simulation with experimental results in order to obtain a first approximation to temperature and flow distributions. Then the model can be upgraded to include further sophistication in terms of reaction gradients along the cells.

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