D6.1 Final Public Report

FCH – JU – 2011 - 1

FCJ JU Grant Agreement number: 303454

TriSOFC

Durable Solid Oxide Fuel Cell Tri-generation System for Low Carbon Buildings

Joint Technology Initiatives – Collaborative project (FCH)

Annex I: date of latest version - 29 April 2015

Reporting period: 1st August 2012- 31st July 2015

By

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July 2015

Summary description of project context and objectives

Due to the increasing concern over the provision of future energy and global warming, there is a significant interest in the development of alternative clean energy sources and efficient power generators. According to the World Business Council for Sustainable Development, buildings consume 40% of the world's primary energy using for cooling, heat and power, and most of it is from electricity generated at centralised power stations, where at present up to 70% of available energy is lost. The overall system efficiency is low leading to high waste of energy resources resulting in considerable CO_2 emissions and unnecessarily high running costs. Reducing the energy consumption of buildings can make a substantial contribution towards attaining the European Union's 20/20/20 targets and at least 80% reduction in its carbon dioxide emissions in 2050. But this will only be achieved by moving from conventional centralised power generation systems to onsite highly-efficient clean micro-generation technology.

One of the more promising possibilities for this future energy generation is the solid oxide fuel cell (SOFC), which uses the hydrogen from the gas stream to generate electricity through chemical reactions in the anodes, and the only by-product is water vapour and a modest amount of carbon dioxide [1]. This is more efficient than simply combusting the fuel. The technical assessment demonstrated that if the CHP (combined heat and power) technology is used with SOFC, the total system efficiency can be as high as 90% [2,3]. CFCL (Ceramic Fuel Cell Ltd, Australia) reported that the SOFC residential market is 17,000 kW per year, thus a big market potential. Even a moderate size city such as Stockholm has a plan to construct green residences incorporating 6000 units (5 kW) fuel cell CHP units.

Unfortunately, although the technical assessment for the SOFC micro-generation system shows a promising future for high energy efficiency with a potential big market, the durability and lifetime of the SOFC system has yet to be solved. These problems arise from fuels, such as natural gas (methane), the widely available fuel in residential buildings, also containing sulfur. Sulfur poisoning [4] and carbon deposition from methane [5] are two major issues inhibiting application of conventional SOFCs with Ni-YSZ (yttrium stabilized zirconia) as anodes [2]. High operating temperature is a further considerable challenge. To achieve a better performance, the conventional SOFCs using YSZ are usually operated around 1000 ºC, but this can only be achieved at technical complexity and consequently cost that inhibits commercialization. A breakthrough on low temperature SOFC (LT-SOFC) materials has been made by the applicant in KTH, based on ceria-carbonate two- or multi-phase nanocomposite, showing an excellent tolerance to the sulphur poisoning and carbon deposition, reaching a high power density of 1.2 W/cm^2 at temperature as low as 500 °C. Furthermore, the invented materials have provided feasibility for manufacturing LT-SOFC stacks below 400 €/kWe, compared to more than 1000 €/kWe of the conventional SOFC stacks. Some of these exciting research achievements were recently highlighted by *Materials Views* [6] and *Nature Nanotechnology* [7].

Desiccant system, in the context of HVAC (Heating, Ventilation, and Air Conditioning) applications of indoor environmental comfort, 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, also called CCHP (combined cooling, heat and power), 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 buildings, but also

cooling and humidity controlling. According to the extensive work carried out by applicant in NOTT [8], this desiccant unit could increase the total system efficiency by 13-16%. So, ***the overall aim of this project*** is to develop a low-cost durable LT-SOFC tri-generation prototype, based on the breakthroughs in LT-SOFC and the desiccant technologies already made by applicants involved in this project. The proposed system could be used for residential and commercial buildings (e.g. school buildings/offices), providing cooling, heat and power for the living space. It will be tested under real-life context using a unique zero-carbon modular home as part of the Creative Energy Homes at the University of Nottingham. The environmental sustainability of the prototype will be assessed by means of Life Cycle Assessments studies, and the result obtained will be disseminated to industry and research as proof-of-concept of fuel cell systems for stationary applications for sustainable low carbon buildings.
Despite SOFC technology lagging PEMFC and MCFC by a number of years it presents a significant opportunity for many applications, including buildings, due to its fuel flexibility. More stimulus is needed to advance SOFC technology, particularly in Europe, and a low carbon building application will provide this. TriSOFC aims to define, develop and deliver LT-SOFC tri-generation technology in low carbon buildings for early market application. The project will be carried out as an integration of material, nanotechnology, device fabrications and stack, unit constructions to system integrations, field-trials and public demonstration joining closely to the marketing explorations.

TriSOFC aims to design, optimise and build a 1.5 kW low-cost durable LT-SOFC tri-generation prototype, based on the integration of a novel LT-SOFC stack and a desiccant unit. Additional components of the system are a fuel processor to generate reformate gas when natural gas utilized as fuel and other equipment for the electrical, mechanical and control balance of plant (BoP). All these components will be constituents of an entire fuel cell tri-generation prototype system to supply cooling, heat and power, which will first be tested in the lab and, after further optimisation and miniaturisation, under real-life context in the Creative Energy Homes platform built at the University of Nottingham. TriSOFC is primarily aiming at the low carbon building platform using natural gas but will also integrate with other available resources (e.g. alcohol, propone, renewable biomass liquid fuel and biodiesel) with simple modifications. Natural gas was chosen as the fuel due to its widely availability in current residential and commercial buildings compared to hydrogen and other fuel resources. Other renewable fuels will also widely suitable for North European regions, e.g. fuels made from biomass resources. The design of the tri-generation system will be primarily driven by the high efficiency, low-cost and long–term duration. It will open opportunities for exploitation in other sustainable low carbon applications.

Project objectives of the period

The main technical objectives of the period are listed below:
Apart from the main technical objectives given above, further major objectives of the project are listed below:

- Improvement of materials for LT-SOFC technology with respect to power density and minimising degradation of cell performance;
- Optimisation of LT-SOFC cell and stack design as well as of the entire generator system for a low cost application; Design of a complete SOFC power system (i.e. including balance of plant and control system) capable of meeting the varying power demands of a low carbon building over a comfortable life space;
- Improvement of materials and design for membrane desiccant technology;

- Integration of LT-SOFC and desiccant components into an application under challenging constraints including system efficiency, lifetime and cost targets to meet market requirement;
- System testing both in the lab and in field-trials under real-life context to improve the whole-system design and the understanding of degradation mechanisms of LT-SOFC stacks.
- Environmental sustainability assessment by Life Cycle Assessments studies carried out according to the International Life Cycle Data System (ILCD) handbook requirements;
- Evaluate the prototype system to international standards and finish the risk assessment, defining the requirements in the applications in sustainable buildings and developing recommended practice for the tri-generation concept.
- Economic assessment and investigation of spin-off opportunities into other market sectors, especially residential building applications;
- Dissemination of information to industry and research via a regularly updated website as well as publications and presentations at relevant conferences;
- Development of exploitation routes for bringing the new technology to market;
- Strengthening of the European position in this technological field.

Summary of the recommendations from the previous reviews and comments on how these have been taken into account

The mid-term review recognised major delays in delivering the project objectives and milestones, which was partly due to the withdrawal of one of our partners, GETT fuel cells (Sweden) who would have been work package leaders in developing the fuel cells from laboratory-scale, to commercial, and the challenging nature of the single component low temperature fuel cell development. The review also highlighted project management that was ill-equipped for the complex tasks required. Following on from the mid-term review assessment, the consortium developed a plan to address the concerns of the reviewers. An amendment to the agreement was submitted and was accepted on the 29/04/15. The main features of the amendment are highlighted below. The amendment requested no further funding or extensions, but some reallocation of funding was required. Details of all amendments requested are given in Appendices A and B of the DoW. The main recommendations of the mid-term review are summarised below.

Recommendations

Improve efficiency and reduce size of the desiccant cooling/storage unit.

Action: a second unit has been designed and tested

Focus on advancements in LT-SOFC technology and the development of the natural gas auto-thermal reformer and integration of the tri-generation system.

Action: WP5 will focus on reformer development using SOFC fuel cell simulation systems

It was suggested that the remaining activities should be focussed on 1-layer planar type SOFC design and purchase a conventional commercial SOFC stack to be used in final prototype testing.

Action: KTH and VSS will concentrate on developing the carbonate free single component material and developing a planar-type stack. The constortium will purchase a SOFC from

Adelan Ltd, UK suitable for integration with the tri-generation system and complete the prototype and system testing (WP6) and field trials (WP7).

The reviewers recommended that the consortium abandon the development of the microtubular SOFC and concentrate all resource on the planar type stack.

Action: The consortium has a great deal of experience in microtubular SOFCs and we would like UBHAM and IVF to work on developing the material for use in such systems. The work would involve developing single tubes that have good performance and durability. Results so far do not show good performance or durability, but the manufacturing methods are different, so if the partners could develop a manufacturing method that gave good performance, then this would be a major outcome for the consortium. We think that for the time left on the project, the consortium would benefit from the work.

The referees recommended that a clearly defined plan for activities should be provided.

Action: An activities plan has been drawn up with stop/go points and has been included in the amendment to the DoW.

The referees recommended that we focus on an exploitation strategy to maximise the impact of the project.

Action: The exploitation manager, Ibrahim Pamuk, is developing an exploitation plan.

Development of the single component LT SOFC membranes and stacks and integration with the tri-generation system should be carried out independently. It was recommended that a SOFC should be purchased that was suitable for tri-generation integration and tested in the field.

Up-scaling of stacks to 1kW and above was considered unachievable and so should be halted.

We recognise the severe delay in the project and acknowledge the difficulties arising from the novel character of the materials and recipes used in developing the LT-SOFC fuel cell, the withdrawal of GETT Fuel Cells from the project due to bankruptcy and inadequate coordination and co-operation between partners. The consortium has agreed to submit an amendment to the DoW to address some of the delays and enable the project to reach a successful conclusion.

Action: An amendment to the DoW has been developed and was submitted to the project scientific officer for consideration. The amendment was accepted by the scientific officer and came into effect on 29/04/16.

We acknowledge the promising work carried out on the single component cells so far, but delays have resulted in lack of progress in developing more than a 2 cell stack.

Action: Professor Binzhu Zhu has invented a new carbonate free nanocomposite material that shows promising potential. Tests at laboratory scale show the potential for good performance, as recognised in the assessment. In order to produce planar fuel cell stacks of up to 200We, a scale-up in production is required. KTH, or the other partners in the consortium do not have the expertise or facilities to mass produce the materials and form them into membranes suitable for stack construction. KTH had requested that the scale-up production and membrane manufacture are carried out by a third party, Hubei University, China.

Action: We have proposed that some of the resources allocated to KTH should be used to pay for sub-contracting of the scale-up production of materials and manufacture of single component cells. The sub-contracting request is described in the amendment letter and amended DoW.

The reviewers recognised a major weakness in the reports, indicating a lack of strategy to overcome difficulties and delays.

Action: The consortium has developed a plan of work that includes contingency plans that will enable us to achieve our objectives if further problems arise.

The reviewers also recommended the development of an exploitation strategy to maximize the impact of the project at EU level and the fuel cell and hydrogen community.

Action: The exploitation manager, Ibrahim Pamuk, has drawn up an exploitation strategy and the consortium will be organizing activities to support engagement with the community.

Description of S & T results/foregrounds

Work packages and tasks of the period

WP1 Project management and co-ordination

WP2 Desiccant unit development

WT2.1 Heat and mass transfer
WT2.2 Working fluid and membrane evaluation
WT2.3 Heating/cooling unit design and test
WT2.4 Heat storage investigation

WP3 LT-SOFC component and single cell fabrication

WT3.1 Material engineering and production
WT3.2 Cell component/MEA development
WT3.3 MEA and single cell fabrication
Task 3.4: Scale up
Task 3.5: Testing and evaluation
Task 3.6: Development of carbonate free nanocomposite cell:

WP4 LT SOFC stack development

WT4.1 Stack construction and development
Task 4.2: Flat-tubular/group type stack
Task 4.3: Planar type stack
Task 4.4: Micro-tubular type stack:
WT4.5 Modelling
Task 4.6: Testing and evaluation

WP5 Tri-generation system integration

WT5.1 Reformer development for natural gas and bio-fuel
WT5.2 Thermal management system
WT5.3 Power management system
WT5.4 Electronic control system
WT5.5 Tri-generation system design

WP6 Prototype system testing

WT6.1 Laboratory test of the components
WT6.2 Assemble of the prototype
WT6.3 Testing and modification of the prototype
WT6.4 Analysis of the testing results

WP7 Field trials of the prototype system

WT7.1 Prototype system installation and commission
WT7.2 Prototype system testing under real-life context
WT7.3 Thermal management analysis

WP8 Economic and environmental assessments

WT8.1 International standard evaluation
WT8.2 Economic evaluation
WT8.3 Environmental sustainability assessment
WT8.4 Risk assessment

WP9 Dissemination activities

WT9.1 project website
WT9.2 Dissemination activities

The deliverables for the period

D2.1	Working fluid and membrane evaluation
D2.2	Desiccant cooling/heating unit
D2.3	Desiccant heat storage unit
D3.1	LT-SOFC material and production report
D3.2	Component, MEA and single cell fabrication
D3.3	Progress report of on carbonate free nanocomposite fuel cell testing
D3.4	Report on performance and durability of carbonate free fuel cell
D4.1	Device construction report
D4.2	Report planar stack
D4.3	Report on micro-tubular type stack
D4.4	Carbonate free Device/stack modelling and performance testing results
D5.1	Reformer development report
D5.2	Thermal management system
D5.3	Power management system
D5.4	Electronic control system
D5.5	Tri-generation system design report
D6.1	Main component pro-testing results
D6.2	Prototype detail construction data
D6.3	Prototype testing and evaluation report
D7.1	Prototype installation and commission report
D7.2	Prototype testing and analysis results
D7.3	Prototype demonstration
D8.1	International standard evaluation report
D8.2	Economic assessment results
D8.3	Environmental assessment results
D8.4	Risk assessment report
D9.1	Project website
D9.2	Dissemination activity reports

Work Package 2: Desiccant unit development

Working fluid and membrane evaluation

Introduction

Up to a half of all energy consumption and up to a third of carbon dioxide emissions in the developed world are from buildings and almost a half of this is due to heating in winter in cold climates and cooling in summer in hot and humid climates. A combination of energy efficiency measures within buildings and efficient building services systems could dramatically reduce energy consumption and carbon dioxide emissions in the building sector. Combined heat and power (CHP) and combined cooling, heating and power (CCHP), also known as Trigeneration, could reduce carbon dioxide emissions in domestic and non-domestic buildings by exploiting waste heat for heating in winter and cooling in summer, improving the overall efficiency of the power generation system, replacing conventional heating and cooling plant and more fully utilising the waste heat.

The low temperature solid oxide fuel cell being developed through this project, wastes up to a half of the primary energy supplied as heat, and so the exploitation of this heat will improve the performance of the fuel cell in comparison to conventional solid oxide fuel cells.

Waste heat can be stored sensibly in conventional tanks as hot water, stored as latent heat using ice or other phase change materials (PCMs), or chemically, as binary systems that absorb or desorb the heat of absorption/desorption. Partner 4 is carrying out analysis of the options for storing the waste heat from the fuel cell.

Modelling work is an essential task for the design, building, testing and optimisation of the liquid desiccant air conditioning unit for the TriSOFC system. Modelling work has been used to identify the important operating parameters of the desiccant unit, to facilitate optimisation, to predict the performance of the unit under variable conditions and to assist in sizing of a unit suitable for the application. Two stages of modelling work have been conducted for the desiccant unit. A preliminary 1-D model was used to obtain initial estimates and to select a suitable working fluid, then a more comprehensive 2-D model was developed for specific unit sizing and fabrication.

One-dimensional modelling

Preliminary modelling work has been carried out for the desiccant dehumidification system. The performance of a desiccant air conditioning system is strongly related to the quantity of water condensed from the humid air to the desiccant solution in the dehumidifier. In the literature there are numerous validated models predicting this quantity, however it should be stated that the majority of these correlations are only valid to the specific desiccant unit and solutions for which the correlations were obtained. Therefore, a simplified model to estimate the preliminary performance of the novel cellulose fibre packed bed system based on fundamental equations would be valuable at this stage of modelling work.
The preliminary modelling task has called upon the work of (Gandhidasan 2004; Gandhidasan 2005). Gandhidasan describes a relatively simple model for the preliminary design of a liquid desiccant air conditioning system, using dimensionless vapour pressure and temperature difference ratios. These ratios are used to derive an expression to determine the mass of water vapour condensed from the air to the solution in the liquid desiccant dehumidifier shown and

for the mass of water vaporised from the desiccant solution to the scavenging air stream in the regenerator, both in terms of known operating parameters. The model has been validated by well-regarded experimental data presented in the literature provided by Fumo and Goswami (2002) with very good agreement.

Basic working principle

In the dehumidifier mass transfer (dehumidification) occurs due to differences in vapour pressures. The cool concentrated desiccant solution exhibits a vapour pressure which is lower than that of the water vapour present in the humid air, therefore the moisture moves from the air to the solution. In addition to this in summer it is expected that the temperature of the humid air that enters the desiccant dehumidifier is higher than the desiccant solution temperature, therefore sensible heat transfer will also occur. The greater the cooling of the desiccant solution prior to entering the dehumidifier, the greater the heat and mass transfer, and thus the greater cooling output. Following dehumidification, the weak desiccant solutions needs to be regenerated i.e. re-concentrated. This takes place in the regenerator. Prior to entering the regenerator the desiccant is heated first in the desiccant to desiccant heat exchanger (also used to pre-cool the desiccant flowing to the dehumidifier), then using an external source e.g. the fuel cell. In the regenerator, the heated weak desiccant solution will have a vapour pressure higher than that of the scavenging air stream, thus the water vapour present in the solution will transfer to this air stream, thus re-concentrating the desiccant solution ready for dehumidification in the dehumidifier.

The modelling work was carried out using Engineering Equation Solver (EES), a general equation solving program that can numerically solve thousands of coupled non-linear algebraic and differential equations. Air and water property routines are inbuilt functions in EES, making calculations involving psychrometric functions much easier. Once the model had been developed, and adjusted such that the output results were in good agreement with the experimental and theoretical results presented by Gandhidasan (2004) and Fumo, parametric analyses were carried out. Parametric analysis for the dehumidifier and regenerator has looked at the variation of mass condensed/evaporated in the dehumidifier/regenerator respectively with:

- Cooling water temperature
- Regeneration temperature
- Fluid flow rates (air and desiccant)
- Fluid flow rate ratios
- Heat exchanger effectiveness
- Different desiccant solutions – LiCl, $CaCl_2$ and $CHKO_2$

Furthermore a parametric analysis of the inlet operating conditions of the desiccant unit was investigated; this was to see the effect environmental conditions had on performance. In this analysis, the following were assessed in terms of cooling output:

- Air inlet temperature

- Air inlet relative humidity

The parametric analysis has been used to identify the parameters that have the greatest influence on performance. It has also shown the optimum environmental conditions for which the system should be operated in. The initial stage of preliminary modelling results is split into two sections: dehumidifier and regenerator.

Summary of initial modelling results

The moisture removal rate of the process supply air is strongly controlled - assuming constant mass flow rate, by desiccant temperature and cooling water temperature. The air inlet conditions have a large influence on performance in terms of cooling output. The unit will generally perform better in a hot and more humid climate such as southern China, or the Middle East as opposed to drier cooler climates such as the UK. The Potassium Formate desiccant solutions shows the highest cooling performance for the given conditions, and with its lower environmental impact compared to LiCl and $CaCl_2$, is a suitable solution for the desiccant unit in the TriSOFC system.

As the regeneration heat source temperature increases, the mass of water vapour vaporised from the weak desiccant solution increases. Although too high a desiccant concentration is not always required, a higher regeneration temperature could mean a lower desiccant and air flow rates are required (beneficial to COP) in order to yield a similar outlet concentration and for the mass balance between dehumidifier and regenerator to be satisfied.

Although basic, this modelling has helped understand the fundamentals of the liquid desiccant system, namely the interactions observed in the parametric analysis. The current model does however have its limitations and is not particularly robust; for example it does not include the heat and mass exchanger effectiveness of the cellulose fibre membrane, geometry of the contactor or desiccant carry-over. Furthermore, there have been some issues encountered with the described model such as assessing the variation of desiccant concentration and mass flux condensed/vaporised. However the above model has provided a valuable quick evaluation tool for operational performance of liquid desiccant dehumidification systems.

This initial modelling work will be essential for the development of a more comprehensive 2D component based model and future intended experimental work.

The next stage of modelling will aim to develop a model in order to obtain more accurate, specific results for the novel cellulose fibre based liquid desiccant air condition unit, operating with a potassium formate solution. Following the development of the more comprehensive desiccant contactor model, the aim will be to develop a system model, linking the dehumidifier and regenerator models together, including a desiccant to desiccant heat exchanger. This work will enable parametric analyses to be carried out to determine the optimum operating strategies for improved system COP, as this will be crucial to the fuel cell tri-generation systems overall performance.

Desiccant heating/cooling unit

Introduction

The main working parts for dehumidification are a desiccant core (D/C) and a regenerator core (R/C). A water core (W/C) provides evaporative cooling to the water flowing through it and indirectly cools the desiccant returning from the R/C exchanger. The PEC core provides additional indirect evaporative cooling to the supply air before it enters the space. A number of pumps are used to circulate desiccant and water around the system.

The system works as described here: Inlet air (IA) at humid conditions enters the dehumidifier and is directed through fibre membrane heat/mass exchangers. The membranes allow water vapour to pass through, but prevent desiccant liquid or air to pass through. The water vapour close to the surface is absorbed due to differences in vapour pressure and concentration between the air and the liquid desiccant. The air leaves D/C with a lower moisture content and a temperature dependent on the temperature and flow rates of the desiccant entering the D/C core.

The air is supplied to the PEC core where it is cooled indirectly, therefore the moisture content remains the same but the temperature is reduced, with an increase in relative humidity. The PEC core cools the supply air by creating separate channels where supply air, working air (RA) and water flow adjacent to one-another. The working air is in contact with the water through the fibre membrane exchanger. Moisture is evaporated into the working air stream and causes sensible cooling of the water in the channel. This channel is adjacent to the supply air channel, but moisture is prevented from migrating. The supply air is sensibly cooled indirectly by the water which was cooled directly by evaporation into the working air stream.

The desiccant liquid leaving D/C is in a dilute state and is collected and pumped to the regenerator core (R/C). It is passed through a liquid/liquid heat exchanger where hot water from the fuel cell (or other heat source) is used to increase its temperature. The desiccant then enters the R/C core, which is similar to the D/C core in that desiccant and air are separated by fibre membranes which allow moisture to pass. Moisture passes from the liquid desiccant to the air and in the process the liquid desiccant becomes more concentrated. The liquid desiccant is then collected and pumped to the dehumidifier to complete the circuit.

An additional air to air heat exchanger (A/A HX) may be employed to recover heat from the R/C air and reduce heat required from the heat source (fuel cell).

The liquid desiccant that is pumped from the Regenerator is at a relatively high temperature, and this would tend to increase the temperature of the supply air and reduce dehumidification potential so a liquid/liquid heat exchange is usually employed to recover heat and pre-cool the desiccant entering D/C. This may be achieved by either by using domestic water or an evaporative cooling heat/mass exchanger.

As may be seen from the schematic and diagram, the system can become very complicated, take up a lot of space and create losses in ducting, pipework.

We proposed to develop a more compact dehumidification unit which incorporated the heat/mass exchangers in one unit.

In this diagram, we can see that there are three air streams, F and R. There is one supply air, S, and return air, R, and two exhausts, E1 and E2.

The diagram does not show the liquid desiccant or water circuits. Liquid desiccant is delivered to the top of the system and flows through channels which separate air and desiccant. The inlet air is increased in temperature by a heater, which derives its heat from the fuel cell. The difference in temperature, vapour pressure and concentration between the water vapour in air and desiccant drives moisture out of the solution and into the air stream.

The liquid desiccant flows down the channels and leaves the regenerator, where it enters the desiccant cooling section. Here, a separate air steam taken from return air from the room flows though the channels. In this heat/mass exchanger, water is delivered to the top of the desiccant section and flows in channels adjacent to the air stream. Adjacent to the water channels are impermeable desiccant channels. As air flows through the channels, moisture transfers from the liquid to the air stream and evaporates into the air stream, this causes evaporative cooling and sensible cooling of the desiccant flowing next to it (by conduction).

The liquid desiccant leaves the cooling section and enters the dehumidification section. Here, humid air is delivered from the outside to the fibre membrane channels and comes into contact with liquid desiccant in adjacent channels. The difference in vapour pressure drives moisture from the air to the desiccant producing dehumidification and diluting the liquid desiccant.

Instrumentation and equipment

Desiccant and water temperature - *K Type Thermocouples*
Temperature measurement range - 0 to 1100°C

Desiccant and water volumetric flow rates – *Gems digital turbine flow sensor*

- 0.5 – 5 l/min for desiccant flow
- 1 – 10 l/min for regenerator heat exchanger loop
- -20°C to 100°C operating temperature range
- Maximum pressure – 200psi
- Operating voltage – 5 to 24V DC
- Output – 50mA
- Accuracy - +/- 3% of reading

Air temperature and relative humidity – *HMP110 Humidity and Temperature Probe*

- Stainless steel
- Relative humidity measurement range - 0 to 100% (+/- 1.7%)
- Temperature measurement range - $^{-}$40°C to 80°C (+/-0.2C)
- Operating voltage – 5 to 28V DC
- Output voltage – 0 to 5V DC

Data Logger – *dataTaker DT 800*

- 42 analogue senor inputs (42 separate single ended channels or 24 differential channels)
- Measurement across 12 auto-scaling ranges from 10mV to 13V full scale
- All common measurement types are supported
- 16 digital channels
- RS232 port, Ethernet port and Flash card port for dataTaker programming and data retrieval

Pumps – *15W single phase magnetic pump*

- Volumetric flow rate - 10 litre/minute
- Max head – 7 metres
- 3000 rpm

Fan Speed Controllers – *Vent Axia Infinitely Variable Fan Speed Controller, 1.5A, 230V AC*

- Maximum current 1.5A
- Supply voltage 230V AC
- Speed settings – infinitely variable

Results

Desiccant System Test

Test began at 15:34

- Test began with fan speed 1
- Fan speed increased to setting 2 at 15:49 (15 mins)
- Fan speed increased to setting 3 at 16:04 (15 mins)
- Test finished at 16:19
- Desiccant flow, water flow and regenerator flow are all constant though out the test
- All data is on the sheet, just needs manipulating
- The data from the excel sheet has been analysed in EES. Results as follows:

1) Dehumidifier

This graph shows the variation in cooling output from the dehumidifier over time, along with the change in mass flow rate of the air.

2) Regenerator

This graph shows the variation in moisture removal / addition in the dehumidifier respectively. It is evident that these are reasonably balanced.

This chart shows the thermal energy supplied to the regenerator air stream over time

3) Evaporative desiccant cooler

This graph shows the variation in cooling output from the desiccant evaporative cooler over time, along with the change in mass flow rate of the air.

Conclusions

- Need to have a higher inlet air temperature and RH
- Variation desiccant and water mass flow
- Run the direct evaporative cooler at the outlet of the dehumidifier, to increase cooling output and reduce supply air temperature.

Heat Storage Investigation

Introduction

The TriSOFC project started in 1 August 2012 and this report refers to the work developed by the partner IDMEC since the project start, up to the end of July 2013 (first 12 months).
The project programme for this period comprised mostly two Work Tasks: 2.4 – Heat storage investigation; and 2.5 – Storage unit design and analysis.

The objective of this Task is the investigation of heat storage for integration with fuel cell thermal management and desiccant heating/cooling units. Two storage methods were to be investigated for this application, i.e.: PCM heat storage by high temperature salts or PCMs and chemical storage using the desiccant solution as media. The thermal storage methods and storage media were to be evaluated for the merits of high thermal storage density, good dynamic performance and low cost. A survey of possible PCM materials was carried out, considering operating temperatures from 50 to 500ºC, and all types of available substances, namely organic (paraffin based) and inorganic (salt hydrates) ones. Table 1 presents a list of materials and properties.

After the modelling work carried out under Work Task 2.5, it was concluded that the best option seemed to be the use of a storage temperature around 60ºC, in order to be able to recover more heat from the fuel cell exhaust gases. It was also concluded that the best option, to increase heat transfer in the storage tank, consists in using a microencapsulated PCM slurry, by dispersing the PCM capsules in water or liquid metal, with a mass concentration of 40 to 50%. Existing commercial Rubitherm RT60, a paraffin based substance, with a phase change temperature around 60ºC, is a recommendable option. Its present cost is about 6 €/kg.

The use of chemical storage using desiccant solutions as media was investigated next. Lithium Bromide (LiBr), Lithium Chloride (LiCl) and Potassium Formate (HCOOK) aqueous solutions were identified as possible/viable options. Properties for these fluids were gathered, including partial vapour pressure, specific volume, specific heat, thermal conductivity and viscosity, as a function of temperature and desiccant concentration.

A few studies, both numerical and experimental, analysed the use of a desiccant solution as a heat storage medium. Some studies concern long-term (seasonal) storage, such as [1, 2]. Studies based on the so-called Honigmann process were also developed, [3]. In the case of the TriSOFC system, a short-term storage solution (typical daily cycle) is foreseen.

The use of desiccant storage potentially leads to lower storage tank costs, when compared to PCM storage. Although the storage capacity per unit mass is lower (e.g., crystallisation enthalpy of 64.5 kJ/kg for LiBr), the cost of desiccants is significantly lower than that of PCMs (e.g., 3 €/kg for LiBr and 1 €/kg for HCOOK).

Storage unit design and analysis

The objective of this Task is to design a heat storage unit for the prototype of tri-generation system, based on the achievements from Task 2.4, to obtain a high thermal storage density, good dynamic performance and low cost.

In order to be able to simulate the heat storage unit, a system model was developed and implemented in the EES software environment (Engineering Equation Solver). As a first approach, the system configuration consists of a storage tank (with a PCM slurry composed of Rubitherm RT60), including one coil where the fuel cell exhaust gases circulate, delivering useful heat, and another coil that transfers heat to circulating water (this will be later replaced by a flow of desiccant solution). The system model delivered heat to a fan-coil, which then transfers useful heat to a building. This corresponds to the space heating mode (Winter season) – see Fig.2.20. The fan-coil will be replaced by the desiccant heating/cooling heat and mass exchangers for the cooling mode (Summer season).

The fuel cell gases are available at a temperature of 500ºC, according to fuel cell development. According to calculations, it was concluded that a lower storage temperature favours heat recovery from the fuel cell, with about 1200 W recovered for a storage temperature of 60ºC, considering the TriSOFC fuel cell prototype size – see Figure 2.21. The results from Figure 2.21 are valid for coil tube diameters of 1.5” (gases) and 1” (water). The maximum coil temperature on the PCM side (near gas inlet) is equal to about 67ºC, due to the significantly higher outside convective heat transfer coefficient (compared to the gas one).

To model natural convection in the PCM slurry media, previous experimental data for natural convection, obtained for a similar substance (Rubitherm RT6) were used. If it is later decided to choose a PCM slurry, it may be needed to perform new experiments for the substance used, as the geometry and substance have a great influence on natural convection coefficients.

After discussions with partners, it was decided to use for the building model, the planned test building in Nottingham (Creative Energy Homes building). The plans and the corresponding Ecotect description, [4], were provided by UNOTT.

The building is composed of two stories, with a total floor area (2 floors) of 109 m^2. It has a glazed area of 22 m^2. For the purpose of the heat storage/distribution simulation it was transformed into a simplified one-zone building, using average temperatures for the different building elements that were considered: external walls, internal walls, indoor air. A dynamic (unsteady) model was implemented. The building total internal gains were fixed at 500 W (constant).

Several simulations were carried out for Portuguese climatic conditions (Porto), during the heating season. The fuel cell was allowed to operate at nominal conditions (1.5 kW) during a fixed number of hours per day. Excess heat (relative to building heating needs) would then be charging the storage, and released after the fuel cell ceases to operate. It was concluded that for an average day of January (outside average daily temperature of 8.5ºC), the fuel cell needs to operate during 19 hours/day (5:00 to 24:00) to maintain an average indoor temperature of 20.1ºC (within reasonable comfort limits) – see Figure 2.23. The required PCM storage size would be 475 litres, for a slurry of RT60 at 40% mass concentration (with 125 kg of RT60). The energy stored is equal to 5 kWh per charging cycle.

However, with the same system (and building) operating under Nottingham's climatic conditions (average January day, with an average daily temperature of 3.5ºC), and with the fuel cell operating 21 hours/day (3:00 to 24:00), the average indoor temperature would be 16.1ºC – see Figure 2.24. This would be below the minimum comfort standards, and an additional auxiliary heating system would be necessary. For this case study, the stored energy per charging cycle is equal to 3.5 kWh, which means a smaller tank could be used. However, this would not be an interesting situation, with the low indoor temperature. It would be more advisable to run the fuel cell continuously, to increase the heat input to the building, increasing the indoor temperature. Even so, it would not be possible to maintain indoor comfortable conditions: for an indoor temperature of 20ºC, the building heat load is higher than the fuel cell heat output.

The simulation results, and cost considerations, indicated that it would be more interesting to use a heat storage based on a desiccant solution. The same solution will store and distribute the stored heat to the building (through a heat exchanger). By comparison with the scheme of Figure 2.20, no second coil would be needed in the storage tank. The tank model was adapted to include the desiccant solution properties, instead of the PCM slurry, and simulations are underway.

With the present fuel cell capacity and the chosen test building, the use of heat storage doesn't seem very interesting during the heating season. The heat storage unit is more relevant under building cooling conditions (Summer/hot season). Then, under Nottingham's climatic conditions, the heat that is necessary to run the dehumidification/cooling system is presumably lower than the fuel cell heat output, because of the relatively low building cooling load, which makes heat storage feasible and interesting: the fuel cell may operate during part of the day, with the storage tank providing heat to regenerate the desiccant during 24 hours.

In the cooling season, the simplified outdoor air evolution is represented in Figure 2.24. Outdoor air at temperature T_{ext} and relative humidity RH_{ext}, with a corresponding absolute humidity, is dehumidified by releasing water to the desiccant solution (at temperature T and concentration C). Then it is cooled in the evaporative cooler, to the desired supply temperature. For an ideal dehumidifier, outlet air absolute humidity corresponds to a partial vapour pressure identical to the vapour pressure of inlet desiccant solution; this desiccant vapour pressure needs to be lower in order to allow removal of water.

Figure 2.25 represents a comparison between different existing outdoor air conditions (the bars with □ for different air temperatures and relative humidities), and the possible ideal dehumidifier outlet air conditions ($\square_o$) using different desiccant solutions (different T and C values). The results show that LiBr provides the highest dehumidification potential, LiCl satisfies under all conditions, and potassium formate is not suitable for lower temperatures that may occur during the cooling season, even with lower concentrations; it is suitable only for higher temperatures (exceeding 30ºC) and humidities (70-80%).

At the moment, a model is being developed to simulate the system, including information on dehumidifier and evaporative cooler efficiencies for the membrane heat and mass exchangers, for different inlet conditions (provided by UNOTT).

The complete desiccant cooling system, including desiccant regeneration, as proposed by UNOTT is presented in Figure 2.26. A combined regenerator and dehumidifier unit is used. The diagram in Figure 26 also shows the volumetric air flows (not including internal desiccant cooling). Also a cooling tower will be included for water cooling in the dehumidifier.

WP3 LT-SOFC component and single cell fabrication

Contributors: KTH, UBHAM, GETT, IVF

This work package focuses on the optimising the functional nanocomposite materials, ceria-based two or multi-phase materials, to fabricate LT-SOFC components and MEAs. Fabrication protocols with different MEA structures will be considered during developing the program. Various methods will be combined for fabricating single cell. Three types of single cells will be fabricated: the conventional planar type cell, the flat-tubular with completed single cell technology developed by GETT/KTH and the micro-tubular type cell developed by IVF. This amendment proposes that the consortium concentrates on the planar and micro-tubular fuel cells. GETT were tasked with developing and scaling up the stack, but their expertise in flat tubular stacks has been lost to the consortium as well as causing delays in cell development. In the remainder of the project, it is proposed that KTH/VSS develop the planar single cells and UBHAM/IVF develop the micro-tubular single cells. The testing will be performed to components and single cells to evaluate the different process condition and modify the fabrication procedure. Based on the optimization process, the fabrication sizes will be scaled-up to meet applications of LT-SOFC stacks in the tri-generation system.

Materials

The research activities on single-layer fuel cells (SLFCs) or “Three in One” fuel cell have opened new doors for keeping ahead with two major areas of focus: improvement of SLFC performances by contributing new materials, and scientific understanding of the SLFC nature and science as well as technological developments. The successful developments of design and synthesized new materials composed of the ionic ceria based materials and the semiconductors, e.g. mixed transition metal oxides, LiNiCu based-oxide etc., perovskite oxides as well as layered structured metal oxides, combining ionic and semiconducting properties for SLFCs as given below:

- Ion conducting materials:

Doped and co-doped ceria, e.g. SDC (Sm^{3+} doped CeO_2), ceria-composites, with or without carbonates were prepared.

- Semiconducting materials:

1) Various transition element oxides, Ni, Cu, Co, Fe, Mn etc;
2) Perovskite oxides, BaSrCoFe, LaSrCo, LaSrCoFe, LaSrMn, LaSrMnFe, LSCT, SmSrCo, SrFeMo, BaSrFeMo etc (novel perovskite cathode material) and BaCaCoFe composite cathode were synthesized.
3) Layered structured materials: LiMOx (M=Ni, Cu, Co, Fe, Mn, Mo), thousands designs and recipes were tested with extensive efforts.

The main objective of the TriSOFC project is to develop a low temperature (500-600C) solid oxide fuel cell suitable for use in domestic dwellings. The ambitious target of producing a low cost (<400euro/kWe), durable (>40,000 hours) system is being delivered by teams across the European Union with expertise in fuel cells and trigeneration systems. The first year of the project has been targeted at the basic science of developing the novel single component nano-composite material, fabricating and testing single fuel cell elements, developing scale-up methods and investigating novel working fluids, membranes and storage methods for the trigeneration system. Single component materials have been developed by KTH (LiNiCuZn) and tests on pellets have shown improved performance compared to two and three component systems. The maximum performance achieved in this period was

OCV = 0.95 V, I = 1016 mA/cm2 at 230 mV @ 550°C

Compared to a three component pellet with performance of

OCV= 0.95 V, I = 875 mA/cm2 at 180 mV @ 550°C

Nano-composite materials have been developed by KTH with single component characteristics. Tests have been carried out and good results have been obtained. At an operational temperature of 500-550C the OCV achieved was 0.95V and the current density was 1016 mA/cm2 at 230 mV. A 6cm x 6cm x 1mm thickness fuel cell has been developed with a maximum power output of 16W.
Micro-tubular cells have been fabricated by UBHAM by extrusion. Test results show performance comparable with KTH (OCV = 0.9V, I = 0.8A, P = 0.22W. Durability is poor (150-200 min). Micro-tubes thin walled and off-centered. An Investigation into the extrusion of thicker walls to improve performance and durability is to be carried out. New extrusion dies and barrels have been commissioned. Iso-static pressing was to be investigated but the equipment has not been delivered, and so the work has been delayed.

KTH is continuing its efforts for electrolyte free fuel cell recipes which are internationally recognized by fuel cell experts which are success of this project. An article has been accepted for publication in ***Journal of Power Sources*** as given below. FP7 TriSOFC project contribution has been acknowledged in this work. Another paper was submitted in 5th World Hydrogen Technologies Convention (WHTC 2013)-Shanghai Conference. Our research work was selected for oral presentation in the conference where we have successfully presented the work for advanced fuel cell technology. Now the work has been selected for the publication in International Journal of Hydrogen Energy and we have submitted to the Journal. Contribution of FP7 Tri SOFC project has been acknowledged in this paper. The abstract of this work is given below. KTH has got an achievement making joint efforts with its strategic partners and an electrolyte with high conductivity for fuel cell application is generated recently as explained below. By preparing the composite electrodes a very high device performance is achieved. ‘‘Scaled up low-temperature SOFCs with MgZnSDC composite electrolytes for applications’’, in this study, a new type of the $Mg_{0.4}Zn_{0.6}O/Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (MZSDC) composite electrolyte was synthesized using one step co-precipitation method. Recently world record results have been achieved in the experiments with OCV = 1.19 V for EFFC with repeated results by KTH.

At UBHAM, all as-prepared micro-tubular LT-SOFC single cells are tested in the UBHAM lab. Besides of the tubes itself, the influences of temperature, flow rate, cell sealing conditions are also investigated. The durability of some selected tubes was also checked for up to 100 hours operation at 550 ^{o}C. Due to the poor durability of the tubes with current Nanocomposite materials, all testing are still conducted with H_2.The experimental results demonstrated the power performance is highly sensitive to the tube structure, although the testing conditions do have some influence. The power performance of tubular LT-SOFCs can be potentially improved by the optimal structure, but the durability is still a big challenge at the moment and this can hopefully be addressed by the new generation of Nanocomposite material which was recently confirmed by KTH.

The research and development activities have been done on our recent research breakthrough based on the single-layer fuel cells (SLFCs) or “Three in One” fuel cells from new functional semiconductor-ionic materials, technologies for device and stack demonstrations. We have succeeded in the targets according to the project deliverables as below:

1. New materials have been scaled up for production at kgs level thus guaranteed extensive uses for the project (WP3)
2. Scaling up of 6x6 cm^2 cells fabricated and about 2000 of 6x6 cm^2 engineering fuel cells with new materials and new invention of the single layer fuel cell (SLFC) devices instead of the conventional anode/electrolyte/cathode structure. (WP3)
3. Each 6x6 cm^2 SLFC reached at 8-10 watts (Targeted at min 5 watts) below 550 ^{0}C. (WP3)

Scaling up production of the core material and single cells have been performed; Nanocomposite single component materials have been developed by KTH. A variety of single cells have been fabricated with different combinations of semiconductors and ionic conductors. Tests have been carried out and good results have been obtained by KTH. Carbonate-free new single component materials with better performances have been successfully developed and subjected for scaling up productions in kgs. The single-component nanocomposite free electrolyte-free fuel cells (EFFCs) have been scaled up for engineering large size 6x6 cm^2 fabrications by investment for purchasing combined with the hot-pressing machine.

Deviations from DoW

The second amendment to the DoW dated 29/04/16 allowed the consortium to concentrate on developing the nanocomposite materials recently invented by Professor Zhu of KTH, and so there are no deviation from the work plan and deliverables targets.

WP4 LT SOFC stack development

Contributors: KTH, UBHAM, VSS, IVF

A planer-type stack is to be developed by KTH/IVF/GETT. The withdrawal of GETT from the project due to financial difficulties and problems with producing stable and durable materials has delayed this work task. 6cm x 6cm membranes have been tested in a two cell stack. Output of 12W at 550C has been demonstrated. KTH reported durability of over 100hours.
VSS/GETT has carried out mathematical modelling of a SOFC planar stack. A three component (anode/cathode/electrolyte) was analysed and its results compared to work carried out on a fuel cell obtained by VSS.

Dr. Zhu from KTH established a joint lab with a strategic partner matching local finance to develop cells and stack. It involves metal bipolar plate, soft mica sealing materials and single layer engineering and big amount of numbers for large size cells fabrications. The single cell tests have achieved great successes with one cell delivering 10W (6x6 cm^2) in average at 500-600^{o}C; based on the single cell measurements, we started construction of two and five cells short stacks. We have achieved the two cell stack OCVs at 2.2 V (reached perfect expected value) and the power outputs between 3-4 W at temperature 380-500^{o}C. Though we have not enabled to measure our stack at desired temperature 550-600^{o}C as designed power outputs at 20W, these results are the first world record on such extremely low temperature SOFC stack data. It proved our single-component electrolyte free fuel cell (EFFC) has taken away the electrolyte bottleneck with great low temperature breakthroughs. In the latter development, improved the two cell stack power outputs at 12W at around 500^{o}C using the bipolar plates with improved gas distribution channels and sealing-free stack design.

Due to integration of new resources for both invested machine/facilities and team/manpower takes time, our stack developments have just started. Initial results are promising but not reached the expected power outputs. To overcome the current technical problems, our new solutions with new efforts will be soon restarted. For a time being we will overcome the current technical challenges and present more successful results in next term period.

By modelling, according to former planar type stack design studies and experiences two type of stack were designed, verified by performing flow simulations and manufactured. Planar type LT-SOFC stacks fabricated from 6x6 cm2 cells were tested based on 2-5 cells installation, and the optimal stack with 4 cells has been operated in accumulating for 100 hours, subjecting 10 thermal cycling from operational temperature shut-down to room
temperature. A 100 watt stack was successfully demonstrated using 15 pieces of 6x6 cm2 SLFC cells. In parallel, we also co-developed 1000 watt conventional SOFC stack using NiO-YSZ anode supported thin film YSZ incorporated by GDC buffer layer and LSCF cathode, we reached at 1020 watts at 700^{0}C. The conventional 250 eW micro-tubular SOFC stack was also tested with industrial propane for ca. 130 hours, including 19 thermal cycles
from room temperature to operating temperature (ca. 700C), 1 forced stop and 1 severe sulphur poisoning. These joint efforts from Partner 2, 3 and 6 also effectively supported new material stack developments.

Successes:

i) **Two cells reached perfect OCVs, above 2.0-2.2V at temperature above 350^{0}C**

a) **Extremely low temperatures with good catalysts**

b) **Single-component electrolyte free fuel cell (EFFC) by taking away the electrolyte bottleneck showing a great low temperature breakthrough**

For the 5-cell short stack

Due to lack of experience of the new team, our engineers have still lack of skills and practices for more cells installation, the gas leakage is a big problem so far. Though we took risk to test a 5 cell stack, the stack voltage (OCV) reached nearly 5V, but an explosion occurred, the stack could not be continued in a proper way. We are now stopping for some time to improve our stack components, sealing materials and installation of the stack process.

In the latter development, the two cell stack was improved with output power to 12 watts at 500°C with two aspects:

- New bipolar plate design with improved gas distribution channels
- Low temperature and sealing-free focuses

Based on these initial stack developments, KTH team and joint lab have acquired some valuable experience for next project period serious stack developments. Though KTH tasks are assigned for the material and single cell scaling up production and fabrication, but KTH team still need to evaluate and test single cell in device and stack performance in order to verify the single cell quality and to deliver to VSS for the stack installation and reformer system in a complete system. Our scaling up results achieved so far presented in Figure below:

Stack developments Part Three Stack developments WP4
Stack components and installations

In the first designs we have considered some complex installation based on literature (actually almost no such available publication and report) and our engineers´ experience. We integrated all gas inlet and outlet four tubes on one side of the stack terminal plate. This has actually made the gas path ways somewhat complicated also request more supporting components, e.g. mica plate for insulating and separator, additional contact steel plates. Besides everything, during the installation, each single cell and bipolar plate must be mounted in exact collimation; otherwise gas leakage will occur. The last request indeed made our many installations failed because we developed sealant-free stack. This stack technology has actually caused us huge efforts but very low working outputs though we have obtained some successful results, but reproducibility is very low, around 10%.

Four-cell stack development

Then we forwarded to 4-cell stack initiatives immediately based on experience from 2-cell stack. The difficulties we encountered indeed much more than 2-cells, most problems came from the installations and single cells not identical leading to significant gas leakage. These made the stack leakage to very low OCVs, and contact resistances also large to cut down very much the power output as expected. Extensive efforts and learning made us finally to discover the sealant-free stacks which can be installed in a simple way to get rid of all supporting components, only using necessary components. Using a two-cell stack as an example, from left to right, terminal plate bottom, 1st cell, bipolar plate and 2nd cell, top terminal plate for a two-cell stack installation.

100W SLFC stack development

In later stage of the project approaching the end, we have made final effort on the hundred watts level based on our all successes, optimization and control carefully from material, scaling up, and detailed parameters of the hot-pressing process and film production. Finally, installation and demonstration of 100W stack have been made based on extensive 6x6 cm2 successful demonstrations on single cell and tens of watts stack. We have constructed in parallel several 100 watts stacks using 6x6 cm2 cells. A best stack using 15 sets of the 6x6 cm2 cells installed which was successfully operated with a maximum power output actually more than 100W at 550 ^{0}C. But some of these stacks were less than 100W.

Deviations from DoW

The second amendment to the DoW dated 29/04/16 recognised that it would not be possible to develop stacks suitable for integration into a 1kWe SOFC, and so WP4 concentrated on developing stacks using the nanocomposite materials. There are no deviations from the work plan and deliverables targets.

WP5: Tri-generation system integration

Contributors: NOTT, KTH, UBHAM, VSS

Recently, studies have been carried out on the conversion of methane ATR. Authermal reforming of methane (ATR) is a combination of the SRM and noncatalytic partial oxidation of methane (POX), under thermally neutral conditions, considering the heat lost to surroundings. The process associates the cited effects through the feeding of fuel, oxygen and steam on the catalyst bed. By doing this, the process can be operated at much lower temperatures than those in the SRM [1]. In our recent experiments in ATR, average H_2 volumetric percentage is 50-70 % in output gas mixture. Studies have been tried to improve methane conversion with the ATR method.

- Ru-Ni/Al_2O_3 catalyst
- Auto-thermal methane reforming
- Methane flow rate: 600 ml/min
- Air flow rate: 400 ml/min
- Water flow rate: 0.8 – 1.0 ml/min

KTH has developed model for three in one based fuel cells and has validated the experimental data with the model.

1.6.2 $Ba_{0.5}$ $Sr_{0.5}$ $Co_{0.8}$ $Fe_{0.2}$ $O_{3-\delta}$ (BSCF)

Based on work one paper submitted entitled "Modeling and Analysis of Electrolyte (layer)-free Fuel Cell (EFFC) using the perovskite-ceria functional layer", *Sushant Madaan, Muhammad Afzal, Wenjing Dong, Rizwan Raza and Bin Zhu.* An electrolyte (layer)-free fuel cell (EFFC) is developed using a homogenous mixture layer of commercial perovskite, $Ba_{0.5}$ $Sr_{0.5}$ $Co_{0.8}$ $Fe_{0.2}$ $O_{3-\delta}$ and SDC (samarium doped ceria). The open circuit voltage of device reaches up to 1.04 V and delivers maximum power density of 640.4 mW/cm^2 at 560^{0}C; using hydrogen and air as the fuel and oxidant, respectively. A numerical model is designed and an empirical equation,

$$V_{oc} = E - V_a - iR_i - m.\exp(n.i)$$

is presented to fit the experimental cell potential. The exponential term is used to characterize losses in mass transport region. The parameters m and n are introduced to simplify the expression of concentration losses because of non- electrolyte layer used in the EFFC device. The expression of polarization losses is modified as well in the overall losses. The kinetics of anode and cathode reactions are modelled based on electrochemical impedance spectroscopy (EIS) measurements. The theoretical model and simulation results are in agreement with the experimental data of the EFFC and underlying processes are discussed. It is very different from conventional anode/electrolyte/cathode three layer SOFC technology, where two interfaces between the anode/electrolyte and electrolyte/cathode cause major polarization and power loss. The EFFC removes the interfaces to avoid issues related to compatibility and functions as a reactor that can directly convert the fuel to energy at the particle surfaces for electricity generation/power output. Thus EFFC has enhanced the efficiency as compared to conventional device by 18% based on theoretical and our experimental data.

We constructed the EFFC using the core functional layer consisting of perovskite oxide, BSCF ($Ba_{0.5}$ $Sr_{0.5}$ $Co_{0.8}$ $Fe_{0.2}$ $O_{3-\delta}$) as electrode material and Sm^{3+} doped CeO_2 (SDC: $Sm_{0.2}$ $Ce_{0.8}O_{1.9}$) as an ionic conductor (purchased from Sigma-Aldrich, USA), both components were mixed homogeneously in a weight ratio of 40:60 (BSCF:SDC :: 40:60). It can be deduced that higher the exchange current density lower the losses associated with activation, therefore, low temperature fuel cells have higher activation losses as it has small exchange current densities at low operating temperatures which steadily increases and reaches a steady state at higher currents . These losses mainly happen in the reaction zones of the EFFC limited by the electro-catalyst activity and microstructure, determined at triple phase boundary (TPB) regions.

The ohmic resistance in EFFC is governed by the resistance offered by the mixture of electrode and electrolyte materials to the flow of ions and electrons. The internal resistance of the single layer is the internal resistance of the fuel cell deduced from EIS conducted on the homogenous single layer.

The mass-transport over-potential can be expressed as an exponential function of current density.

$$V_c = m.\exp(n.i)$$

Where, m (units of Volt) and n (units of reciprocal of current density) are constants that depend on the conditions inside the fuel cell and have to be determined by non-linear regression analysis. In the model the value of m and n used are 5e-3 and 3e-3, respectively. After including all the expressions of various losses, the operating voltage can be depicted as:

$$V_{oc} = E - V_a - i.R_i - m.\exp(n.i)$$

The interpretation of parameters m and n is important to understand their effect on the V vs I plot. Therefore, a theoretical study is conducted by keeping all the factors constant in the above equation, and only values of m or n are changed, which is discussed in the following section. The open circuit voltage and maximum power density obtained from the model are 1.051 V and 645.5 mW/cm^2 at current density of 1020 mA/cm^2 at 560 ^0C and 1 bar, respectively, whereas the corresponding values from experiment are 1.04 V and 640.4 mW/cm2 at current density of 1043 mA/cm^2 at 560 ^0C and 1 bar respectively. From the figure, it is evident that modelled curve and experimental curve are in good agreement with each other.

Electronic control system

According to existing prototype that mentioned on the Deliverable 6.2 three type of control card design was made and manufactured such as: processor card, mainboard and external analogue/digital converter (ADC) card.

STUDY OF CARD DESIGN

Processor Card

The card which is known as single board computer is entirely designed as software and hardware by Vestel Defence Industry. It works as the brain of the system and is the card that produce and evaluate the control signals, external data buses and address buses come from the processor and the mainboard. It commands the specially designed cards that controls the pumps and for measuring the pressure, temperature and reading the flow meters by addressing the CS, IOW and IOR signals.

Technical properties are listed below:

- NXP 32-bit ARM926EJ-S Core Microprocessor
- 256 KB internal SRAM
- Max. 266MHz working frequency
- 64MByte SDRAM DDR ram
- 128/512 MByte NAND Flash memory
- 2MByte Nor Flash memory
- 32.768KHz RTC
- Watchdog timer
- 16/24 Bit 40-pin Ressiztive touch operated TFT LCD interface
- Micro SD card interface
- ESD saving mini-B type USB OTG 2.0 interface
- 7 quantity of UART
- 1 quantity of Ethernet MAC

- 2 quantity of 3x27 pin (Processor interface connector)

Mainboard

The card works as the connector between the externally designed sensors, control cards and processor card by using AMBA databus on it. At the same time feeding of the IC’s located on the externally designed sensor cards is realized on this card.

The cards whole design was made by Vestel Defence Industry and the technical properties was given below.

Mainboard data communication interface specs:

- Serial port
- 6 x RS232 UART
- 1 x RS-422/485 UART
- 1 x USB UART
- AMBA Bus
- 10 Bit Address Bus and 16 Bit Data Bus, CS, Reset, Read/Write, INT Signals
- Ethernet: 10/100Mbps, RJ45 connected
- I2C 2Kbit EEPROM

Mainboard Input/Output interface specs:

- 1 quantity of Reset button
- 4 quantity of programmable button
- 1 quantity of Stereo earphone connection interface
- 1 quantity of microphone connection interface
- 21 quantity of I2C ve SPI included inlet outlet pini (I/O)
- External RTC ve CR2032 Battery
- 1 quantity of buzzer
- Power meter LED’s

External Analog/Digital Card (ADC)

The card has 15 quantity of thermocouple, and the connection of the card with processor card is supported on AMBA databus. It can process the intended data on the buffer real time by address decoding with CPDL located on it. The received signals coming from the outlet of the 12 bit, 8 channels analog/digital converter are passed on the buffer integration and arrives to AMBA databus.

Output Enable and direction pins of buffer integration are taken of the outlet of the decode circuit that designed on the CPDL. As total 2 quantity of ADC are used and 15 quantity of thermocouple are connected on them. 4 mA-20 mA data as output of thermocouples are dropped on very low resistors and the composed voltage goes into ADC as being single ended.

Via the write only register in the ADC, required thermocouple measurement can be collected or searched on the software interface between required range by addressing.

External Role Card

The card has 6 channel role output and is based on AMBA databus. Air, water and fuel pumps connected otside via the terminal connectors and are controlled on roles. Beside that, if it is required the card has 3 extra control input and has the role control unit that can be extended from 6 to 16.

At the same time, address decoding on the card was designed with CPLD and via the adressing process, it is possible to connect new cards extended to quantity of 48. Card has high voltage and high ESD saving and was isolated via optocoupler. Also it has active role LED's and configurable open/close role output.

The data bus coming from the AMBA goes through the 8 bit LATCH integration and controls the role drivers. Via the signals taken from the output of the LATCH and BUFFER address decoding design it can be possible to control almost realtime.

Reformer development

In our studies direct decomposition, steam reforming and autothermal reforming of methane that are used to obtain hydrogen rich gas mixture were examined. In this conversion process the catalysts containing "Ni", "Fe" and "Ru" metals were prepared by using commercial alumina as carrier. Methane conversion was examined by experiments and the gas mixture which came into effect as experimental result was analysed by the help of Agilent branded gas chromatography device and the volumetric percentages of hydrogen which went out were compared. In the conversion experiments of methane with steam reforming and autothermal reforming the effect of parameters like temperature, gas feeding velocity and the amount of steam to "H_2 " quantity was examined. The coking period was associated with the decrease of hydrogen quantity in the gas mixture going out during the direct decomposition, steam reforming and autothermal reforming of methane experiments. It is observed that the coking periods differ according to conversion methods and depending on the experimental conditions in three applied methods as well.

The Direct Decomposition of Methane with Temperature and Catalyst

The various catalysts are tried in this process. The direct decomposition of methane is given at the following equation:

$$CH_4 \rightarrow C + 2H_2 \qquad \Delta H_{298} = \quad 75 \text{ kJ/mole}$$

Hydrogen and catalytic filamentous carbon (CFC) are products of direct catalytic cracking. Hydrogen produced in such a way is free of carbon monoxide, which is an undesirable impurity. The precipitated carbon causes stress in the metal structure. Eventually, the stress becomes so large that the nickel crystallite is removed from the metal structure. As more carbon is deposited, a carbon filament, carrying a metal particle on top of it, is formed. The influence of the metal particles on the coke formation decreases steadily as the metal surface becomes covered by a carbon layer. The deactivated catalyst can be fully regenerated by either oxidation in air or steam gasification of the deposited carbon. Additional hydrogen is produced during the steam regeneration process. Formation of carbon oxides (CO_x) can be separated in time from H_2 production, since in this case CO_x is formed during the coke removal from the catalytic surface.
While the oxidation step is being done to remove coke, the carbon filaments on the catalyst surface are burned out and they are converted to COx compounds.

Results

It is observed that the catalysts which consist of iron and nickel can be used in the decomposition process of methane during the long hours. The catalyst performed very well between 650- 800^0C temperature range. As a result of reaction in direct decomposition of methane H_2 can be obtained at high ratio; but due to the carbon accumulation on the catalyst, the performance of catalyst falls quickly. The effects of temperature are observed during the direct decomposition experiments of methane which was made by using 15g $Ni\text{-}Fe/Al_2O_3$ catalyst. 100 ml/min CH_4 is given to reactor in specific temperatures. In 800^0 C the average volumetric percentage of H_2 which outputs as a result of direct conversion of methane is 94.84 % ,in 750^0C the average is 74.36%, in 700 ^{0}C 74.04% and in 650 ^{0}C

59.64 % according to chromatography device. In the direct decomposition experiment of methane which is made by using Ni- Fe/Al_2O_3 catalyst. It is observed that H_2 ratio falls due to temperature decline. When the 100 ml/min CH_4 is given to the reactor directly at 800^{0}C, it is observed at that in the course of time the output gas velocity declining. This falling is indication of the initiation of coking which result from the carbon accumulated on the catalyst.

The reactor employed in experiments by using 15g Ni-Fe/Al_2O_3 catalyst is shown at the (Figure 6.20). It is provided to break up in catalytic condition by giving methane from the bottom entrance of reactor and H_2, which is obtained as a result of conversion, is sent to the fuel cell.

The reactor is constituted from two parts which are catalyst reservoir and heat exchanger, the air which comes from fuel cell provides preserving the temperature of reformer. Ni-Fe/Al_2O_3 catalyst is placed into 21 pieces of holes in 1mm diameter which are available in catalyst reservoir of 45mm length.

The deposition of carbon on the catalyst's pores, diffusion and decomposition is the basic coking problem. Due to the reaction at high temperature the coking might be with gas phase reaction. It is openly understood that the coking is a kind of condition exists in conversion processes. The factors such as using the appropriate catalyst, checking the surface reactions are important in preventing the coking.

The Conversion of Methane with Steam:

In H_2 production ''The Conversion of Methane with Steam'' is one of the most important and known method. This is an endothermic reaction and it needs temperature from the outside: The methane steam reforming (MSR) process is commonly described by three reactions: methane conversion to H_2 and CO (Eq. 1), the water gas shift (WGS, Eq. 2), and the direct (overall) MSR reaction (Eq. 3).

$$CH_4 + H_2O + \text{heat} \rightarrow CO + 3\,H_2 \qquad \Delta H = 206\ \text{kJ/mole} \qquad (2)$$
$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H = -41\ \text{kJ/mole} \qquad (3)$$
$$CH_4 + 2H_2O \rightarrow CO_2 + 4\,H_2 \qquad \Delta H = 165\ \text{kJ/mole} \qquad (4)$$

SMR operates at high temperature and under pressure. The replacement of ceramics with structured, metal-based catalysts improves the heat transfer, the catalytic performance and therefore the efficiency of the process.

Alumina is a typical support in catalysts but tends to induce coke formation during steam reforming due to its surface acidity with coke formation a primary steam reforming deactivation process.

Generally, the composition of reforming catalyst typically comprise of transition metals (Ni, Co, Fe, etc.) or noble metals (Pt, Pd, Rh, etc.) deposited or incorporated into carefully engineered supports such as thermally stabilized alumina, doped alumina with promoters to accelerate carbon vaporization and mixed metal oxides. Ni-Fe metals are cheaper than noble metals so they were used as support for alumina in this experiment.

The experiments in relation with temperature effect, coking period and removing period of coke with H_2 are made by using the reactor at Figure-2.3.2 and Ni-Fe/Al_2O_3 catalyst. During the conversion of methane the carbon oxides such as CO_2, CO are also released in addition to H_2.

Methane Steam Reforming Experimental

In the experiment set-up which is established to provide conversion of methane by steam methane is sent to the reactor by passing inside the warm water. The amount of steam is tried to control by using measured cap and by adjusting temperature of electronic heater. When the condition is at 650 ^{0}C 100 ml/min T_{heater}=100 ^{0}C and when the methane and steam is sent to the reactor, approximately 57.9% H_2 volumetric percentage is measured from the gas chromatograph device. When the condition is at 650 ^{0}C 100 ml/min T_{heater}=200 ^{0}C and the methane and steam is sent to the reactor, approximately 60.4% H_2 is measured in the output gas. When the condition is at 700 ^{0}C 100 ml/min T_{heater}=150 ^{0}C and the methane and steam is sent to the reactor, approximately 79.1% H_2 is measured in the output gas. The graphs in relation to these experiments are given at the bottom.

In the (Figure 6.21) methane and steam is being passed from the reactor at 650 ^{0}C and 100 ml/min. In this experiment in which the results are shown, the purpose is to observe the decreasing of H_2 ratio outputs from the reactor and also examine declining of methane volumetric percentage.

Deviations from DoW

The second amendment to the DoW dated 29/04/16 recognised that it would not be possible integrate the LT-SOFCs and so it was proposed to develop the integration using conventional fuel cells. Work was done in developing reformers and other ancillary equipment needed for LT-SOFC and the results are reported here. There are no deviations from the work plan and deliverables targets.

WP6: Prototype system testing

Desiccant unit development

Work package 2 described development and testing of a combined desiccant dehumidification, cooling and regeneration system. The results showed excellent performance with a cooling capacity of over 1kW, moisture removal rates of up to 270kg/h and a coefficient of performance (ratio of cooling output to work and heat input) of above 1.0.

However, some problems were encountered during testing which resulted in the development of an alternative system for use in the prototype development, including

- Leakage of desiccant from the membrane channels into the supply air flow,
- Difficulty of controlling the three systems independently,
- Poor or inadequately even distribution of desiccant liquid and cooling water across individual membranes,
- Excessive system size.

In order to address these issues a second desiccant dehumidification, cooling and regeneration system was designed, developed and built.

Prototype dehumidification unit

The system comprises three separate tanks, a cooler tank (T/K), a dehumidifier tank (D/T) and a regenerator tank (R/T) and three separate membrane heat exchanger units which contain the membrane, blower fans and delivery pipework, a cooler membrane H/X (C/M), a dehumidifier H/X (D/M) and a regenerator H/X (R/M). Variable speed 24v dc axial flow fans deliver air to the various membrane exchangers, Fan A (C/M), Fan B (D/M) and Fan C (R/M). 230v ac centrifugal pumps provide flow for the membrane exchangers, a cooler pump (C/P) a dehumidifier pump (D/P) and a regenerator pump (R/P). Plate heat exchangers provide heat recovery between the desiccant and cooling circuits (Plate H/X1) and heat transfer from the heat source to the regenerator circuit (Plate H/X 2).

Instrumentation and equipment

Desiccant and water temperature –
Temperatures at inlet and outlet of the desiccant and water circuits are measured by K-Type Thermocouples
Temperature measurement range - 0 to 1100°C
Accuracy 0.2%

Desiccant and water volumetric flow rates –
Calibrated variable area flow meters
0 – 2 l/min

Air temperature and relative humidity –
Vaisala HMP110 Humidity and Temperature Probe

- Stainless steel

- Relative humidity measurement range - 0 to 100% (+/- 1.7%)
- Temperature measurement range - $^{-}$40°C to 80°C (+/-0.2C)
- Operating voltage – 5 to 28V DC
- Output voltage – 0 to 5V DC

DataLogger – DataTaker DT 800

- 42 analogue senor inputs (42 separate single ended channels or 24 differential channels)
- Measurement across 12 auto-scaling ranges from 10mV to 13V full scale
- All common measurement types are supported
- 16 digital channels
- RS232 port, Ethernet port and Flash card port for dataTaker programming and data retrieval

Pumps –

15W single phase magnetic pump

- Volumetric flow rate - 10 litre/minute
- Max head – 7 metres
- 3000 rpm

Fans

Fan A: PMD DC Axial Fan, 120 x 120 x 38 mm, 323 m/h, 18.2 W, 24 V dc: PMD: PMD2412PMB1-A(2).GN

Fan B and C: Orion DC Axial Fan, 172 Dia. x 51mm, 399.5m/h, 23.28W, 24V dc: OD172SAP-24HB

Water heater

A 3kW water heater was used to provide a hot water source to the prototype desiccant unit in the temperature range 50-70C.

Results

Dehumidifier

Latent cooling achieved increased from 450W at 25°C to 800W at 35°C, and total cooling increased from 300W at 25°C to 650C at 35°C. Total cooling is lower than latent cooling because the temperature of the water in the tank is close to its dew point at high RH, reducing the ability of the air to absorb moisture and so reducing its cooling effect. The desiccant liquid in the tank is close to the temperature of the surrounding air and so it would only be able to provide sensible cooling if it was below the temperature of the air. The results demonstrate the high dehumidification effect of the system at high RH and medium to high temperatures, but the total cooling effect is reduced if the system is used in a high RH and temperature environment without other means of sensible cooling such as a chilled water supply or an indirect evaporative cooling system. The COP of the system increases from about 3 to about 8 with increase in temperature from 25°C to 3°5C. COP in this case is based in the ratio of the latent cooling effect to the electrical work input.

Latent effectiveness increases from 30% at 25°C to about 33% at 30°C then decreases to 28% at 35°C. It appears to peak at about 29°C. This shows that the absolute humidity is reduced by about 30% compared to the maximum possible.

Moisture removal rate varies with supply air flow at a constant RH of 70% and a constant inlet temperature of 30°C. At about 100m^3/h moisture removal is approximately 0.11g/s and increases to approximately 0.24g/s at 260m^3/h.

Latent cooling increases from 300W at 100m^3/h to 600W at 260m^3/h. COP increases from 4 to just under 6 as air flow increases. Latent cooling is greater than total cooling because the potential for evaporative cooling is reduced at high RH and the desiccant temperature is equal to or above the surrounding air temperature causing heat to be added to the system.

Latent effectiveness decreases from about 42% at 100m^3/s to 34% at 260m^3/h. The reduction in effectiveness is due to a reduction in absolute humidity difference, despite an increase in moisture removal rate, and this is because the increase in volume flow increases total moisture removal rates, but an increase in velocity within the air channels reduces the time available for mass transfer.

Regenerator

Inlet air temperature and RH were held constant at 30°C and 70% respectively whilst the air volume flow was 260m^3/hr. Moisture addition increases from approximately 0.2g/s at 1.5l/min to 0.3g/s at 3 l/min. The increase in mass removal rate is due to the increase in mass flow.

Heat input increases from approximately 1200W at 1.5l/min and peaks at 1500W at 3l/min. Heat exchanger effectiveness increases from 70% at 1.5l/min, peaks at 75% 2.5l/min and then decreases to 73% at 3l/min.

A comparison between dehumidifier and regenerator moisture change showed that a balance can be achieved at 0.24g/s, at an air flow of 260m^3/hr and this will be balanced by the moisture added in the regenerator at a desiccant flow of 2.5l/min. The conditions in this case are constant and inlet temperature and RH of 30°C and 70% and air flows of 260m^3/hr in both the dehumidifier and regenerator. We can compute the equilibrium COP and for the balanced condition we find that the COP is approximately 0.4. This is low compared to previous tests and is the result of the system using high inlet air temperature and RH, which also increased the temperature of the desiccant liquid and water and so reduced effectiveness. If we were to use re-circulated air from the building which would be at a lower temperature and RH than the surroundings to supply air to the evaporative cooler and regenerator then we could reduce regenerator heat input, increase dehumidification and evaporative cooling effect and so increase COP.

Stack development

Initial tests: the gas leakage limited the OCVs lower than the expected 2.1V, but only 1.8V was achieved. Contact resistance was too high and caused large power loss, one cell only reached 2 watts.

Extensive efforts have been done for the improvements over several months, and we have reached the expected OCV and power outputs of 12 watts at 530^{0}C.

In the best case, we even achieved 2.2V OCV and 20W power output. Each single cell can deliver 10W, but reproducibility has been a large problem.

Four-cell stack development

Then we, KTH joint lab in Hubei University further step forwarded to 4-cell stack initiatives immediately based on experience from 2-cell stack. We encountered more difficulties compared to the single cell and 2 cell stacks but most problems came from the installation and single cells not being identical. These led to high stack leakage and very low OCVs, and large contact resistances which reduced power output compared to the output expected.

In the initial tests, many stacks failed due to gas leakage without using the sealing materials in our stack. However, some of results showed that we could obtain in the good performance. In one of the best results we achieved 44.5 W at 1,65V and 27 A (3.95 V OCV) at 530-550^{0}C.
The reason that we did not use sealing materials was that we found no suitable sealing materials for LT, below 600^{0}C. So we developed our own seal-free stack technology, which is in particular suitable for small-scale of stack, say 100W.
Stack development based on sample single cells provided by KTH performed in Vestel using the sealing materials and four single cells in parallel connections, photos are attached below.

In the initial efforts, they VSS encountered problems with uneven thickness of the single cells, which caused difficulties in sealing each single cell to a four cell. Poor sealing resulted in reduced performance.
One solution to the problem was put forward and concerned the configuration of single cell in series connection rather than in parallel, since a parallel connection makes the four cells dependent on each other.
In addition, series connection stacks are commonly used in SOFC technology worldwide. But on the other hand, the VSS stack design is their unique IP and product design.

WP 7: Field trials of prototype system

Contributors: NOTT, UBHAM, KTH, VSS, COMPLEX, INEGI

Solid oxide fuel cell

BlueGEN is a commercially available SOFC CHP system designed for small to medium scale building applications. Operating on natural gas (NG), the unit can be power modulated from $500W_e$ (25%) to $2kW_e$ (100%), however it achieves its highest net electrical efficiency of 60% at a $1.5kW_e$ output. As a result, CFCL have optimised the default operation of the unit at $1.5kW_e$ to provide the highest electrical efficiency and thus greatest economic benefit to the user. The BlueGEN unit consists of 51 planar type YSZ electrolyte layer sets (each layer consist of four cells), and operates at 750°C. Hydrogen is produced from natural gas by internal steam reforming (endothermic) on the fuel cell anode, therefore utilising the heat of the electrochemical reaction (exothermic) to create a chemical combined cycle. The BlueGEN unit was selected for field trial testing because (1) it is commercially available, (2) is certified for domestic building installations and qualifies for the UK FiT, and (3) it fulfils the technical objectives of the thesis.

The SOFC is connected electrically, in parallel, to the national grid in order to export or import power as required. The SOFC is connected to the natural gas grid. A heating water circuit delivers the generated heat from the SOFC unit directly to the homes 300L hot water cylinder, which is supplemented by an auxiliary gas boiler. For tri-generation system integration, the intention was to install the SDCS outside of the home in-line between the SOFC and hot water cylinder. Three way diverter valves direct thermal energy to the regenerator during tri-generation system operation.

Field trial electrical performance data were collected from the SOFC, using the online CFCL interface, from 24 March 2014 (point 1) to 12 December 2014 (point 8). This is equivalent to 4865 hours of operation (8 months 18 days). During this period the SOFC unit shows stable operation, i.e, electrical efficiency of 55-60%, with availability for power generation of 91.7% and demonstrating the potential for the development of an efficient and effective tri-generation system. Due to the time taken to heat the stack to 750°C and to avoid thermal cycling, the unit operated continuously, always aiming to maintain a $1.5kW_e$ output. As the stack efficiency degrades over time the fuel input is increased to compensate for this. At an electrical efficiency of 60% the fuel input is 2.5kW. After 4000 hours of operation (point 2 to 5), the stack displayed an electrical efficiency degradation of approximately 6%.

Three key events in the lifetime of the unit have meant that it is not available for tri-generation system integration. These events were as follows: (1) an unforeseen gas shut-off causing stack cool down and thermal contraction, leading to an electrical efficiency drop, and eventual stack failure (point 5) and replacement (point 6), (2) A 415 volt voltage surge at The Creative Energy Homes causing irrevocable damage to the power electronics and thus stack cool-down, again leading to the requirement of power electronic and stack replacement (point 8). (3) CFCL going into administration, and thus not being able to carry-out the required repair works post voltage surge. During the operational period, the WHR circuit was only connected for a short period, thus there is limited thermal output data. However, Sommer (2013) and Foger (2013) have carried out extensive electrical and thermal performance characterisation of an identical BlueGEN SOFC CHP system in a building application. During the performance evaluation, Foger (2013) used a $2L.min^{-1}$ water volumetric flow in the WHR circuit.

It was evident that the net electrical efficiency increases as the electrical capacity increases, from 14% at 200We up to a maximum of 60% at 1500We, it then falls to approximately 56%

at a 2000W_e capacity. The thermal output from BlueGEN increases fairly linearly from 320W_{th} at 200We up to 540W_{th} at 1500kW_e. The thermal output increase is then much steeper, up to a maximum of 1000W_{th} at 2000W_e. At the optimised 1500We output a CHP efficiency of 81.6% is achieved.

The field trial data demonstrated that a net electrical efficiency of 60% is achievable and maintainable at a 1.5kWe output in a real life building application and thus the data presented can be used with confidence.

A 2L.min^{-1} water volumetric flow and a 45°C return water temperature. The flow water temperature ranges between 47°C at 100We electrical power output up to a maximum of and 52°C at a 2000W_e electrical power output. As highlighted in reports for WP2 and 6, it is primarily the desiccant systems operation that needs to be optimised to facilitate effective tri-generation system integration. Using the WHR flow water temperature and SDCS empirical data presented in WP6, the thermal COP of the SDCS can be identified, and the cooling output calculated. Results from the theoretical integration of the BlueGEN SOFC and SDCS into a complete tri-generation system at a net 1.5kW_e and 2kW_e output, operating with a 30°C and 70% relative humidity inlet air condition. The parasitic energy consumption (110W) of the SDCS has been included in the evaluation.

Table 7.1 SOFC tri-generation system performance evaluation

	1.5kW_e	2kW_e
η_{elec} (%)	60	56
$\dot{Q}_{\text{CH}_4}(W)$	2500	3571
$\dot{Q}_{\text{WHR}}(W)$	540	1000
$T_{\text{WHR,flow}}(°C)$	48.87	52.16
η_{CHP} (%)	81.6	84
Desiccant volume (L.min^{-1})	1.74	3.16
COP_{th}	0.614	0.649
$\dot{Q}_{\text{cooling}}(W)$	332	649
MRR (g.s^{-1})	0.2515	0.2941
η_{tri} (%)	68.9	71.1
Δ% PED (CHP/TRI)	51.41 / 46.98	50.21 / 46.79
Δ% Cost (CHP/TRI)	62.84 / 60.67	61.53 / 60.53
Δ% Emissions (CHP/TRI)	51.21 / 68.96	50.01 / 68.26

The theoretical integration study based on empirical data demonstrates that high tri-generation efficiency in the range of 68-71% is attainable when combining SOFC and liquid desiccant air conditioning technology. The SOFC unit has a low heat to power ratio, particularly at the 1.5kW_e condition, this is because it is an electrically optimised device (fuel utilisation of ~85%). As a result, there is limited thermal output available for desiccant solution regeneration. However, the SDCS operating with a potassium formate working fluid at a 0.65 – 0.7 solution mass concentration has a low regeneration temperature requirement, and thus makes good use of the low-grade SOFC WHR output to generate a meaningful quantity of dehumidification/cooling. At the $2kW_e$ condition, electrical efficiency is lower, but the thermal efficiency is higher. As a result, almost 650W of cooling is produced. The inclusion of liquid desiccant air conditioning technology provides an efficiency increase of up to 28% compared to SOFC electrical operation only. The performance of the novel tri-generation system is competitive with other systems of this capacity reported in the literature

CHP and tri-generation efficiency are highest for the $2kW_e$ case. However the PED, cost and emission savings are highest for the $1.5kW_e$ case. Electricity has a higher associated cost and emissions compared to natural gas, therefore greater savings are made for the $1.5kW_e$ case due to the higher electrical efficiency. In tri-generation cooling mode, relative cost and emission reductions compared to a conventional separated system for the $1.5kW_e$ and $2kW_e$ cases are 60% and 70% respectively, demonstrating the potential of the first of its kind SOFC liquid desiccant tri-generation system for building applications. The novel tri-generation system increases the utilisation of thermal energy from the SOFC during periods of low/no thermal demand, to provide a comfortable indoor building environment through dehumidification/cooling. The operational issues encountered with the BlueGEN SOFC illustrate the real challenge of fuel cell deployment in the built environment. Reliability, durability and cost currently pose a great barrier to their wider use. Not until these issues are addressed will the operational advantages of fuel cells operating in the built environment be realised. Although experimental integration was not possible due to unforeseen circumstances, the stable nature prior to stack failure of the BlueGEN SOFC unit highlights the potential for the development of an efficient and effective tri-generation system.

The work has established that SOFC and liquid desiccant are a viable technological pairing in the development of an efficient and effective tri-generation system. It has been demonstrated that high tri-generation system efficiency is attainable at low system capacities. The proof-of-concept study has achieved one of the technical objectives of this thesis, namely a $1.5kW_e$ system operating at an electrical efficiency of 45% or higher.

Microtubular SOFC tri-generation field trials

In the previous section, it was explained that the Bluegen SOFC suffered a series of incidents which meant that it was not possible to use the unit for field trials. In the amendment (29/04/15) it was proposed to use an off-the-shelf SOFC for the purposes of proving the concept. We obtained a microtubular SOFC from ADELAN Ltd, which had a rated electrical output of 250W and a waste heat output of 1000W.

Liquid desiccant air conditioning component

The liquid desiccant air conditioning unit employs a potassium formate solution at a solution mass concentration of 0.65 – 0.7. A comprehensive SDCS rig schematic and photograph is provided in the report on WP6, along with rig description, experimental set-up, instrumentation, and experimental testing method. Therefore it will not be repeated again, only with respect to the complete tri-generation system testing. The next section describes the instrumentation used in the experimental tri-generation system.

Instrumentation

This section describes the instrumentation used in the experimental tri-generation system. The tri-generation system is made up of the micro-tubular SOFC CHP and liquid desiccant components, therefore their instrumentation are described accordingly.

In the micro-tubular SOFC CHP system, the electrical power output is determined by measuring the voltage and current output. The operating voltage is displayed on the SOFC display panel and the result logged. The current is measured using a GMC-I CP41 current clamp meter. This is placed over the positive wire connecting the micro-tubular SOFC to the battery pack, and the result logged. K-Type thermocouples have been placed in the SOFC exhaust gas stream before and after the recuperator heat exchanger. The water volumetric flow in the WHR circuit is measured using an RS 1–15L.min^{-1} piston flow meter. K-Type thermocouples are placed on the WHR circuit at the recuperator HX inlet and outlet, and in the water tank. All micro-tubular SOFC thermocouples are connected to a DT80 DataTaker datalogger. Data readings are recorded every ten seconds. The SDCS employs Type-K thermocouples on all desiccant solution and water flows. All inlet and outlet air flows have been instrumented with Vaisalia HMP110 humidity and temperature probes. A DataTaker DT500 datalogger is used to record data from the thermocouples and humidity and temperature probes every ten seconds. All outlet air velocities are measured using an RS AM4204 hot wire anemometer. The density of the desiccant solution is measured using a differential pressure density meter with temperature compensation. Further information regarding the SDCS instrumentation can be referred to reports for WP 6.

Experimental method

To start the micro-tubular SOFC CHP system, the gas valve on the propane cylinder is opened. The micro-tubular SOFC electrical output cables are then connected to the battery pack. The micro-tubular SOFC ON button is then pressed. The digital display on the micro-tubular SOFC unit will show the operational voltage of the battery pack and the number of hours of operation the unit has completed to date. The voltage of the battery pack needs to be at 11.8V for the micro-tubular SOFC unit to begin start-up. If the voltage of the battery pack is greater than this, the electrical load needs to be connected to discharge the battery. Once 11.8V is achieved the micro-tubular SOFC will go into heat-up mode. Heating of the micro-tubular SOFC system is achieved through the combustion of propane in the afterburner. This takes approximately 20 minutes. During this time a current flow of 2.95 amps from the battery pack to the micro-tubular SOFC is observed: this is due to the micro-tubular SOFC parasitic energy consumption (35W). Once the system is up to temperature (~600°C), it goes into power production. Now a current flow of approximately 20 amps (when operating at a 250W$_e$ output) from the micro-tubular SOFC to the battery pack is observed. It is important that the electrical load (lamps) on the battery pack is maintained during micro-tubular SOFC operation to avoid the battery voltage exceeding 13V and the micro-tubular SOFC shutting down. Voltage and current readings are taken every two minutes, and the results logged. The sulphur trap has a lifetime of 250 hours. It is essential this is not exceeded as sulphur poising will damage the stack. The micro-tubular SOFC unit's operational hour counter is on a 250 hour loop so that the replacement milestones are clear. Throughout micro-tubular SOFC CHP and tri-generation system tests, a constant fuel input of 100g.hr^{-1} is assumed.

During the micro-tubular SOFC heat up period, the pump in the WHR circuit is switched on and the water volumetric flow is set to the required test conditions. During micro-tubular SOFC CHP tests, the water in the WHR is simply circulated from the tank and through the recupertaor HX using the by-pass loop. The WHR inlet and outlet water temperatures are logged and used to calculate the WHR thermal output. The tank volume is sufficient to act as a thermal load to the micro-tubular SOFC. During tri-generation system testing the micro-tubular SOFC CHP system is operated in the same manner as described above. However, the water in the WHR loop is diverted through the regenerator plate heat exchanger (PX1) to heat the desiccant solution. The SDCS experimental method has been provided previously in detail in reports from WP6. The experimental metrics used to evaluate the performance of the micro-tubular SOFC CHP and tri-generation system are provided below.

Experimental tri-generation system results and analysis

The performance of the SDCS is documented in detail in WP6, in which the regenerator thermal input values (water volumetric flow and water flow temperature) were selected based on a range that matches the 1.5kWe (BlueGEN) SOFC CHP system. However, due to the BlueGEN SOFC not being available for tri-generation system integration, a 250W_e (Adelan Ltd) micro-tubular SOFC unit had to be acquired. Actual thermal output values for this unit were not known before testing because the micro-tubular SOFC WHR system was developed specifically for this project by The University of Nottingham. Prior to this the micro-tubular SOFC had only been used for electrical production.

Micro-tubular SOFC CHP system component analysis

In this section the micro-tubular SOFC CHP system component test results are presented and analysed. The results are provided to show (a) the performance of the micro-tubular SOFC unit (electrical and thermal) over time and (b) to characterise the thermal performance to facilitate effective tri-generation system integration. The micro-tubular SOFC CHP unit operates at a constant output. The input fuel flow rate is fixed and thus so power and thermal output is approximately constant. The water volumetric flow in the WHR circuit is set to 2L.min^{-1} to replicate the SDCS testing conditions presented in WP6.

Before being supplied to The University of Nottingham, long term stability testing of the micro-tubular SOFC unit was carried out at The University of Birmingham. The micro-tubular SOFC was run for 130 hours, with 19 thermal cycles. A steady state electrical output of 250W has been demonstrated. However, after 75 hours of operation severe sulphur poisoning of the micro-tubular SOFC stack occurred. The sulphur trap had been previously used and went over the 250 hour operating limit. In the hours following sulphur trap replacement very little power output could be gained from the micro-tubular SOFC. However, after approximately 95 hours of operation, the micro-tubular SOFC had recovered to a final maximum power output of 140W. The micro-tubular SOFC has now recovered a little more to a 150.4W electrical output, which is approximately 60% of the manufacturer's quoted 250W capacity. Sulphur poisoning and the regeneration of Ni-based anodes in SOFCs has been studied by Zha, Cheng et al. (2007). The degradation in cell performance is attributed to rapid adsorption of sulphur onto the Ni surface to form nickel sulphide, which blocks the active sites for hydrogen adsorption and oxidation. Following removal of H_2S (hydrogen sulphide) from the fuel stream, the anode performance can, depending on operating conditions and duration of H_2S exposure, recover fully or partially. The rate of the recovery process increases with operating temperature and cell current density.

In the first 28 minutes, the micro-tubular SOFC outlet temperature increases. During this period the micro-tubular SOFC uses gas burners to reach operating temperature and has a 35W parasitic load on the batteries. Following heat-up, the micro-tubular SOFC goes into power production. During this period there is an electrical and thermal output. At 322 minutes, the micro-tubular SOFC is turned off, and it takes 22 minutes to cool down.

During the power production period the micro-tubular SOFC produces an average of 150.4W of DC electrical power (12.2V at a current flow of 12.33A). This equates to an electrical efficiency of 11.68%, in comparison to 19.4% at the original 250W electrical output.

At a 2L.min^{-1} water volumetric flow, a maximum WHR outlet water temperature of up to 65°C is possible, demonstrating the potential for desiccant solution regeneration in a tri-generation system context. Over the power production period, the average water temperature difference across the recuperator HX is 3.2°C, this equates to an average thermal output of 446.9W. The pinch temperature reaches a peak of 20.01°C at 70 minutes then gradually falls to 11.53°C at 322 minutes. The decline in pinch temperature is because the rate of increase in flue gas outlet temperature over time is greater than the rate of increase in the WHR outlet water temperature. This indicates a reduction in thermal energy extraction.

Based on the averaged values over the power production period, the micro-tubular SOFC achieved a CHP efficiency of 46.39%. This compares with 54.1% based on the micro-tubular SOFC unit before sulphur poisoning, which had an average power output of 250W_e. The stable operational nature of the micro-tubular SOFC CHP unit demonstrates the potential for tri-generation system integration. The maximum calculated relative uncertainties in the SOFC $\dot{Q}_{WHR}$ and η_{CHP} are ±9.1% and ±6.8% respectively.

In comparison to other combustion based micro-CHP technologies of this electrical capacity, the electrical efficiency of the micro-tubular SOFC is reasonable. Compared to planar type SOFC systems, the micro-tubular SOFC has a low electrical efficiency. However, the significant advantage of micro-tubular SOFC technology has been confirmed. Quick start-up and shut-down times of 20 minutes have been demonstrated, meaning the unit can respond quickly to supply and demand.

The company (Adelan Ltd.) supplying the micro-tubular SOFC have not previously attempted to provide WHR, and thus the WHR system was developed for this project by the University of Nottingham. The low thermal output from the micro-tubular SOFC highlights the need for future work on optimising and refining the WHR provision in order to maximise the thermal output and thus elevate the system efficiency. Future work should aim to improve the connection between the afterburner outlet and recupertaor HX flue inlet. As demonstrated in reports submitted for WP6, a regenerator thermal input of less than 500W will result in limited regeneration capacity. In order to maintain balanced liquid desiccant system operation, a restricted cooling output will have to be assigned to the dehumidifier. The micro-tubular SOFC was acquired at short notice to replace the building installed 1.5kW_e BlueGEN SOFC. As seen in the low thermal output, it is not the ideal match for the developed SDCS. However, the novel concept of integrating SOFC and liquid desiccant technology is still successfully demonstrated in the next section.

The previous section presented component testing of a micro-tubular SOFC CHP unit. Due to sulphur poisoning the micro-tubular SOFC unit has suffered a 40% drop in electrical output from 250W to 150W. Water flow temperatures of up to 65°C at a 2L.min^{-1} water volumetric flow have been demonstrated. The micro-tubular SOFC has a low thermal output of approximately 450W, and thus it is anticipated that regeneration capacity in the tri-generation system will be limited.

Tri-generation system analysis

In this section the micro-tubular SOFC is integrated alongside the SDCS to form the complete tri-generation system. As previously highlighted, the micro-tubular SOFC operation is fixed, it has no provision to modulate or alter output. Therefore, it is the liquid desiccant systems operation that is controlled in order to investigate tri-generation system performance.

In the tri-generation system the connection between the micro-tubular SOFC and liquid desiccant components is through the regenerator. As a result of this arrangement, the tri-generation system analysis evaluates the performance of the regenerator at three different desiccant solution flows using the micro-tubular SOFC thermal input. This is to determine the instantaneous performance of the novel system. Following this, a daily tri-generation performance analysis is presented which serves to demonstrate the novel system operating in a building application.

For efficient and effective tri-generation system operation, a moisture balance between the dehumidifier and regenerator is required. As a result, the achievable regenerator moisture addition rate is equated, using the data presented in WP6, to a suitable dehumidifier moisture removal rate. From the dehumidifier moisture removal rate, the achievable cooling output can be obtained, and the tri-generation system efficiency calculated. In Reports for WP6, the SDCS dehumidifier was tested in the environmental chamber to simulate real life operational conditions. Thus the tri-generation system results presented are representative of the novel system in a real working environment.

Testing of the tri-generation system is carried out by operating the micro-tubular SOFC CHP system until an outlet water temperature of 50°C is achieved with a 2L.min^{-1} water volumetric flow in the WHR circuit. This normally takes approximately 120 minutes from ambient. The by-pass loop is then closed and the hot water is directed to the regenerator desiccant solution plate heat exchanger (PX1). The regenerator desiccant solution and air flow is then turned on. The regenerator tests last for 90 minutes or until steady state output data is achieved. The micro-tubular SOFC and regenerator are then turned off.

Three desiccant solution volumetric flows have been investigated: 1.2, 2.2, 3.2L.min^{-1} at a potassium formate desiccant solution mass concentration of 0.65-0.7. The regenerator volumetric air flow used is 256m^{3}.hr^{-1}. The aim of the investigation is to determine the conditions, at which the regenerator moisture addition rate is highest, and thus the cooling output can be maximised. As previously highlighted, during tri-generation system testing the regenerator uses ambient laboratory air.

The regenerator moisture addition rate is related to both the solution volumetric flow and temperature. Operating with the micro-tubular SOFC thermal input, the highest regenerator moisture addition rate of 0.11g.s^{-1} is achieved at a 2.2L.min^{-1} desiccant solution flow. This is because it achieves a balance between the volume and temperature of solution passing through the regenerator HMX. As a result, a 2.2 L.min^{-1} solution volumetric flow has been selected for tri-generation system evaluation.

Table 7.1. Operational values for microtubular tri-generation system evaluation

Variable	Value	Variable	Value
microtubular SOFC fuel flow (g.hr^{-1})	100	Deh air temperature (°C)	30
WHR flow (L.min^{-1})	2	Deh air relative humidity (%)	70
Reg $\omega_{a,in}$ (kg$_{vapour}$/kg$_{dryair}$)	0.006412	Deh air volumetric flow (m^{3}.hr^{-1})	102
Reg air flow (m^{3}.hr^{-1})	256	Deh desiccant flow (L.min^{-1})	3.2
Reg desiccant flow (L.min^{-1})	2.2	Desiccant mass concentration (%)	65 - 70

Table 7.2 presents the instantaneous performance of the novel micro-tubular SOFC liquid desiccant tri-generation system. The performance evaluation is provided at the 150.4W electrical output. The 110W parasitic energy consumption of the SDCS has been accounted for.

Table 7.2. Instantaneous performance of the novel tri-generation system

	Value		Value
$\dot{W}_{elec,DC}$ (W)	150.4	$\dot{Q}_{cooling}$ (W)	278.6
$\dot{Q}_{WHR}$ (W)	442.6	Deh_{MRR} ($g.s^{-1}$)	0.1114
$\dot{Q}_{C_3H_8}$ (W)	1288	Reg_{MAR} ($g.s^{-1}$)	0.11
η_{elec} (%)	11.68	COP_{th}	0.63
η_{CHP} (%)	46.04	η_{tri} (%)	24.77

The marginal difference in the dehumidifier moisture removal and regenerator moisture addition rates is deemed insignificant enough for the purpose of tri-generation system evaluation. The novel system can generate 150.4W of electrical power, 442.6W of heat output and 278.6W of waste heat driven cooling with a tri-generation efficiency of 24.77%. At the original 250W electrical output, the tri-generation system efficiency is 32.5%. Without considering the parasitic energy consumption of the SDCS, the tri-generation system efficiency is 33.31% at a 150.4W electrical output and 41.04% at the 250W electrical output.

From Table 7.2, it is evident that the tri-generation system efficiency is low. However, the initial micro-tubular SOFC CHP system efficiency is below 50%. Tri-generation system analysis shows that the low thermal output from the micro-tubular SOFC is insufficient to maintain a flow temperature of 45-50°C and thus the regenerator moisture addition rate is low, resulting in a small instantaneous cooling output. However, the novel concept of integrating SOFC and liquid desiccant air conditioning technology into the first of its kind tri-generation system has been successfully demonstrated. The SOFC has been used to generate simultaneous electrical power, heating and/or cooling. The inclusion of liquid desiccant air conditioning technology provides an efficiency increase of up to 13% compared to SOFC electrical operation only, demonstrating the merit of the novel tri-generation system in applications that require electricity, heating and dehumidification/cooling. Improvements to the micro-tubular SOFC WHR provision will improve tri-generation system performance.

An operational advantage of a SOFC liquid desiccant tri-generation system is the potential for nonsynchronous operation. If the dehumidifier needs to be operated at a higher cooling capacity, the regenerator can be operated for an extended period to make up the moisture addition shortfall. Based on the assumption that the SOFC operates for 24 hours a day, with a 6 hour cooling period, Table 4.3 shows the system performance.

The daily tri-generation system efficiency is 37.9%. At the original 250W electrical output the daily tri-generation efficiency is 45.6%. As the cooling period is increased the daily tri-generation efficiency falls. This is because the SDCS has a COP_{th} of less than one. The proposed daily tri-generation system operating concept demonstrates that the novel system can produce 527W of cooling over a six hour period, however the system would require the provision of sufficient desiccant solution storage in order balance the dehumidifier and regenerator operation. Continuous micro-tubular SOFC operation is a reasonable assumption in a (domestic) building application as the small electrical output can be used for base load applications (lights, standby etc.). The developed system is easily scalable and is therefore be suitable for a range of building applications/scales.

Table 7.3. Daily tri-generation system performance

Variable	Value	Variable	Value
$\dot{W}_{elec,DC}$ (W)	150.4	Deh_{MRR} (g.s^{-1})	0.21
$\dot{Q}_{WHR}$ (W)	442.6	Reg_{MAR} (g.s^{-1})	0.11
$\dot{Q}_{cooling}$ (W)	527	Electrical energy (Wh)	3610
$\dot{Q}_{C_3H_8}$ (W)	1288	Heating energy (Wh)	5607
Electrical time (hr:min)	24	Cooling energy (Wh)	3162
Cooling time (hr:mim)	6:00	Fuel input (Wh)	30912
Regenerator time (hr:min)	11:27	$\eta_{tri,day}$ (%)	37.91
Heating time (hr:min)	12:33		

The micro-tubular SOFC can operate on natural gas, in such a scenario the novel tri-generation system generates a cost and emission reduction of 56% and 42% respectively compared to a base case scenario of grid electricity, gas fired boiler and electrical driven VCS. The encouraging economic and environmental performance demonstrates the potential of the novel tri-generation system in applications that require simultaneous, electrical power, heating and/or cooling.

We have presented the analysis of the novel tri-generation system based on SOFC and liquid desiccant air conditioning technology. The novel concept has been proven, experimentally, in the first of its kind system; however the reported performance is low. This is primarily due to the low thermal output from the micro-tubular SOFC. Possible solutions to improve performance have been discussed.

Conclusions

Technical and commercial issues have meant the 1.5kW$_e$ building installed (BlueGEN) SOFC CHP system was not available for tri-generation system integration. However, using collected empirical SOFC and SDCS data, a theoretical tri-generation system integration analysis has been completed. The tri-generation system performance has been evaluated at a 1.5kW$_e$ and 2.0kW$_e$ capacity. The two cases generate a cooling output of 332W and 649W respectively. The highest tri-generation efficiency of 71.1% is achieved at a 2.0kWe capacity; however the electrical efficiency is lower than the 1.5kW$_e$ case. As a result, the 1.5kW$_e$ case produces the greatest cost and emission savings of 61% and 69% respectively. The inclusion of liquid desiccant air conditioning technology provides an efficiency increase of up to 28% compared to SOFC electrical operation only. The performance of the novel tri-generation system is competitive with other systems of this capacity reported in the literature. The results demonstrate effective pairing of SOFC and liquid desiccant air conditioning technology in a tri-generation system application. The theoretical tri-generation system integration analysis has achieved the thesis technical objective of a 1.5kW$_e$ system operating at an electrical efficiency of 45% or more. The encouraging performance is primarily due to the high electrical efficiency of the SOFC and the reasonable thermal COP of the liquid desiccant system. Technical and commercial issues with the SOFC highlight the real challenge of fuel cell deployment in the built environment.

Following the failure of the 1.5kW$_e$ SOFC, a 250W$_e$ micro-tubular SOFC had to be acquired. The novel tri-generation system concept has been proven experimentally using the micro-tubular SOFC. 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 2.2L.min^{-1} regenerator desiccant volumetric flow facilitates best performance. The novel system can generate 150.4W of electrical power, 442.6W of heat output and 278.6W of cooling. Due to its low temperature regeneration requirement, potassium formate at a 0.65–0.7 mass concentration is an appropriate desiccant solution for a SOFC tri-generation system. When integrated with the micro-tubular SOFC, the SDCS demonstrates a COP$_{th}$ of 0.62, an encouraging value for a waste heat driven cooling system of this capacity. Instantaneous tri-generation system efficiency is low at approximately 25%. This is primarily due to the low capacity and poor performance of the micro-tubular SOFC. Sulphur poisoning has caused a 40% reduction in micro-tubular SOFC electrical output to 150W. Insufficient WHR means only 450W of thermal energy is available for regeneration purposes, and thus the cooling output is low. However, it has been suggested that if these issues are addressed, the novel system can provide higher overall efficiency. A daily tri-generation performance analysis is presented which serves to demonstrate the novel system operating in a building application. In such a scenario, 527W of cooling is produced and a daily tri-generation efficiency of 37.91% is presented. This is an encouraging value for a tri-generation system of this capacity. Compared to a base case scenario, the novel tri-generation system generates a cost and emission reduction of 56% and 42% respectively, demonstrating the potential of the novel tri-generation system in applications that require simultaneous, electrical power, heating and dehumidification/cooling.

The difference in performance seen between the two tri-generation systems presented demonstrates the significance of (a) the performance of the SOFC component and (b) the requirement of optimal pairing of components, in the development of an efficient and effective tri-generation system. The micro-tubular SOFC was acquired at short notice to replace the 1.5kWe BlueGEN SOFC. As seen in the low thermal output, it is not the ideal match for the developed SDCS. However, the novel tri-generation concept has been successfully demonstrated. Both tri-generation system analyses presented have considered balanced liquid desiccant system operation. This is a stipulation other tri-generation systems employing liquid desiccant technology reported in the literature have not reported and demonstrates the strength and rigour of the work presented.

The aim of the prototype development is to design, develop and test an efficient and effective tri-generation system based on SOFC and liquid desiccant air conditioning technology. This chapter has demonstrated a clear contribution to new knowledge with the development and evaluation of two SOFC liquid desiccant tri-generation systems and as a result it is proposed that the thesis aim has been completed.

Based upon the experimental work presented in this chapter, three general conclusions are provided with respect to the design, development and testing of an efficient and effective tri-generation system based on SOFC and liquid desiccant air conditioning technology for building applications.

SOFC and liquid desiccant is an effective technological pairing. The inclusion of liquid desiccant can bring significant improvement to system performance, particularly in applications requiring simultaneous electrical power, heating and dehumidification / cooling.

Overall tri-generation system performance is more influenced by the SOFC component than the liquid desiccant. Appropriate matching of component capacity is necessary.

The novel tri-generation system concept has been demonstrated experimentally. Future work needs to focus on improving the current unreliability and sensitivity of fuel cell technology.

Deviations from DoW

The second amendment to the DoW dated 29/04/16 it was reported that the BlueGen SOFC was inoperable and it was proposed to use an off-the-shelf SOFC to carry out the field trials. A microtubular SOFC was acquired and integrated with the desiccant unit. The DoW target was for the system to prototype to operate successfully for more than one week. This milestone was achieved.

WP8: Economic and environmental assessment

Participants: NOTT, INEGI, VSS

Economic assessment

We have presented an economic assessment comparing the novel tri-generation system to an equivalent base case system. NPC, EUAC and SPBP have been used as the means of assessment. Sensitivity analysis has been used to assess the impact electricity unit cost, natural gas unit cost, country of operation and SOFC capital cost has on economic performance.

Within a UK economic climate it has been demonstrated that the NPC of the novel tri-generation system is only favourable when FiT is considered, in which case the 2.0kW$_e$ output is best. The tri-generation system has a lower annual operating cost than the base case; however, NPC and SPBP analysis demonstrates that the novel system is currently uneconomical. This is primarily due to the SOFC capital cost and the requirement of stack replacement, not the liquid desiccant unit capital cost. In the current UK economic climate the SOFC capital cost needs to be less than £9000 for the tri-generation system to be competitive. This is a cost estimate supported by Staffell and Green (2013) in their economic evaluations of SOFC CHP systems. PEMFC technology has demonstrated considerable price reduction over the last six years. The 1kW$_e$ Panasonic unit had a unit cost of £27,300 in 2009, but as of 2015 it is being supplied to energy companies for £3600. CFCL forecast that they can supply the BlueGEN unit for £5200 once in mass production. Currently, the much lower PEMFC unit costs are due to the technology being around five years ahead of SOFC. Many commercial developers believe the future of cheaper fuel cell technology lies with SOFC systems as they do not need to use expensive platinum catalysts like PEMFC. Based on the example of PEMFC cost reductions, significant SOFC cost reductions can be anticipated. The SOFC cost target figures presented in this chapter are therefore sensible and could be realistically achieved in the next five to ten years, making the tri-generation system economically viable in almost all cases.

Currently, the tri-generation system becomes competitive, and even demonstrates good profitability, compared to the base case system when government incubator support, such as the FiT is considered. With continued instability in governmental support for low carbon sustainable energy, the novel tri-generation system needs to become economically viable in its own right for it to be considered a viable alternative to conventional energy supply. Furthermore, a 2.0kW$_e$ base load capacity is large, and effective electrical utilisation may be problematic, particularly in a domestic building context. With the possibility of future withdrawal of government support for fuel cell CHP, maximising in-house electrical consumption will be essential to maintain economic viability. A lower electrical capacity fuel cell would therefore be required. The Japanese domestic market, which is estimated to be ten years ahead of the European market, is now focussing domestic fuel cell CHP development at capacities of 750W$_e$ (Ellamla, Staffell et al., 2015), a possible insight into the future of where European domestic fuel cell development needs to go.

Like other small scale tri-generation systems presented in the literature, the economic performance of the SOFC liquid desiccant tri-generation system is most sensitive to the unit cost of natural gas (Huangfu, Wu et al., 2007). The tri-generation system is economically superior, compared to the base case system, when the unit cost of electricity is greater than 0.24£.kWh^{-1} and as a result Denmark is currently the only country investigated where the tri-generation is economically viable. However, with the extraction of easily accessible fossil fuels diminishing, the unit cost of electricity in many countries is set to continue to rise, thus strengthening the economic case of the tri-generation system (DECC, 2013).

Next, we provide an environmental assessment of the tri-generation system.

Environmental assessment

This chapter has provided an economic and environmental assessment of the novel tri-generation system operating in a UK economic and energy system context. The assessment has used the BlueGEN SOFC tri-generation system performance data presented in section 7.2. The tri-generation system has been compared to a base case system comprised of grid electricity, natural gas fired boiler and electrically driven VCS. Sensitivity analysis has been used to assess the performance of the tri-generation system across a range of operating scenarios.

The economic assessment has demonstrated that the novel tri-generation system is viable only in certain cases. The tri-generation system has a lower annual operating cost than the base case, however, the high capital cost of the SOFC and requirement of stack replacement means that the tri-generation system NPC is only favourable when FiT is considered. However, with anticipated SOFC capital cost reductions the economic performance is predicted to improve. The current tri-generation system does not have a SPBP of less than five years, and is thus not immediately attractive to investors. Furthermore, with the possibility of future withdrawal of government support, a move mirroring the Japanese market towards smaller electrical capacity domestic fuel cells may be required to achieve/maintain economic viability. The economic performance of the tri-generation system is sensitive to natural gas and electrical unit cost. The future economic feasibility of the system will therefore be dependent upon future energy prices, which can be highly volatile. Currently, the tri-generation system is only economically viable in Denmark due its high unit cost of electricity.

The environmental assessment has demonstrated that the novel tri-generation system is viable across a large range of operational values. Within a UK energy system context, annual CO_2 emission reductions of up to 51% compared to the equivalent base case system have been demonstrated. The environmental performance of the tri-generation system is more sensitive to changes in the natural gas emission factor than the base case system. The CO_2 emissions of the tri-generation system are insensitive with respect to electricity emission factor. However, electricity emission factor does affect the relative performance of the tri-generation system with respect to the equivalent base case system. The tri-generation system is environmental superior when the electricity emission factor is greater than $0.23kgCO_2.kWh^{-1}$. As a result, the tri-generation system is not currently viable in France and Norway. Australia and China demonstrate the greatest environmental benefit from adopting the novel tri-generation system. With a transition to hydrogen-fed fuel cells, the novel tri-generation system will be highly competitive in almost all scenarios.

This chapter has provided a detailed economic and environmental assessment of the novel tri-generation system. The following general conclusions, with respect to the chapter aims set out in section, are as follows:

(1) The system is currently only economically viable with government support. SOFC capital cost and stack replacement are the largest inhibitors to economic viability. Environmental performance is closely linked to electrical emission factor, and thus performance is heavily country dependent.
(2) The countries, in which the system is environmentally viable, are in general the counties in which the system is not economically feasible. This is primarily due to the play off between cheap electrical generation from fossil fuels and more expensive cleaner electrical generation from renewables or nuclear.
(3) The economic feasibility of the novel tri-generation system will improve with predicted SOFC capital cost reductions and the transition to clean hydrogen production.

Although the SDCS has been developed with the aim of integration alongside a SOFC into a complete tri-generation system, the SDCS shows significant potential for integration with other CHP prime mover technologies such as ICE or SE. Due to the lower capital cost of ICE and SE technology (roughly ten times that of SOFC) and cheaper maintenance/part replacements, the economic performance of an ICE/SE based liquid desiccant tri-generation system can be expected to be much better than the current SOFC based system. However, the environmental performance of the SOFC based system will remain favourable compared to alternative options due to high electrical conversion efficiency and the provision for zero carbon energy conversion with the transition to a pure hydrogen fuel feed.

This chapter has demonstrated that the novel tri-generation system is, in certain cases, economically viable.

WP9: Dissemination activities

Contributors: All participants

Work progress and achievements during the period

Project website development

The consortium has secured the unique domain name of www.trisofc.com for use in disseminating information about the activities of the consortium to the public and as a central depository and for the transfer, sharing and storage of information and material between partners. The website was up and running within a month of the start of the project and is being regularly updated and improved.

The website has developed into a site with six pages;

1) Home. This gives an introduction to the project and describes the background and the broad reasoning/rationale behind the project.
2) TriSOFC System. This describes the TriSOFC system that is to be developed and the technology the different partners will be bringing to the project. This section also describes the timeline of the project and the objectives.
3) Project Partners. This gives a brief description of all of the partners involved in the project, personal and organisation profile and contact details.
4) Project News. This is a news feed feature, therefore any news from the project such as invited talks, participation in events, future events and awards can be updated. Any website viewer, including project partners will be able to access the page and increase awareness of the project and its outcomes.
5) Published work. This section will contain details and links to any publications related to the TriSOFC project.
6) Project gallery. This will include any images from the project. Content could range from images from meetings, events and conferences, photographs of prototype equipment not subject to IP restrictions, experimental rigs, and field trials.

The link to the website is: www.trisofc.com

Dissemination activities report

The consortium has been very active in promoting and disseminating results from the research and development emerging from the project. Many significant results and discoveries have been unearthed as a result of the project and this report highlights these achievements. We have also taken on board comments by the mid-term reviewers, who recommended that we should engage more with the international fuel cell and hydrogen community, therefore we highlight these activities as well as reports on publications and conference participation. The following section lists the activities undertaken by each consortium member, but many of the activities were either engaged in jointly with other members, or materials and content were shared between members. The signifier (J) indicates joint efforts.

NOTT

Journal papers

Elmer, T., Worall, M., Wu, S. and Riffat, S, (2015) Emission and economic performance assessment of a solid oxide fuel cell micro-combined heat and power system in a domestic building: Applied Thermal Engineering, (*In Press*, available online April 2015)

Elmer T., Worall M and Riffat S, (2015) Fuel cell technology for domestic built environment applications: State of the art review. International Journal of Renewable and Sustainable Energy Reviews, 42, 913-931.

Conference papers

Elmer T., Worall M and Riffat S, (2013) A Novel Solid Oxide Fuel Cell Tri-Generation System for Low Carbon Buildings, 12th International Conference on Sustainable Energy Technologies. 26th – 29th August 2013. Hong Kong, China

Worall M., Elmer T., Riffat S and Wu S, (2013) Simulation of a desiccant dehumidifier for a low temperature solid oxide fuel cell (LT-SOFC) Trigeneration system, 12th International Conference on Sustainable Energy Technologies. 26th – 29 August 2013. Hong Kong, China

Elmer T and Riffat S, (2012) State of the art review: Fuel cell technologies in the domestic built environment, 11th International Conference on Sustainable Energy Technologies. September 2012. Vancouver, Canada.

Book Chapters

Elmer, T. and Riffat, S, (2014) Chapter 14, State of the Art Review: Fuel Cell Technologies in the Domestic Built Environment *In:* Progress in Sustainable Energy Technologies Vol. II, Springer International Publishing, 247-271.

Fuel Cell and Hydrogen dissemination activities

FCH-JU Programme Review Days Brussels, 11-12th November 2013 (J)

FCH-JU Programme Review Days Brussels, 10-11th November 2014 (J)

Elmer T., Worall M and Riffat S, (2013) An Innovative Solid Oxide Fuel Cell Tri-Generation System for Low Carbon Domestic Buildings, Hydrogen & Fuel Cell SUPERGEN Researcher Conference. 16th – 18th December 2013. University of Birmingham, UK. (Poster) (J)

Elmer T., Worall M and Riffat S, (2013) Tri-generation solid oxide fuel cell for low carbon building applications, MEGS Conference, 12th December 2013. Birmingham, UK. (Poster) (J)

Worall, M, Elmer, T, Riffat, S, (2014) A fuel cell tri-generation system for domestic buildings, SIRACH (sustainable innovation in refrigeration, air conditioning and heat pumps)meeting, 2nd September 2014, Mitsubishi Electric HQ, Livingston, Scotland. (Presentation)

Worall, M, Elmer, T, Riffat, S, (2015) A fuel cell tri-generation system for domestic buildings, Fuel Cell and Hydrogen Technical Conference 19-21st May 2015, Birmingham, UK. (Presentation) (J)

KTH

Journal papers

Zhu, B.*, Lund, P., Raza, R., Ma, Y., Fan, L., Afzal, M., Patakangas, J., He, Y., Zhao, Y., Tan, W., Huang, Q., Zhang, J. and Wang, H.*, (2015) Schottky junction effect on high performance fuel cells based on nanocomposite materials, Adv. Energy Mater, 5, (8), 1401895. (*In Press*, available Jan 2015)

Hu, H., Lin, Q., Muhammad A., and Zhu, B., Electrochemical study of lithiated transition metal oxide composite for single layer fuel cell, J. Power Sources 286 (2015) 388-393.

Yanyan Liu , Yongfu Tang, Zhaohui Ma, Manish Singh, Yunjuan He, Wenjing Dong, Chunwen Sun & Bin Zhu, (2015) Flowerlike CeO2 microspheres coated with

Sr2Fe1.5Mo0.5Ox nanoparticles for an advanced fuel cell, Scientific Reports 5:11946, 2015 (doi:10.1038/srep11946).

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International conferences for keynote and plenary lectures. All conferences outside of European are financed by KTH own funding to support this project.

International Conference on Electrochemical Materials and Technologies for Clean Sustainable Energy, 2013, July 5-9, Guangzhou.

International Workshop on Molten Carbonates & Related Topics (2013) (IWMC 2013), September 25-27, South Korea.

International conference on impact of Nano-science on energy technologies (NanoSET-2014), 18-20 March; 2014, Pakistan, Plenary lecture: The Role of nanotechnology in energy technologies;

2014 Global Conference on Polymer and Composite Materials (PCM 2014) May 27-29, Ningbo,China. http://www.cpcmconf.org,

ICCE2014, 8-12 June 2014, Istanbul, Turkey. www.icce2014.net/icce2014/index.php?conference=icce2014&schedConf=icce2014

International Congress on materials and renewable energy (MRE 2014), Hong Kong, China, with certificate http://www.mreconference.com/speakers.html

The 1st International Symposium on Catalytic Science and Technology in Sustainable Energy and Environment, October 8-10th, 2014, Tianjin, China.

The 4th Annual World Congress of Advanced Materials-WCAM-2015, May 27-29, 2015, Chongqing, China.

Fuel Cell and Hydrogen dissemination activities

World Congress for Hydrogen Technology, (2013) WHTC2013, September 26-29, Shanghai, China.

Royal Society Chemistry (RSC, UK) 2nd Int. conf. on Clean Energy Science, 13-16, April, Qingdao, China. keynote: Challenges and opportunities for SOFCs, http://www.icces.cn/ ;

International Conference on Nanotechnology, Nanomaterials & Thin Films for Energy Applications, 1-3 June 2015, Manchester, UK.

6th International conference on Advanced Nanomaterials and International conference on Hydrogen Energy, 20-22 July 2015, Aveiro, Portugal.

UBHAM

Journal papers

Muhammad Afzal, Rizwan Raza, Shangfeng Du, Bin Zhu. Preparation and Testing of $Ba_{0.3}Ca_{0.7}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BCCF) as Novel Nanocomposite Cathode Material for Low Temperature Solid Oxide Fuel Cells. Submitted to International Journal of Hydrogen Energy. (J)

Book Chapters

Du, S.F, Pollet, B.G.,(2014) Chapter 7, Applications of Nanomaterials in Fuel Cells, *In* Nanotechnology for Sustainable Manufacturing, Ed: Rickerby, D, CRC Press, ISBN 9781482214826.

International conference papers
Presentations and invited teaching

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Du, S, Tsai, T, Zhu, B, Steinberger-Wilckens, R, (2014) Single component micro-tubular solid oxide fuel cells: a new electrochemical aspect of nano-redox. Oral presentation in Electrochem 2014, 7-9 September, Loughborough, UK. (J)

Outreach activities

Outreach activities with China- Europe 2020: Climate Change Challenge Initiative in Birmingham on 19/11/2012, 16/05/2013, 23/10/2013 and 08/01/2014.

Outreach activities to inspire young people working on clean fuel cell technology at Bordesley Green Girls School and Ninestiles School, Birmingham on 21/01/2014, 20/03/2014 and 03/03/2015, respectively.

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Du, S, Tsai, T, Zhu, B, Steinberger-Wilckens, R, (2014) three-in-one: single layer low temperature micro-tubular solid oxide fuel cells. Poster presentation at 11th European SOFC and SOE Forum (EFCF 2014), 1-4 July, 2014, Lucerne, Switzerland. (J)

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B. Timurkutluk, S. Celik, C. Timurkutluk, M.D. Mat and Y. Kaplan, (2012) Novel electrolytes for solid oxide fuel cells with improved mechanical properties, International Journal of Hydrogen Energy 37, 13499-13509.

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B. Beyribey, B. Timurkutluk, T.Y. Ertuğrul, C. Timurkutluk, M.D. Mat, (2013) Electrochemical behaviour and sulfur tolerance of $V_xMo_{(1-x)}O_y$ as SOFC anode, Ceramics International, 39, 7053-7061.

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B. Timurkutluk, and M.D. Mat, (2015) A performance prediction tool for solid oxide fuel cells after single redox cycle, Fuel Cells, 15, 71-89.

Conference papers

Bora Timurkutluk, Cigdem Timurkutluk and Sadig Kuliyev, (2013) High performance electrolyte supported solid oxide fuel cell (SOFC) with novel electrolyte design, 10th International Electrochemistry Meeting (ECM10 2013), Konya, Turkey.

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E. Sanlı, V. Uysal, M. Canavar, A. Mat, S. Celik, Y. Kaplan, B. Timurkutluk and O. Genc, (2015) Investigation of temperature distribution and performance on single SOFC stack with/without machined gas channels, International Symposium on Materials for Energy Storage and Conversion, Ankara, Turkey.

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Y. Ciflik, B. Timurkutluk, C. Timurkutluk, H. Korkmaz and Y. Kaplan, (2014) Effects of YSZ addition on thermal cycling performance of glass ceramic sealant, IV. National Solar and Hydrogen Energy Congress, Eskişehir, Turkiye.

Nanosmat 2015 Workshop, Manchester, May 2015. (J)

IVF

International Journals

Stiernstedt J, Carlström E and Mellander B-E, Solid Oxide Fuel Cell Manufacturing using Aqueous Tape Casting – 1. Controlling Porosity by Colloidal Processing", *submitted to Fuel Cells - From Fundamentals to Systems, April 2015.*

Billemar J, Mellander B-E and Stiernstedt J, Solid Oxide Fuel Cell Manufacturing using Aqueous Tape Casting – 2. Effect of Anode Porosity", *submitted to Fuel Cells - From Fundamentals to Systems, April 2015.*

International Conferences

Stiernstedt J, Carlström E and Mellander B-E, Co-Sintering of Solid Oxide Fuel Cells made by Aqueous Tape Casting. Proceedings of the 10th European SOFC Forum, 2012, Kultur- und Kongresszentrum Luzern, Lucerne, Switzerland.

Stiernstedt J, Trendspaning Bränsleceller – TriSOFC Durable Solid Oxide Fuel Cell Tri-generation System for Low Carbon Buildings, Teknik & Tillväxt, 4, 2012, 6-7.

Stiernstedt J, Carlström E and Mellander B-E, Manufacturing of Solid Oxide Fuel Cells by Aqueous Tape Casting, *Proceedings of the 10th International Conference on Multi-Material Micro Manufacture*, Eds Azcarate S, Dimov S. Research Publishing, Singapore, 141-144 (2013).

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Stiernstedt J, Oral presentation on fuel cells. 12th International Conference on Ceramic Processing Science 2013, Portland, Oregon, USA, 4-7 August 2013.

Eriksson M, Oral presentation: TriSOFC - Durable Solid Oxide Fuel Cell Tri-generation System for Low Carbon Buildings, Swerea IVF, Mölndal, Sweden, 17 March 2014.

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