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An experimental investigation of a micro-tubular SOFC membrane-separated liquid desiccant dehumidification and cooling tri-generation system

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Abstract

This paper reports the results of experimental work carried out on a micro-tubular solid oxide fuel cell tri-generation system that uses the waste heat from the fuel cell for dehumidification and cooling through the integration of an open cycle liquid desiccant dehumidification and cooling system. The experimental results demonstrate regeneration of the potassium formate solution using the thermal output from the SOFC in the first of its kind tri-generation system. Optimisation has shown that a $2.2\text{L}\cdot\text{min}^{-1}$ regenerator desiccant volumetric flow facilitates best performance. When integrated with the micro-SOFC, the open cycle desiccant system demonstrates a COP of approaching 0.7, an encouraging value for a waste heat driven cooling system of this capacity. A tri-generation performance analysis is presented which serves to demonstrate the novel system operating in a building. The system achieved an electrical efficiency of 11% and regeneration efficiency of approximately 38%. The electrical efficiency is lower than that predicted by the company supplying the micro-tubular SOFC, because the unit suffered sulphur poisoning during preliminary tests. The electrical power output decreased from 250W to 150W, which reduced the electrical efficiency from around 18% to 11% and the overall efficiency from approximately 45% to just over 38%. Low temperature (33-36°C) regeneration was demonstrated.

Keywords: fuel cell, SOFC, microtubular, tri-generation, desiccant, dehumidification

1. Introduction

One of the more promising possibilities for clean small scale generation is solid oxide fuel cell (SOFC) technology, which can generate electricity through an electrochemical process that brings together hydrogen from the fuel and oxygen from the air (Boyd, 2008). The only by-products are waste heat, water vapour and carbon dioxide. Chemical to electrical energy conversion efficiencies can be over 50% compared to 30-40% in combustion processes. Technical assessments have demonstrated that if combined heat and power (CHP) technology is used with SOFC, the total system efficiency of as high as 90% can be achieved.

Liquid desiccant systems in the heating, ventilation, and air conditioning (HVAC) applications, are used primarily where simultaneous maintenance of temperature and humidity control is an important benefit to the user. This technology is often used in tri-generation systems, where the desiccant system is driven by the heat by-product. If the waste heat from SOFCs is used to drive the desiccant unit, then a tri-generation system will result, supplying not only the power and heat as the conventional CHP technology to the building, but also cooling and humidity control.

This paper will describe the development, design, construction and testing of a micro-tubular SOFC tri-generation system for low carbon buildings.

1.1 Fuel cells

Fuel cells have recently been identified as a key technological option for improving both building energy efficiency and reducing emissions en-route to a zero carbon built environment (Hawkes, *et al*, 2009, Kazempoor, *et al*, 2011). Fuel cells are not heat engines, and thus their efficiencies are not limited by the Carnot efficiency. Fuel cells consist of an anode, a cathode and an electrolyte, and when hydrogen is fed to the anode and oxygen is fed to the cathode, the reaction across a solid electrolyte membrane produces electrical energy (Crabtree and Dresselhaus, 2008). By combining hydrogen and oxygen in electrochemical reaction, as shown in figure 1.1, fuel cells have the potential to produce highly efficient electrical power with little or no emission of environmentally damaging pollutants, such as CO₂.

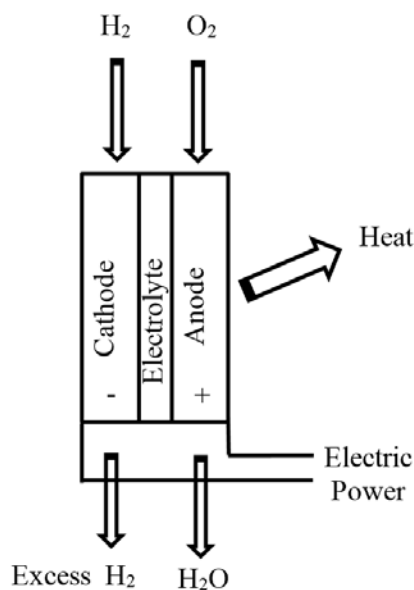


Figure 1.1. Fuel cell concept

The exothermic nature of the electrochemical reactions makes fuel cells ideal candidates for CHP and tri-generation system applications. Solid oxide fuel cells (SOFC) are being developed as viable power generators with the ability to provide process heat as a by-product and so this review will focus on these SOFC developments rather than the whole fuel cell market. SOFCs come in many forms, but the most common are planar type units. The fuel cell consists of many membranes connected in parallel and series, and some of the most common are planar type units, which are flat (usually square) and are arranged in stacks. More recently, micro-tubular fuel cells have been developed. In the early 1990s the micro-tubular type SOFC was invented, according to Howe, *et al*, (2011), which feeds hydrogen and oxygen to opposite sides of a hollow extruded tube. The structure of this design is shown in Figure 1.2a.

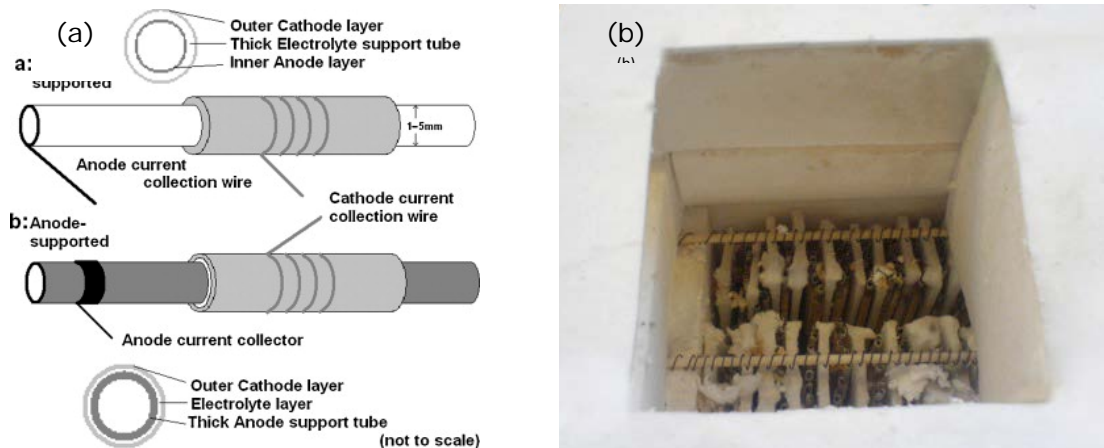


Figure 1.2. (a) basic SOFC micro-tubular designs (Howe, *et al*, 2011), and (b) a 100 tube SOFC stack

Although micro-SOFCs show desirable operational characteristics such as high volumetric power density, good endurance against thermal cycling, and rapid start-up, important performance parameters, such as fuel utilisation and electrical efficiency are comparatively low. By more fully utilising the energy available, micro-SOFCs could be applicable in small stationary applications that require heat, coolth and back-up power. A micro-SOFC tri-generation system integrating open cycle desiccant dehumidification and cooling could provide valuable functionality to the system as well as enhancing the efficiency of the system.

1.2. Fibre membrane separated dehumidification and cooling

A desiccant transfers moisture because of a difference between the water vapour pressure at the surface and that of the surrounding air (ASHRAE, 1997). A recent study by Kozubal, *et al*. (2011) of a desiccant enhanced evaporative air conditioning system demonstrated a 30-90% reduction in energy demand compared to an equivalent vapour compression system. Most liquid desiccant systems employ organic salt-based solutions such as lithium chloride or calcium chloride, which have very low vapour pressures and so readily absorb moisture, but most are highly corrosive, many are harmful to health and some are toxic. In direct contact liquid dehumidifiers, desiccant liquid carry-over can be a major disadvantage as droplets can come into contact with people and incompatible materials, thus posing a potential health hazard and causing corrosion issues. In order to take advantage of the excellent absorption performance, but eliminate the disadvantages, fibre membrane heat/mass exchangers have been developed.

Figure 1.3 shows a diagram of the fibre membrane mass/heat exchanger. Fibre membranes form channels that separate the humid air and liquid desiccant solution. The desiccant solution is introduced at the top of the membrane channels and flows vertically downward, whilst air is introduced in cross-flow through adjacent channels. The fibre membranes are constructed so that the pore sizes are small

enough to prevent liquid desiccant to pass through, but large enough to allow moisture to pass through (Liu, *et al* 2009). Figure 1.3b illustrates how a typical liquid desiccant cycle works: (1-2): absorption of moisture from air, causing increase in vapour pressure and reduced solution concentration, (2-3): regeneration of moisture, causing an increase in vapour pressure and an increase in solution concentration. (3-1): sensible cooling of solution, causing a reduction in vapour pressure. The open cycle desiccant system is simple, cyclic, has comparatively high performance and can regenerate at relatively low temperatures (45-65°C). It is ideally suited to low temperature solid oxide fuel cell applications such as buildings, in which low grade heat is required for heating in winter and cooling in summer.

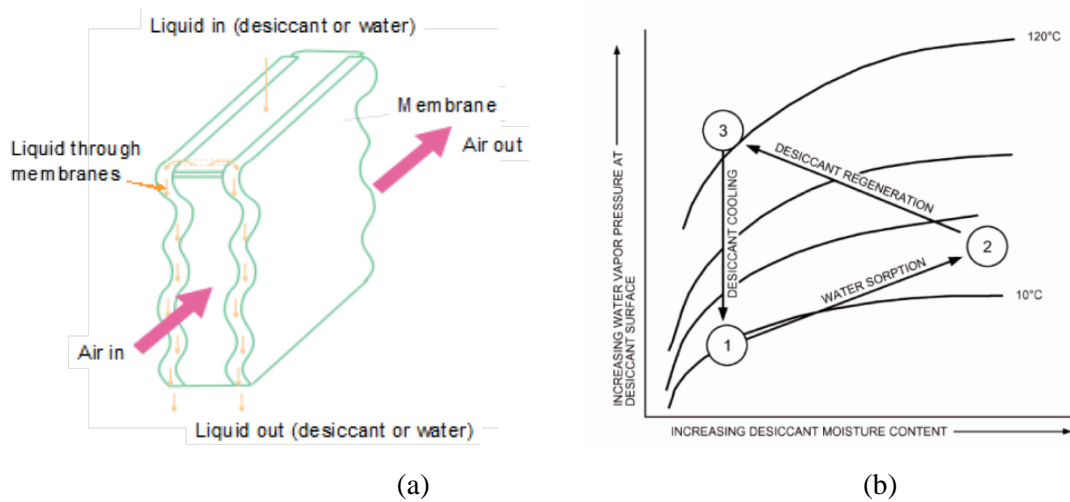


Figure 1.3. Sketch of a fibre membrane heat/mass exchanger and the dehumidification process.

2. Performance parameters

The object of the experimental work is to investigate the performance of the novel micro-tubular SOFC tri-generation system under realistic operating conditions. In order to understand the system performance, important performance parameters are described below.

The change in vapour content in the air, and therefore the mass regenerated, was determined from the difference between inlet and outlet relative humidity and temperature, and regeneration and latent heat transfer rates were determined from the difference in enthalpy between inlet and outlet air streams.

The electrical efficiency of the system is defined as the ratio of the electricity generated to the total chemical and work input

$$\eta_{\text{elec}} = W_e / (Q_{\text{fuel}} + W_{\text{e-out}}) \quad [1]$$

Where W_e (W) is the electrical power output from the fuel cell, Q_{fuel} (W) is the chemical input from the fuel and $W_{\text{e-out}}$ (W) is the electrical power consumed by the fuel cell and dehumidification system (pumps, fans, switches, etc).

The instantaneous tri-generation system efficiency is the ratio of the total useful heat and work output to the total chemical and electrical power input.

$$\eta_{\text{tri}} = (Q_{\text{regen}} + W_e) / (Q_{\text{fuel}} + W_{\text{e-out}}) \quad [2]$$

Where Q_{regen} (W) is the heat recovered from the exhaust gases and available for use in the system.

The purpose of the regeneration process is to remove water from the solution in order to increase its concentration and enable it to be used for dehumidification, therefore we define the regeneration efficiency as;

$$\eta_{\text{regen}} = (Q_{\text{lat}} + W_e) / (Q_{\text{fuel}} + W_{e\text{-out}}) \quad [3]$$

Where Q_{lat} (W) is the latent heat transferred in removing the moisture from the solution.

The instantaneous coefficient of performance (COP) of the system is defined as the ratio of total cooling provided to the total regenerator heat and work input.

$$\text{COP}_{\text{tri}} = Q_{\text{cool}} / (Q_{\text{regen}} + W_{e\text{-out}}) \quad [4]$$

3. Description of micro-tubular SOFC tri-generation test rig

This paper is mainly concerned with disseminating knowledge about the development and testing of a micro-tubular SOFC tri-generation system, but initially will also describe bench tests carried out by one of our consortium partners, the University of Birmingham (UoB), who investigated the operation of the micro-tubular SOFC alone.

3.1. Micro-tubular SOFC bench tests

Figure 3.1a shows a photograph of the micro-tubular SOFC bench test rig. It consists of the micro-tubular fuel cell (size of a desk-top computer), a propane cylinder, a propane regulator, a sulphur trap, a battery pack, an electrical load (12v dc heater elements and lamps) and measuring instruments.

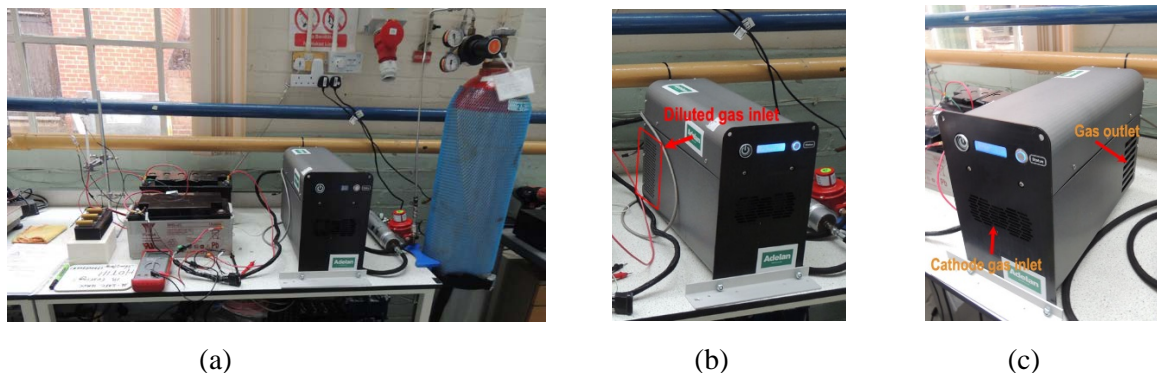


Figure 3.1. Photograph of the micro-tubular SOFC bench test rig

Figures 3.1(b) and 3.1(c) show the fuel cell with indications of air inlet and exhaust outlet points.

3.2. Micro-tubular SOFC tri-generation test rig construction

Figure 3.2 presents a schematic diagram of the experimental micro-SOFC liquid desiccant tri-generation system. The three main sections (1) SOFC power generation system, (2) SOFC waste heat recovery (WHR) circuit and (3) liquid desiccant system.

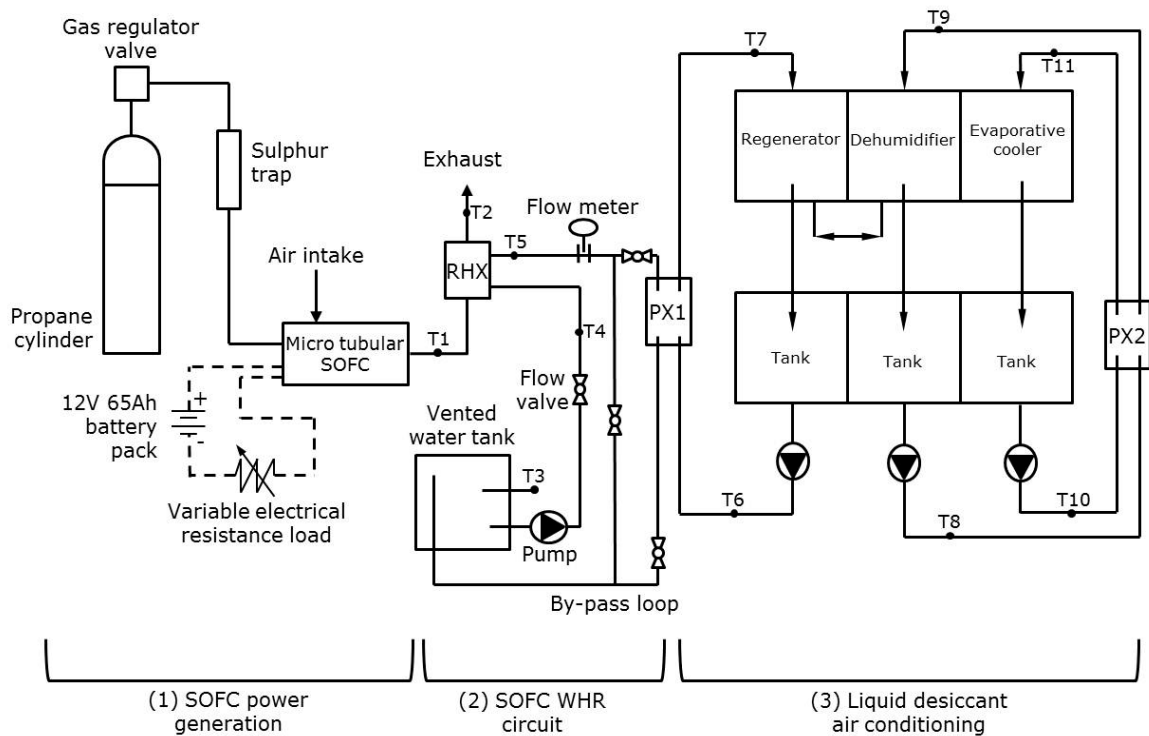


Figure 3.2. Diagram of the micro-SOFC dehumidification and cooling rig

Section 1 consisted of a micro-tubular SOFC of 250W of electrical output and 1000W of heat output, a propane cylinder, a regulator, a sulphur trap, an electrical load provided by an array of 50W DC lamps, and a 12V DC 65Ah battery pack. Section 2 consisted of the exhaust heat recuperator (RHX), a water circuit, a pump, a flow control valve and a flow meter. The liquid desiccant air conditioning unit (3) consisted of a dehumidifier, a regenerator and an evaporative cooler.

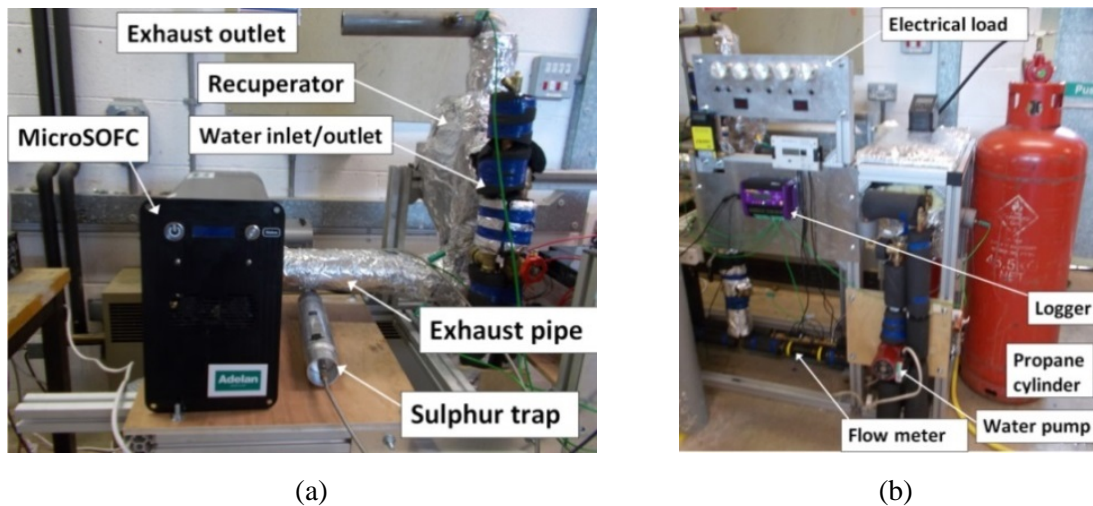
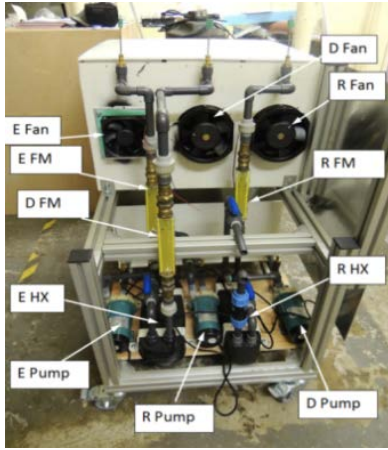


Figure 3.3. Photograph of (a) the SOFC power generation and (b) WHR circuit



(a)



(b)

Figure 3.4. Photograph of (a) desiccant unit (b) membrane section

Figure 3.3(a) shows the micro-tubular SOFC, the exhaust pipe, the recuperator, the sulphur trap and the exhaust outlet. Figure 3.3(b) shows the propane cylinder, the regulator, the electrical load, the datalogger, the pump and flow meter. Figure 3.4(a) and 3.4(b) shows the dehumidifier, which consists of three distinct sub-cycles, a dehumidifier, a regenerator and an evaporative cooler. In each circuit, a magnetically driven centrifugal pump delivers liquid from a tank situated at the bottom of the rig to the membrane mass/heat exchangers at the top of the rig. In the dehumidification circuit, a pump (D Pump) delivers strong desiccant solution from a tank at the base of the unit to the membrane mass/heat exchangers at the top of the unit (Dehumidifier). The desiccant flows through a plate heat exchanger (E HX) which transfers heat from the desiccant system to the evaporative cooling system. An axial flow fan (D Fan) directs air through the dehumidifier mass/heat exchanger. A pump (R Pump) delivers dilute solution to the top of the regenerator via a plate heat exchanger (R HX) which transfers the heat from the fuel cell to the solution. An axial fan (R Fan) directs air through the regenerator heat/mass exchanger. The unit was placed in an environmental chamber where temperature and humidity could be controlled. Worall *et al* (2012) described modelling and analysis, which concluded that potassium formate (CHKO_2) was the most suitable desiccant because of its good regeneration capacity at the low temperatures and its reduced corrosion risks compared to other liquid desiccant solutions. Elmer *et al* (2015a), Elmer (2015b) and Elmer *et al* (2016) described the development and testing of the desiccant unit. Table 3.1 lists the measurement devices along with their ranges and accuracies.

Table 3.1 Instrumentation equipment and associated accuracy

Measurement device	Measurement subject	Measurement Range	Accuracy (of the reading)
HMP110 relative humidity and temperature probe	Air relative humidity and temperature		$RH_a = \pm 1.7\%$ $T_{\text{air}} = \pm 0.2^\circ\text{C}$
RS AM4204 hot wire anemometer	Air velocity	0 to 20 m/s	$u_{\text{air}} = \pm 5\%$
Type-K thermocouple probe	Desiccant solution and water temperature	0 to 1100°C	$T_{\text{des}} / T_{\text{w}} = \pm 0.5^\circ\text{C}$
Parker Liquid Flow Indicator	Desiccant solution and water volumetric flow	1.5 to 10 L/min	$v_{\text{des}} / v_{\text{w}} = \pm 2\%$

3.3. Test rig operating procedure

At the start of the experiment, a valve from the propane cylinder is opened, and then the micro-tubular SOFC, the WHR pump, and the environmental chamber are switched on. WRR pump and chamber temperature/humidity is then set. Valves to the dehumidifier are switched off and a by-pass loop is opened to allow the system to gain working temperature rapidly. For the first 30 minutes or so, the micro-SOFC does not produce electrical power because it needs to reach a temperature of 200-300°C to enable it to reform fuel into hydrogen. The system is allowed to operate in by-pass mode until the water outlet temperature reaches approximately 50°C. In advance of the system reaching 50°C, the fans and pumps in the dehumidifier rig are started and flows are set. Once the system temperature reaches 50°C, the by-pass valves are shut and the valves to the regenerator are opened. Temperatures and humidity are recorded by a datalogger and voltage, current and volume flows and recorded until the completion of testing.

Once testing is complete, the micro-SOFC is switched off. It takes about 30 minutes for the micro-SOFC to shut down. The desiccant system is switched off, the valves to it shut and the by-pass valves opened. Once the micro-SOFC shuts down the water flow and propane gas are switched off.

4. Results

4.1. Micro-tubular SOFC bench tests

According to the manufacturer, the nominal power output of the micro-tubular SOFC was approximately 250W. Figure 4.1 shows the bench test results.

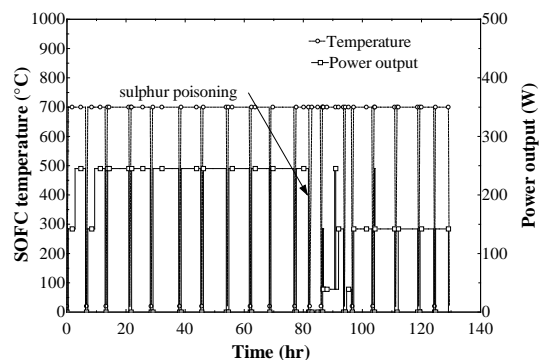


Figure 4.1. Variation in power output, voltage and temperature with time

The micro-tubular SOFC unit was tested for approximately 130 hours, including 19 thermal cycles from room temperature to operating temperature ($\sim 700^{\circ}\text{C}$), one forced stop and one severe sulfur poisoning event. High purity propane gas (99.5%) was used for the first 8 cycles, or approximately 66 hours, and then BBQ propane gas was used from the 9th thermal cycle until the end of testing. Prior to bench testing at UoB, the system had been running for 190 hours.

Figure 4.1 shows that the power output and temperature remained constant throughout the tests, with very little deviation or degradation. From the beginning of the test until the 11th cycle, the power output was approximately 250W, whilst the SOFC temperature remained constant at approximately 700°C.

The graph shows excellent start-up and stop characteristics, with very little degradation over the period. At approximately 80 hours of operation and after 11 cycles, the power output drops to zero. Power output then recovers slowly, until it reaches a maximum of approximately 140W. The reason

that the power output drops and is below the original value is that sulphur poisoning occurs. A sulphur trap was installed in the system, but unfortunately it became full before a replacement could be installed. However, this shows that sulphur poisoning has not completely caused the failure of the fuel cell and that it can recover significant performance after such an event.

4.2. Micro-SOFC CHP system component analysis

Figure 4.2 presents typical micro-SOFC output and Figures 4.3 to 4.5 compare the performance of the tri-generation system at different regenerator solution flows of 3.2 l/min, 2.2 l/min and 1.2 l/min, respectively. In Figure 4.2, during the first 26 minutes, gas burners generate heat to bring the micro-SOFC to its operating temperature. During this period, a parasitic load of approximately 35W was observed as well as waste heat output. The flue gas temperature leaving the micro-SOFC and entering the RHX remained approximately constant at around 340°C. During electrical power generation, the output was approximately constant at 150W. From the start of the test to approximately 130 minutes, the system was in by-pass mode and the heat recovered raised the temperature of the WHR system, therefore there was no external heat transfer. At this point the WHR outlet temperature reached approximately 52°C, the valves to the regenerator were opened and the by-pass valves closed. As heat was transferred to the solution, the WHR inlet and outlet temperatures decreased. Even though the temperatures steadily decreased over time, regenerator heat transfer was approximately constant at 580W.

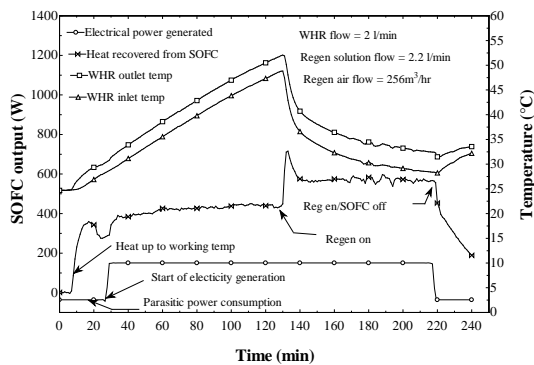


Figure 4.2. Variation in SOFC output and temperature with time, at constant WHR, Regen solution and Regen air flows of 2l/min, 2.2l/min and 256m³/hr, respectively.

In figure 4.3, the regenerator heat absorbed increases rapidly following the opening of the valves and steadily decreases over time. The latent heat absorbed by the regenerator increases rapidly on opening of the flow and then steadily decreases over time until regeneration ceases at approximately 120 minutes. Beyond this point the moisture is desorbed by the air and therefore the regenerator acts as a dehumidifier. The main reason that there is a reverse in sorption is that the solution inlet temperature decreases to a value of approximately 31°C after about 100 minutes. This reduces the solution vapour pressure, and therefore the pressure difference between the air and solution.

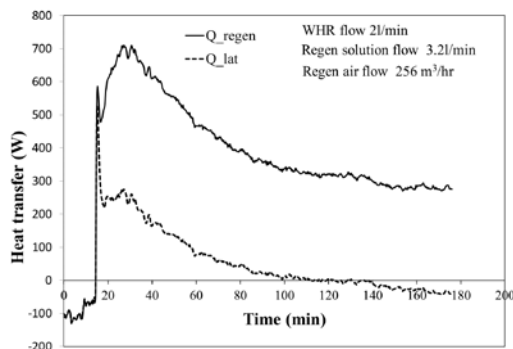


Figure 4.3. Variation in heat transfer with time, at constant WHR, Regen solution and Regen air flows of 2l/min, 3.2l/min and 256m³/hr, respectively (Case A).

Figure 4.4 shows results from tests carried out at a solution flow of 2.2 l/min. In this case, regeneration continues and tends to a constant value of approximately 550W. At a solution flow of 2.2 l/min, the regeneration heat recovery was approximately 600W and the latent heat absorbed was around 400W after 60 minutes. The solution inlet temperature was approximately 33.5°C.

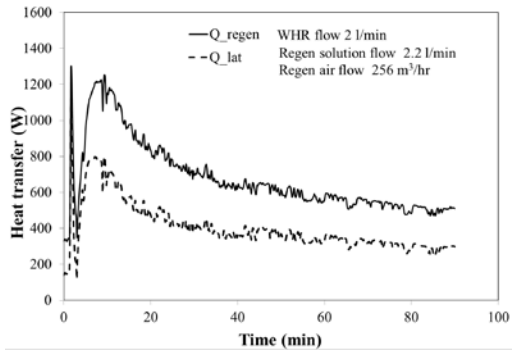


Figure 4.4. Variation in heat transfer with time, at constant WHR, Regen solution and Regen air flows of 2l/min, 2.2l/min and 256m³/hr, respectively (Case B).

In figure 4.5, the regenerator heat absorbed and the latent heat absorbed decrease over time. At 100 minutes, the regeneration heat recovery was approximately 500W and the latent heat absorbed was approximately 200W. The solution inlet temperature at this point was 36.4°C.

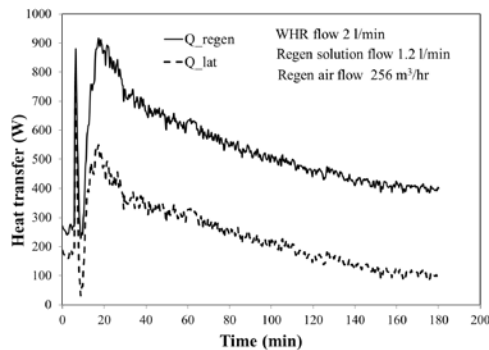


Figure 4.5. Variation in heat transfer with time, at constant WHR, Regen solution and Regen air flows of 2l/min, 1.2l/min and 256m³/hr, respectively (Case C).

The mass regenerated in the three cases was estimated from integration of the curves over an 80 minute period starting from peaks observed following start-up. The mass of water regenerated for Cases A, B and C was 211g, 721g and 596g, respectively. Over the 80 minute time period, the regeneration heat transfer was 0.67kWh, 0.87kWh and 0.85kWh, respectively, whilst the latent heat transfer was 0.15kWh, 0.51kWh and 0.42kWh, respectively. Therefore, Case B produced the highest mass regenerated and therefore was the most effective in converting the waste heat from the micro-SOFC into regeneration. For case B, the regeneration and latent heat transfer rates approximate a steady state after about 70 minutes, with average values of 516W and 300W, respectively.

The main reason for the decrease in desorber temperature over time was due to the desiccant unit operating in an environmental chamber with set temperature and relative humidity, creating a thermal sink for the system. Heat recovered from the recuperator was circulated to the desiccant unit and returned at temperatures close to the environmental chamber temperature. The temperature difference across the recuperator remained approximately constant, with the consequence that the outlet

temperature from the recuperator decreased over time. The system was set up in this way to enable us to investigate the system directly integrated through the recuperator and desiccant unit plate HX and operating in a real conditions.

The results showing regeneration at relatively low liquid absorber temperatures (33-36°C) was surprising, as we expected to require temperatures of above 45°C to obtain any moisture desorption. This demonstrates that liquid desiccants are able to desorb at relatively low pressure gradients between the liquid desiccant pressure and the pressure of water vapour above the surface, and could be effective in utilising waste heat and low temperature heat resources normally dismissed as unusable.

It was observed that even at relatively low absorber temperatures, regeneration (desorption) can be carried out. Not only does this provide instantaneous desorption, but the concentrated liquid that results from the process can be stored for use at other times. The storage of concentrated liquid solution is a form of coolth storage; one that can provide dehumidification and cooling from the difference between the vapour pressure differences between the solution and the water vapour in the air. As long as moist air is prevented from coming into contact with the solution, the concentration will not decrease over time, and therefore the coolth can be stored almost indefinitely. This is a valuable thermal storage resource that is underused, unappreciated and can be produced at relatively low temperatures (40-60°C).

Table 4.1 shows the durations of operation and energy transfers of various parts of the system.

Table 4.1. Experimental micro-tubular SOFC trigeneration efficiency parameters over 80 minutes

Variable	value	Variable	value
Duration	80 min	Regeneration input	0.870kWh
Electrical output	150W	Latent regeneration	0.510kWh
Electrical energy	0.200kWh	Dehumidification cooling Q_{cool}	~527W*
Fuel input Q_{fuel}	~1288W	Dehumidification cooling	0.703kWh
Fuel energy input	1.717kWh	$\eta_{tri-daily}$	57.4%
Parasitic power (pumps/fans, etc)	~ 110W	$\eta_{regen-daily}$	38.1%
Parasitic energy consumption	0.147kWh	COP_{tri}	0.691
η_{elec}	10.7%		

*Elmer, *et al*, 2016

The results reported in this paper refer to regeneration only, but we introduce cooling performance values from earlier publications on testing the same desiccant unit under dehumidification operation. Please refer to Elmer, *et al*, 2016, and Elmer 2015b for full details. An electrical efficiency of 11% is very low compared to other SOFC systems, however, the micro-tubular SOFC is still at an early stage of development, and if issues such as electrical connections, efficient power extraction, manifold design and optimised fuel and oxygen flow regimes (Lawler et al, 2009) are addressed then more efficient systems will be available, with the advantages of good stop-start characteristics, the ability to withstand large thermal cycles and long term performance and durability. Tri-generation efficiency is 57.4%, which shows that the integration of the desiccant dehumidification and cooling system with the fuel cell enhances its performance significantly. The heat recovered (0.870kWh) could be used for any purpose, but we want to use it for regenerating moisture, therefore, the regeneration efficiency is 38.1%. When we investigate the cooling side of the system, we find that the tri-generation COP is 0.691. This represents the proportion of the cooling that can be achieved from the waste heat, taking

into account the parasitic losses. This value is quite a good achievement at these low regeneration temperatures (33-36°C).

The micro-tubular SOFC unit is designed to generate 250W of electrical power, but the unit suffered sulphur poisoning during bench testing, and so performance was poorer than expected. At 250W_e, an electrical efficiency of 17.9%, a tri-generation efficiency of 64.5% and a daily regeneration efficiency of 45.2% would be achieved, assuming similar parasitic power, fuel input and cooling requirement.

5. Conclusions

This paper has described a micro-SOFC tri-generation system integrating a microtubular solid oxide fuel cell and an open cycle membrane separated dehumidification and cooling system. We have demonstrated regeneration of moisture from a liquid desiccant at relatively low temperatures 33-36°C, using heat recovered from the SOFC. The maximum moisture regeneration rates were in the region of 0.1-0.15 g/s, which equates to about 300W of latent heat absorbed. Electrical efficiency was low at around 11%, but we have showed that the integration of the dehumidification unit more than doubled the efficiency to just over 38%. The fuel cell we used was originally 250W of electrical output, but sulphur poisoning reduced its performance. A unit with design specification output would achieve an electrical efficiency of 18%, a tri-generation efficiency of 65% and a regeneration efficiency of 45%.

Acknowledgements

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