UNIVERSITYᴼᶠ BIRMINGHAM

University of Birmingham
Research at Birmingham

Control system design for micro-tubular solid oxide fuel cells

Tsai, T.-i.; Du, S.; Fisher, P.; Kendall, K.; Steinberger-wilckens, R.

Link to publication on Research at Birmingham portal

Control system design for micro-tubular solid oxide fuel cells

Tsang-I Tsai*, Shangfeng Du, Peter Fisher, Kevin Kendall
and Robert Steinberger-Wilckens

School of Chemical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

Abstract

Fuel cells have been widely studied in the past decades due to their high energy conversion efficiency and low-carbon emissions. Solid oxide fuel cells (SOFCs) work at a high-temperature range, allowing the use of several types of fuels such as natural gas or methane. However, in operation, too high a fuel utilization (FU) leads to a large internal temperature gradient, thus the thermal shock of ceramic cracking; while a very low-FU results in carbon deposition and thus a decrease in the overall efficiency. In this work, a control system was designed for a small-scale micro-tubular SOFC (μ-SOFC) stack by employing the National Instruments™ Labview Programme and Data acquisition (DAQ) 6009 as well as related electronic components which enabled the control of the fuel flow rate for the stack and the temperature inside the furnace. The results showed that a well designed control system can not only improve the overall efficiency but also extend the working life, finally achieving a more economical μ-SOFC system.

Keywords: micro-tubular SOFC; control system; fuel utilization; energy efficiency

1 INTRODUCTION

In the past few decades, more and more concerns have been paid to the global warming issue. Greenhouse gas (GHG), e.g. carbon dioxide or methane from burning fossil fuels, is regarded as one of the main factors which lead to climate change [1]. Among several possible low-carbon technologies to reduce GHG emission, fuel cells have attracted many efforts due to their high energy efficiency and low-carbon emission [2].

Pure hydrogen is the main fuel accepted by low-temperature fuel cells, e.g. polymer electrolyte fuel cells working at a temperature $<80°C$ [3], while different types of fuels could be utilized by high-temperature fuel cells, e.g. solid oxide fuel cells (SOFCs). They have a high fuel flexibility, e.g. methane and propane [4], benefiting from the high operating temperature $(600–1000°C)$ [5]. However, to reach such a high temperature, the stack could be broken due to the thermal stress if the temperature goes up rapidly [6, 7]. Additionally, fuel flow rate is another issue should be considered. On the one hand, too high inlet fuel flow rate decreases the overall efficiency. On the other hand, very low flow rate with too high a fuel utilization (FU) causes damage to the cells due to the large internal temperature gradients in the fuel cell components [6].

SOFCs with several types of structure such as planar, tubular and micro-tubular have been intensively investigated [8–10]. Regarding the most common planar SOFC stacks, despite the advantage of ease of stacking, a long heating-up time is required to prevent damage caused by thermal stress. Although this problem could be partially solved by using micro-tubular SOFCs with an improved thermal shock resistance, a fine control of the heating-up rate is still vital to prevent thermal shock damage. The aim of this work is to design a control system to regulate the temperature and inlet fuel flow rate to optimize the operation of a micro-tubular SOFC system, as shown in Figure 1.

2 EXPERIMENT

2.1 Micro-tubular solid oxide fuel cell

The anode-supported micro-tubular SOFC (μ-SOFC) employed in this work is supplied by Adaptive Materials, Inc., with 55 mm in length and 2.3 mm as inner diameter. The inner anode layer with a thickness of 200 μm is made of Nickel-yttria-stabilized zirconia (Ni-YSZ) surrounded by a 10-μm electrolyte consists of YSZ as shown in Figure 2a [11]. Lanthanum
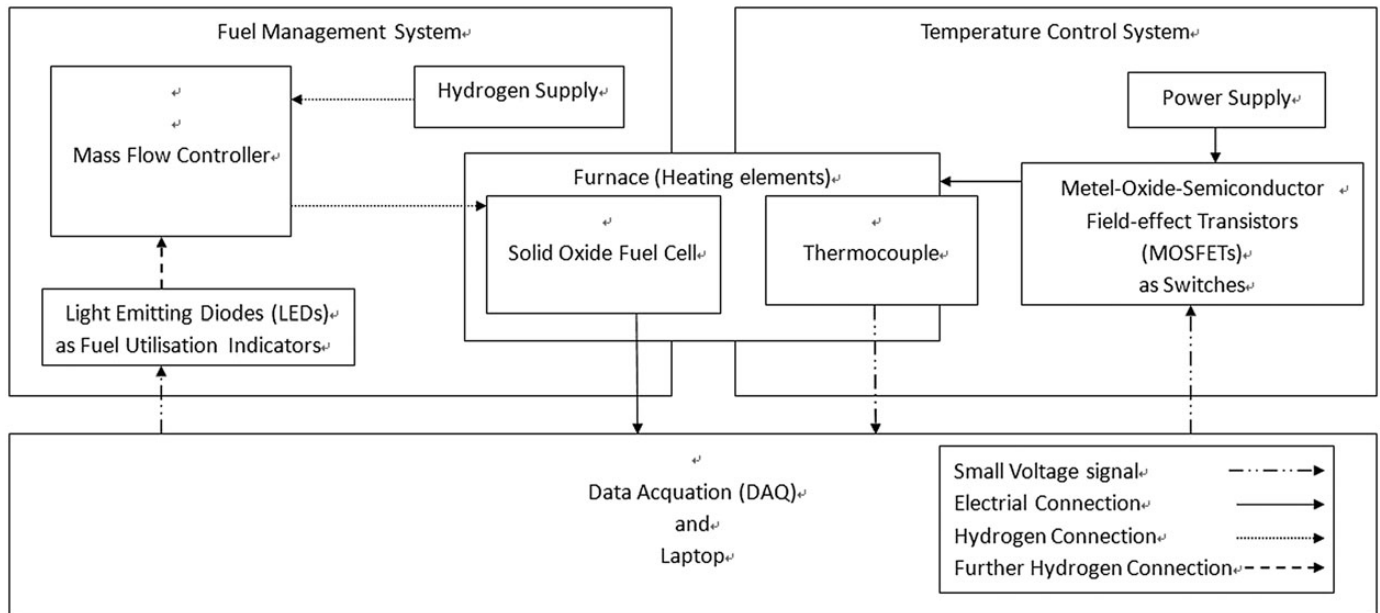
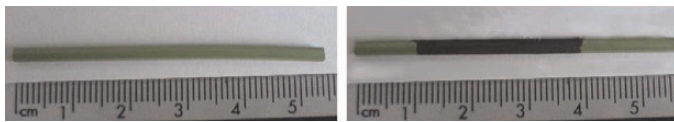**Figure 1.** *The overview diagram of the system.*

Figure 2. *The appearance of a μ-SOFC without (**a**) and with (**b**) a cathode layer.*

strontium manganite ink is painted with a length of 30 mm on the surface as cathode layer, as shown in Figure 2b [11], and then the cell is sintered and reduced. On the top are three bands of silver ink and a 70-cm 99.99% silver wire wounded to connect the cell itself and the external load (Figure 3) [11].

2.2 Control strategy—temperature control

The aim of this work was to design a control system to optimize the control of the temperature inside the furnace to extend the lifetime of the μ-SOFCs. A furnace, thermocouple, high-resistant wires and some electronic components like metal–oxide-semiconductor field-effect transistors (MOSFETs) and inductors were used in building the temperature control system.

Figure 4 shows the furnace built with two hollowed out thermal ceramic bricks. Four 80-cm Ni-Chrome wires are wounded on the ceramic rods with MOSFETs as the switches to control the circuit connected to the power supply. This arrangement allows more flexibility in the temperature control. Besides, a *k*-type thermocouple was used to monitor the temperature. National Instrument data acquisition (DAQ) 6009 was placed between the system and the computer to receive/send signals from/to thermocouple and the gates of MOSFETs to control the current flow and then the temperature of the furnace.
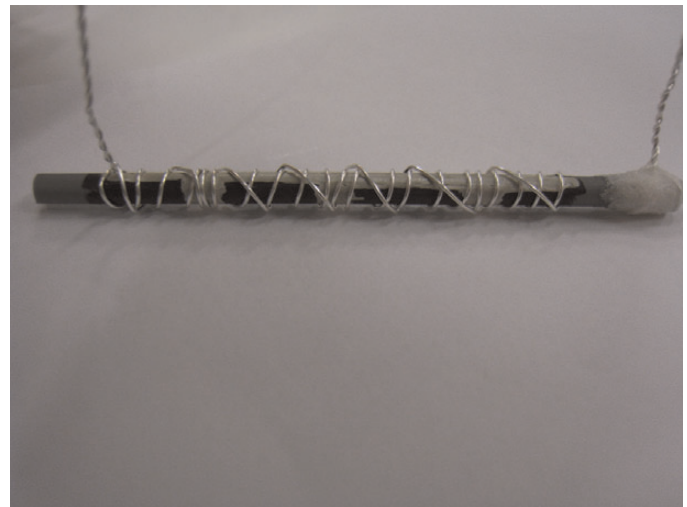
Figure 3. *Silver ink bonds and wires wounded on the cell.*

The furnace was powered by a 500-W power supply fed through MOSFETS into the high-resistance wires. A temperature-related voltage signal was produced by the thermocouple and then sent through DAQ back to the computer where decisions were made by a designed Labview programme. Another signal representing the decision would be generated and sent through DAQ to MOSFETs to close or open the heating circuit. Half of the MOSFETs would be cut off when the temperature reaches 725°C while the other half would remain in conducting to make up for the heat losses. The programme was designed to return to full power when the system temperature falls below 715°C.

Diodes were placed parallel to the MOSFETs to protect them from being destroyed by the back electromotive force (emf) because the loads were highly inductive resistance wires in the experiment, as shown in Figure 5. Besides, lots of heat was produced inside the MOSFETs when the high current flows through the internal resistance during the heating-up stage which can cause damage to the system. Aluminium made heat sink/cooling rib was employed here to absorb the excess heat and release it to the atmosphere.

2.3 Control strategy—fuel management

The control system in the fuel management part was expected to manage the inlet fuel flow rate in the system in order to use the fuel more economic and optimize the system efficiency. The Unit Instrument UFC 7300 mass flow controller with an accuracy of $\pm 1\%$ was employed to control the inlet fuel flow rate in the experiment. The FU was calculated from the electrical output power of the cell measured directly by the DAQ from National Instrument. However, as a prototype, the fuel
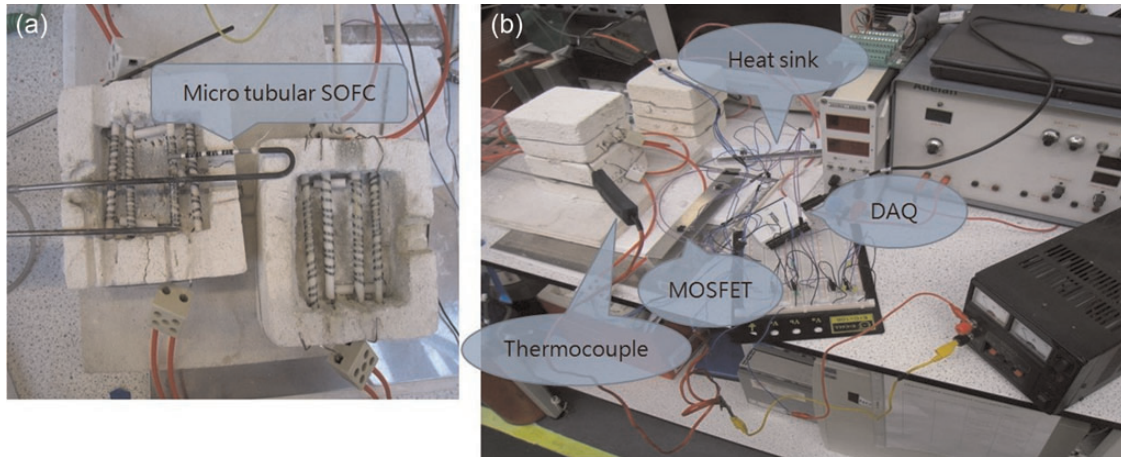

Figure 4. *The furnace and μ-SOFC (**a**), and the set-up of a temperature control system (**b**).*
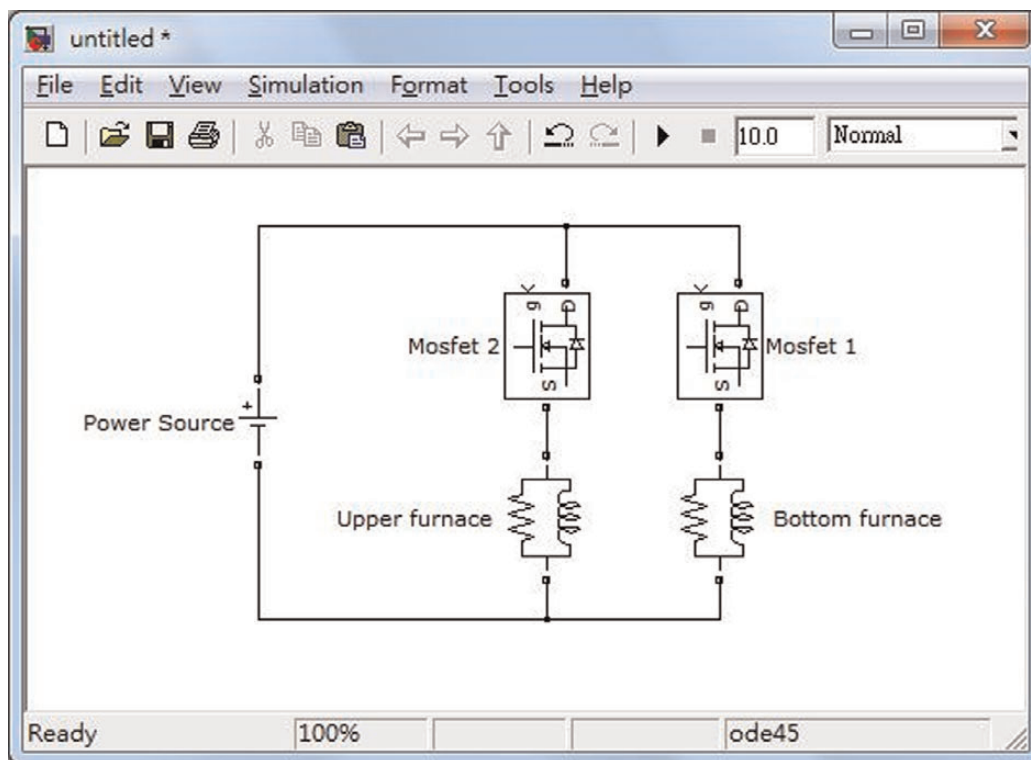

Figure 5. *The heating-up circuit.*

management here was an open-loop control system and mass flow controllers were not connected to the control system and DAQ. Instead, light-emitting diodes (LEDs) were used to indicate different levels of FU in this stage.

3 RESULTS AND DISCUSSION

3.1 Impact of fuel on energy efficiency
More than 10 cells were tested under different hydrogen flow rates and the conclusions are shown in Figure 6a and b. The results indicated that the output power was not directly proportional to the inlet fuel flow rate. The output power increased significantly when the fuel flow rate went up from 10 to 20 ml/min, but this became much smaller as the flow rate increase to 30 ml/min. As a result, the overall efficiency decreased with the inlet fuel flow rate because a high inlet fuel flow rate led to a low-FU. This is not expected because a high efficiency and specific power requirements are always required by the applications.

3.2 Temperature control
The temperature inside the furnace was heated up to 725°C within 10 min, as shown in Figure 7, with a fluctuation of $\pm 5°C$

which showed that both the heating-up elements and control system were capable of meeting the planned requirements. The time constant for the temperature of the furnace is about 173 s.

This work demonstrated the concept of temperature controlling by using an electrical heating set; however, as mentioned earlier, the fuel should not be fully utilized by μ-SOFCs because it could cause damage to the cells. As a result, it is expected that the heat could be recycled from burning the residual fuel of μ-SOFCs. In further work, heat exchangers will be used to recycle the heat for the stack and the whole system would be more efficient and economic.

3.3 Fuel management
The output voltage and current of the cell were accurately measured and LEDs correctly responded to the FU as shown in Figure 6. The FU and total efficiency could then be calculated based on the following formula [8]

$$\text{Fuel} \quad \text{utilization} \ = \ \frac{I}{n \times F \times \mu}$$

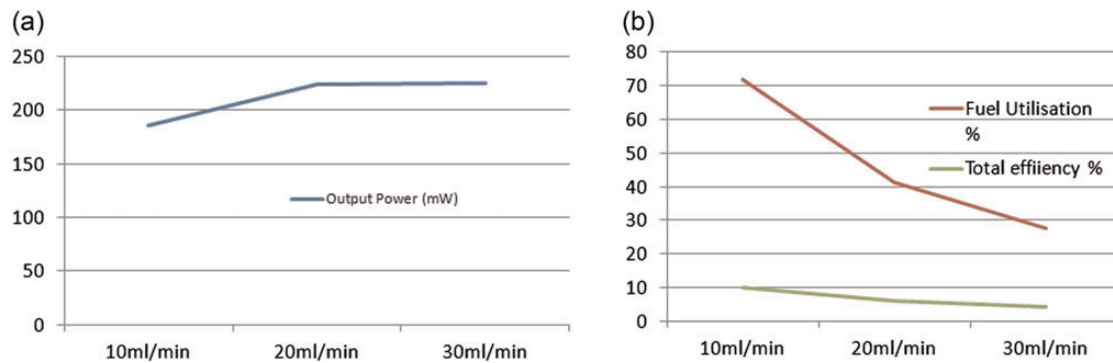$$\text{Total efficiency} = \frac{W_{el}}{\Delta H}$$

Figure 6. *The electrical output power (a), the overall efficiency and fuel utilization (b) under different hydrogen flow rates.*
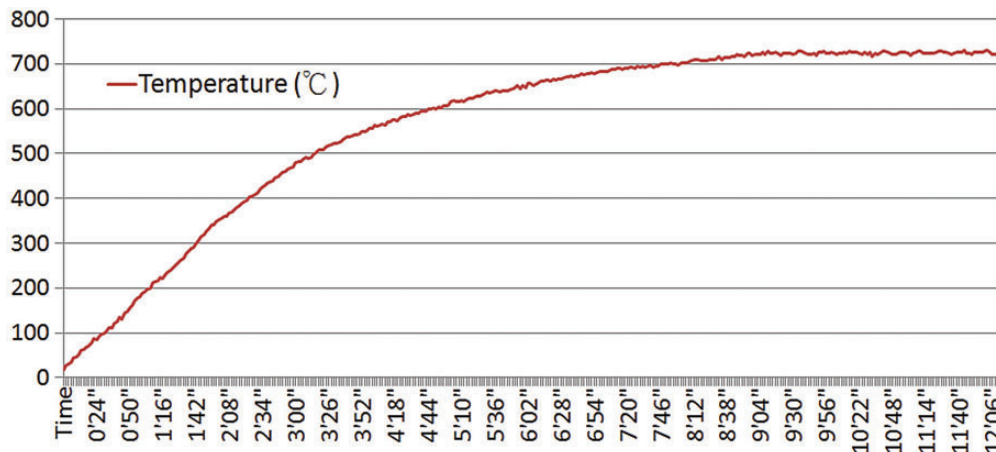

Figure 7. *The temperature of the furnace against time in heating up.*

Where n is the electron transfer number and 2 is the value when using hydrogen as fuel. F is Faraday's constant and μ is the fuel flow rate with the unit of mole per second. W_{el} is the SOFC electrical power output and ΔH is the enthalpy change in the reaction [12].

Three levels of FU were defined in this experiment: $<60\%$, between 60 and 75%, as well as over $>75\%$. Suitable reactions such as decreasing, maintaining or increasing the inlet fuel flow rates were made by the control system to optimize the whole system. To make the whole system fully automatic, a mass flow controller will be placed between the cells and fuel supply and connected to the control system in the future to form a closed-loop system and control the fuel flow rate. Furthermore, at different situation, μ-SOFC applications are expected to export different powers, and the fuel control system could optimize the parameters to meet these different demands.

As a study of a single cell here, the heat from the unutilized fuel was only 1.8 J/s (LHV) with an assumption of 50% FU with a 20 ml/min total inlet fuel flow rate. It was quite insignificant in comparison with the power required by furnace which was 500 W here. However, in a full-scale system which could consist of thousands of fuel cells, the heat produced would not only be sufficient for heating up the furnace, but also providing additional heat to the CHP unit.

4 SUMMARY

The high operating temperature allows SOFCs to work with high flexible fuels whereas some thermal effects require more efforts to deal with. A good control system could not only optimizes, but also extend the working life of the overall system and make it more economic. The concept of designing a control system for a micro-tubular SOFC has been demonstrated in this work. Fuel management like controlling the inlet fuel flow rate could optimize the FU and thus prevent the system from energy wasting. It could be achieved by a well-design temperature controller for a reasonable start-up time and avoiding the cell from damages at the same time. More information about the system operation on the correct electrical voltage and current output measurement will make μ-SOFC stacks and their applications to be built easier.

REFERENCES

[1] Uzunoglu M, Onar OC, Alam MS. Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications. *Renewable Energy* 2009;**34**:509–20.

[2] Neef HJ. International overview of hydrogen and fuel cell research. *Energy* 2009;**34**:327–33.

[3] Andújar JM, Segura F. Fuel cells: history and updating. A walk along two centuries. *Renewable Sustainable Energy Rev* 2009;**13**:2309–22.

[4] Brouwer J. On the role of fuel cells and hydrogen in a more sustainable and renewable energy future. *Curr Appl Phys* 2010;**10**:S9–17.

[5] Singhal SC, Kendall K. *High Temperature Solid Oxide Fuel Cells*. Elsevier Ltd, 2003.

[6] Stiller C, Thorud B, Bolland O, *et al*. Control strategy for a solid oxide fuel cell and gas turbine hybrid system. *J Power Sources* 2006;**158**:303–15.

[7] Nakajo A, Stiller C, Härkegård G, *et al*. Modeling of thermal stresses and probability of survival of tubular SOFC. *J Power Sources* 2006;**158**:287–94.

[8] Sammes NM, Du Y, Bove R. Design and fabrication of a 100W anode supported micro-tubular SOFC stack. *J Power Sources* 2005;**145**:428–34.

[9] Ahmad Hajimolanaa S, Azlan Hussaina M, Ashri Wan Daud WM, *et al*. Mathematical modeling of solid oxide fuel cells: a review. *Renewable Sustainable Energy Rev* 2011;**15**:1893–917.

[10] Lee S-B, Lim T-H, Song R-H, *et al*. Development of a 700W anode-supported micro-tubular SOFC stack for APU applications. *Int J Hydrogen Energy* 2008;**33**:2330–6.

[11] Dhir A. Improved microtubular solid oxide fuel cells. Vol. Ph.D. Thesis. The University of Birmingham 2008.

[12] Jiang W, Fang R, Khan J, *et al*. Parameter setting and analysis of a dynamic tubular SOFC model. *J Power Sources* 2006;**162**:316–26.