

NPL REPORT
DEPC-TH 007

**Applications of Thermal
Imaging in Solid Oxide Fuel
Cell Research**

Stephan Schöttl
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APRIL 2006



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Applications of Thermal Imaging in Solid Oxide Fuel Cell Research

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ISSN 1744-0289

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1. Executive Summary

Fuel cells are devices generating electricity from the chemical energy stored in hydrogen or other fuels containing hydrogen. This report looks at a specific type of these devices, solid oxide fuel cells (SOFC), which operate at temperatures between 550 °C and 900 °C. This work applies the thermal imaging technique to SOFC research devices, and materials samples related to SOFC. It is an attempt to explore the potential benefits of this technique in the SOFC field, where it has hardly been used before.

This structure of this report is as follows:

- The introduction explains the various thermal issues that arise from the SOFC principle and current designs.
- The experimental part lists the equipment used.
- Data obtained from working SOFCs are shown.
- Other experiments that can help advance SOFC material research are described and initial results shown.
- The results are summarised.

The main conclusions are:

- Temperature rise in operation can be observed and has an impact on the current-voltage curve; non-uniformity can indicate material processing problems.
- New data help validating models.
- Redox reactions can be observed and valuable data show their dynamics.
- SOFC materials are shown to be less sensitive to thermal stress than expected.
- A technique for combinatorial measurements is suggested but required bigger samples.

A wealth of data and ideas is collected in this study. More detailed investigations promise better insight and faster development.

Part of this work is being published in [1].

2. Introduction

Fuel cells provide a versatile way of generating electricity from hydrogen as part of a diversified and environmentally friendly energy scenario. While their operating principle has been known since the mid 19th century, and they have been used in niche applications, there is still a significant development effort necessary to make them suitable for widespread use. This involves improvements in the manufacturing process and of the durability of the cells.

Fuel cells use hydrogen or other fuels and oxygen from the air to create electricity. Electrons are transferred from the hydrogen to the anode of the cell and then sent as electric current through an external load to the cathode, where they ionise the oxygen. The circuit is closed by ions travelling between anode and cathode through the electrolyte. The ions then react to produce a fuel cell's only emission, water.

One class of electrolyte materials are ceramics that become conductors for oxygen ions at high temperatures. Fuel cells made from these electrolytes are called solid oxide fuel cells, SOFC [2]. Among the various types of fuel cells, the solid oxide fuel cell has the advantages of high efficiency and of accepting a variety of different fuels while demanding only modest levels of fuel purity. Its disadvantage is the high operating temperature of 600 °C to 900 °C due to the low, thermally activated mobility of the oxygen ions in the ceramic electrolyte. Current research aims to reduce the operating temperature by finding electrolyte materials with higher ionic conductivity. SOFC are immune to the most common fuel contaminants but need long start-up times to reach their operating temperature. Therefore, their envisaged main application is stationary cogeneration, e.g. domestic or small industrial combined heat and power systems, grid support and uninterruptible power supply.

In the manufacturing process, the cells require a complicated sequence of heat treatments. With better understanding of the thermal response of SOFC, this sequence can be accelerated and yield increased. During operation, the cells undergo thermal stress due to initial warm-up, exothermic fuel oxidation, endothermic fuel reformation (in some cases), and ohmic heating due to the electric current. The resulting complicated distribution of heat and electric power is poorly understood.

Temperature gradients across SOFC are a major cause of failure both during production and use. They can result in materials failure either by delamination of the electrodes from the electrolyte or by cracking of the ceramic electrolyte.

Within the energy and environment theme of the Measurement for Emerging Technologies (MET) programme of the Department of Trade and Industry, in-situ measurements of fuel cells have been made. They aim to improve the understanding of thermal behaviour of SOFC materials and operating cells. For the first time, thermal imaging measurements on working SOFC have been made.

Thermal imaging presents unique advantages as a way to address the thermal issues in SOFC: as a non-contact method it does not disturb the behaviour of the cells; it allows in-situ measurements while the cell is operating; the spatial resolution helps identify under-performing areas; fast response enables recording of dynamic phenomena.

The aim of this study is to explore the potential benefits of the infrared imaging technique to a new field. This is achieved by demonstrating the feasibility of detecting signals from a working pellet SOFC. Other ideas for experiments are explained and

briefly evaluated. The initial data are expected to be useful as boundary conditions and for validation of SOFC models.

3. Experimental set-up

3.1. Thermal camera

The imaging data were obtained using a Cedip Silver infrared camera [3]. This camera is based on an InSb focal plane array detector. The detector is cooled to below 80 K by an internal Stirling cooler. It is sensitive to infrared radiation with wavelengths from 3 μm to 5 μm . For temperatures above 200 $^{\circ}\text{C}$ a narrow band filter was used, which limited the sensitivity to the range 3.97 μm to 4.01 μm . The image consists of 320 $\times$ 256 pixels and can be recorded at up to 100 Hz with any of the used integration times. In some cases up to ten successive images were averaged to reduce the noise.

The camera has been calibrated at the factory for a variety of different combinations of integration time, filters and lenses. This calibration includes corrections for non-uniformity of the detector array and bad pixel replacement. In this study, the factory calibration was used and the camera settings chosen accordingly.

The resolution of the AD converter is 14 bit and the resulting, temperature-range dependent temperature resolution is given below for each experiment.

The camera was used with its standard 27 mm lens and mounted either on a flexible arm or on a bench-mounted translation stage. The sample distance was always between 0.3 m and 0.5 m, resulting in a spatial resolution of the order of 0.5 mm.

3.2. Additional instrumentation

All experiments were monitored with a type N thermocouple located as close as possible to the sample. This also served as a crosscheck for the thermal camera calibration. Its cold junction was either placed in ice water or controlled at room temperature. The thermocouple had been annealed at 950 $^{\circ}\text{C}$ but not individually calibrated. Nevertheless consistent readings between the furnace control thermocouples, infrared camera and monitor thermocouple were obtained.

For the fuel cell experiments, a range of gases was available with individual flow rate controllers. The flow controllers operate at room temperature, 18 $^{\circ}\text{C}$. Hydrogen mixed with nitrogen was used as fuel and humidified by bubbling through water at room temperature.

3.3. Furnaces

Due to the high operating temperature of SOFC, the experiments were carried out in furnaces. Two cylindrical furnaces were used: one horizontal tube furnace of 0.6 m length with an inner diameter of 40 mm, and one vertical split-case furnace with a 90 mm diameter sample space and 0.6 m total length. The furnaces were temperature controlled using thermocouples located between the sample space and the heaters. One end of the sample space was blocked using thermal wool or bricks, whereas the other end was left open to allow optical access.

Before the actual experiments, the thermal stability of the furnaces was characterised with the monitor thermocouple. The results are shown in Figure 1. The horizontal furnace originally exhibited oscillations of 4 °C peak to peak due to poor tuning of the PID controller. Limiting the maximum heater output reduced them to about 1 °C. The vertical furnace is stable to within 0.2 °C, but suffers from fluctuations due to convection.

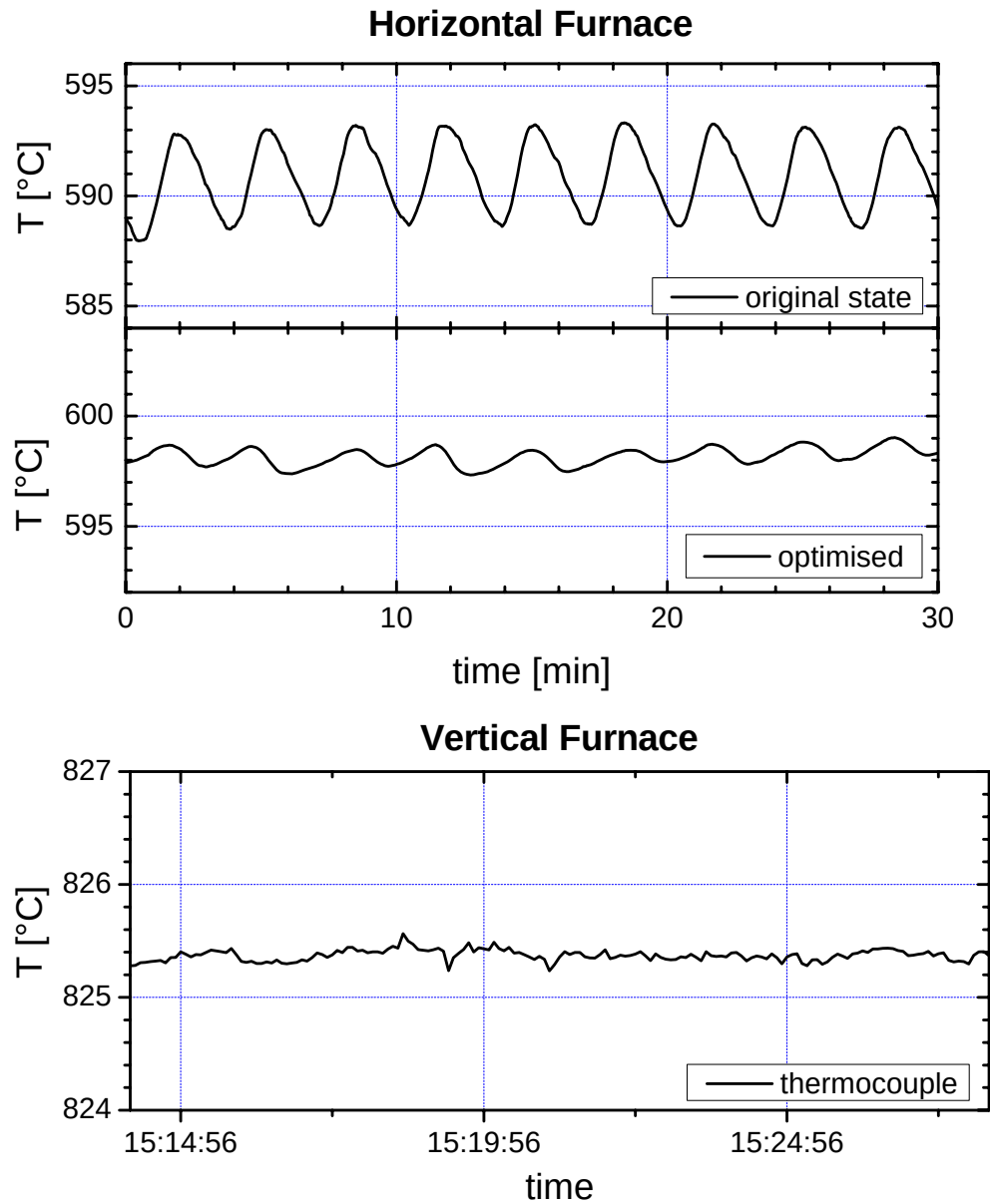


Figure 1 Temperature stability of the furnaces, shown as variation of temperature as measured with the monitor thermocouple.

4. Thermal imaging of operational SOFC

4.1. Samples

Two samples of the electrolyte-supported pellet, P1 and P2, type are used. They are based on a 16 mm diameter disc of gadolinium doped ceria (CGO) ceramic, serving as the electrolyte [4]. The anode and cathode materials (nickel oxide-gadolinium doped ceria and lanthanum strontium cobalt ferrite, respectively) are screen printed from ink to the electrolyte and sintered to give porous reaction zones with high internal surface areas. The active zone is 10 mm in diameter or 0.785 cm^2 in area. This type of SOFC is called pellet SOFC and routinely used in research, see for example [5].

To collect the current, a fine platinum gauze and platinum wire are connected to the electrodes. To enhance the infrared emissivity of the cathode side, cathode material itself was used instead of silver paint to glue the platinum to the cell. This is done by applying a paste of cathode material and sintering it with the gauze and wire in place. The cathode current collector wire is shaped as a ring around the active zone.

The samples are glued and clamped to the end of a ceramic tube that also transports the product gas away. The anode faces the inside of the tube. The thermal camera is directed towards the air-breathing cathode. Along the axis of the product gas tube there is a thin tube to supply the fuel to the cell. The assembly is shown in Figure 2.

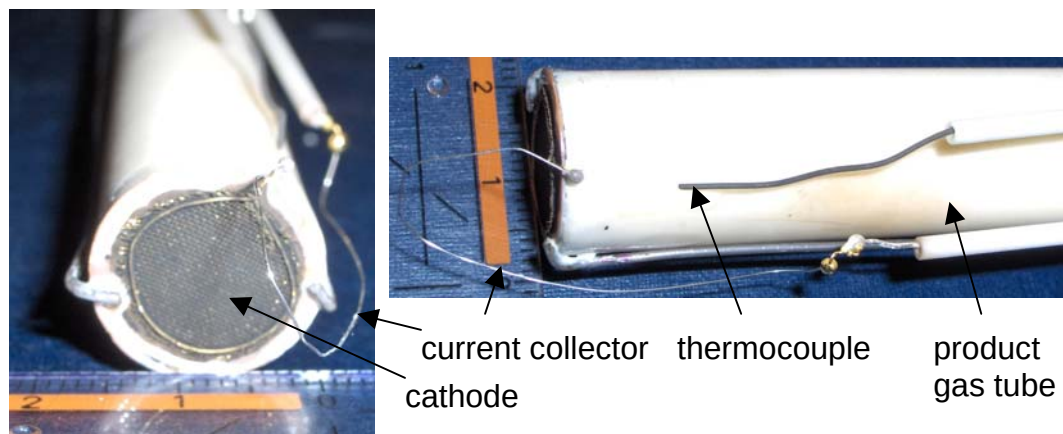


Figure 2 Pellet SOFC assembly for thermal imaging; the length scale shown is in cm

4.2. Assessment of the measurement capabilities

Before supplying fuel to the SOFC, a thermal image has been recorded at stable temperature. The image is shown in false colours in Figure 3, red and magenta representing hot areas, blue cold areas. The central red area is the active area of the SOFC.

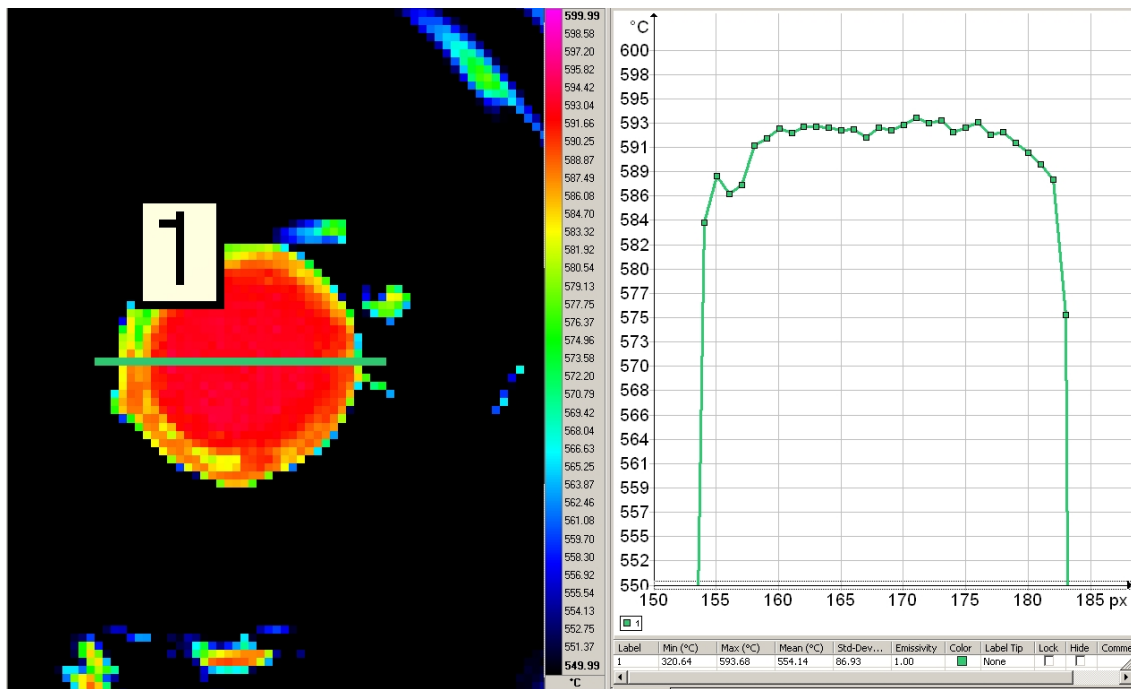


Figure 3 Pellet SOFC at constant temperature. Left: thermal image in false colours. Right: temperature profile across the cell, along the line labelled “1” in the left panel.

The camera calculates a temperature of 593 °C from the amount of radiation it detects in this area, with an assumed emissivity of 1. The thermocouple reading for this image is 590 °C. From this it follows that the emissivity of the cathode is very near 1. Causes of this high emissivity are the large number of cavities due to the porosity of the material, and the oxidation of the nickel in the cathode material with air at high temperature. The absolute accuracy of the measurement cannot be expected to be better than a few °C.

Around the active area, Figure 3 shows a green and yellow coloured ring. This ring is plain electrolyte material. It has lower emissivity, therefore radiates less infrared light and appears colder than it is. The two green spots just above and to the right of the fuel cell are the thermocouple and current collector wire. Further out some hot parts of the furnace tube are visible.

A temperature profile along the green line across the cell (labelled “1”) is shown on the right panel of Figure 3. The whole SOFC disk has a diameter of about 30 pixels and the active area 20 pixels. This corresponds to a pixel spacing of 0.5 mm. Vibrations of the camera due to the Stirling cooler generate jitter of the image. Originally this was just under one pixel and could be further reduced by strengthening the camera mount. Apparent temperature variations within a range of 1 °C occur over the active area and are visible in the graph. They are found not to vary with time. Since there is no reason for a real temperature gradient over such small length scales, they are most likely a manifestation of the non-uniformity of the sample emissivity.

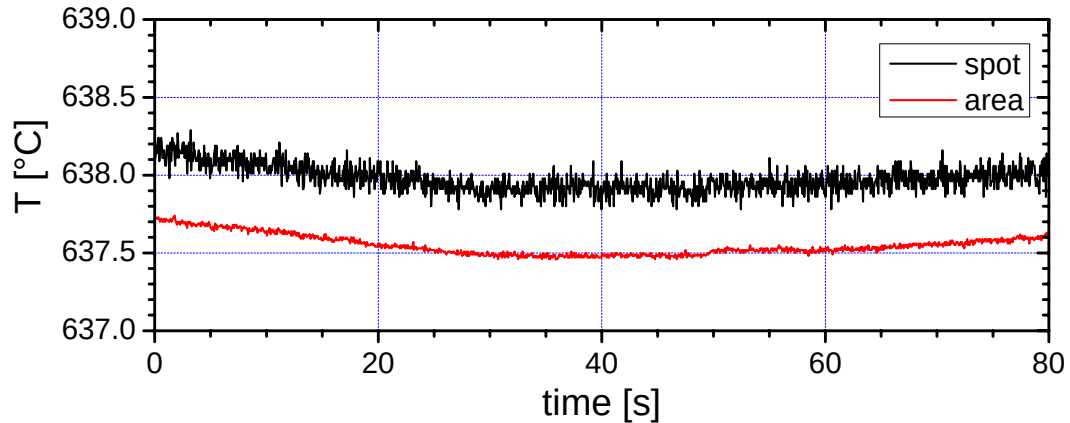


Figure 4 Sensitivity of the measurement of a pellet SOFC using the thermal camera. Black: measurement of a single pixel. Red: Average over 70 pixels.

A measure of the sensitivity of the measurement can be obtained from a graph of the temperature reading versus time as shown in Figure 4. In this case, each point represents an average over five frames. A time resolution of 50 ms is still possible and sufficient for all experiments. For a single point, the noise band is about 0.15 °C wide. However, taking an average over 70 pixels (one-fifth of the active area) reduces the noise to little above the digitisation resolution of 0.01 °C. Drift and oscillation in the furnace control remain a significant problem.

4.3. Fuel cell operation

Fuel cell sample P1 has an open circuit voltage (OCV) of 0.966 V at 592 °C. To characterise the performance of a cell, a polarisation curve is measured as shown in Figure 5. This type of curve establishes the relation between the electrochemical potential and the output current. From Figure 5, a maximum power output of 39 mW or 50 mW/cm² can be calculated. This is a good value for a pellet SOFC. At high currents or low voltages, the reaction rate may be high enough to degrade the electrodes. The measurement is repeated at 642 °C. Due to the increased ionic conductivity of the electrolyte, the current is higher. The maximum power in this case is 63 mW or 81 mW/cm². The OCV is reduced, however, due to internal short-circuiting by electronic conductivity of the electrolyte. This also affects the efficiency.

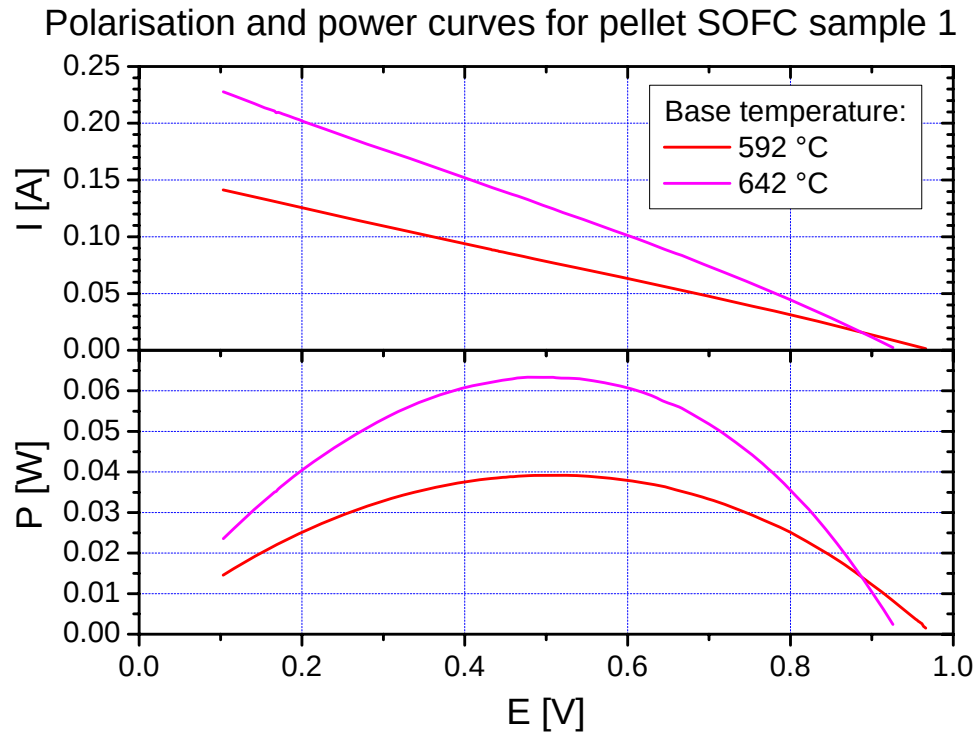


Figure 5 Polarisation curves of pellet cell P1 at 592 °C and 642 °C, and corresponding power output.

While this measurement is taken, fuel oxidation takes place and an electric current flows through the cell. Both processes generate heat locally. The resulting warm-up is shown in Figure 6. Although the maximum power output occurs at 0.5 V, the highest self-heating occurs at the largest difference from open circuit voltage, in this case 0.1 V. The maximum temperature increase is 1.6 °C and most of the active area exhibits at least 1.0 °C temperature rise. The steepest gradient, approximately 0.7 °C/mm, appears as expected around the edge of the active zone. However, the temperature increase is not entirely symmetric: The hottest area is located somewhat to the bottom right of the centre and the upper left side of the sample is clearly less strongly heated. Despite taking a small difference of two large temperature values, this measurement demonstrates a temperature resolution of less than 0.1 °C. Figure 6 also shows that non-uniformities in pellet cells can occur and be detected on length scales of below 1 mm.

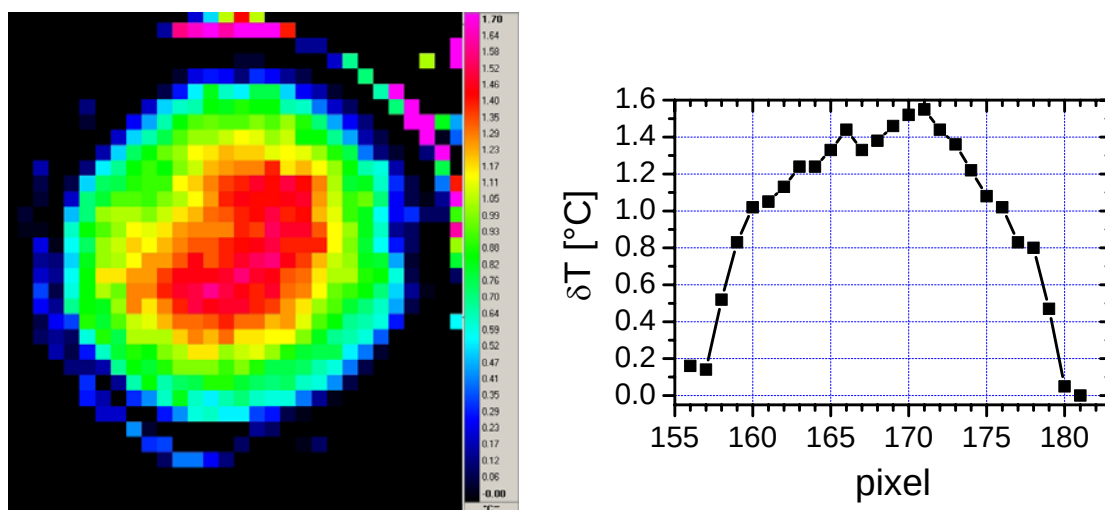


Figure 6 Temperature change δT during a polarisation curve measurement at 592 °C. Left: temperature difference between open circuit and 0.10 V. Right: profile of this temperature difference across the cell. The active zone spans approximately pixels 158 to 179 (10 mm).

A look at the variation of the cell temperature with time shows that the self-heating effect is superimposed by the furnace control instability as described in Section 3.3. Therefore it is not possible to obtain quantitative information about the self-heating as a function of voltage from slow polarisation measurements. Accordingly, another set of experiments has been performed, in which the voltage was changed rapidly from open circuit (or small voltage drop) to finite voltage. The two techniques are compared in Figure 7.

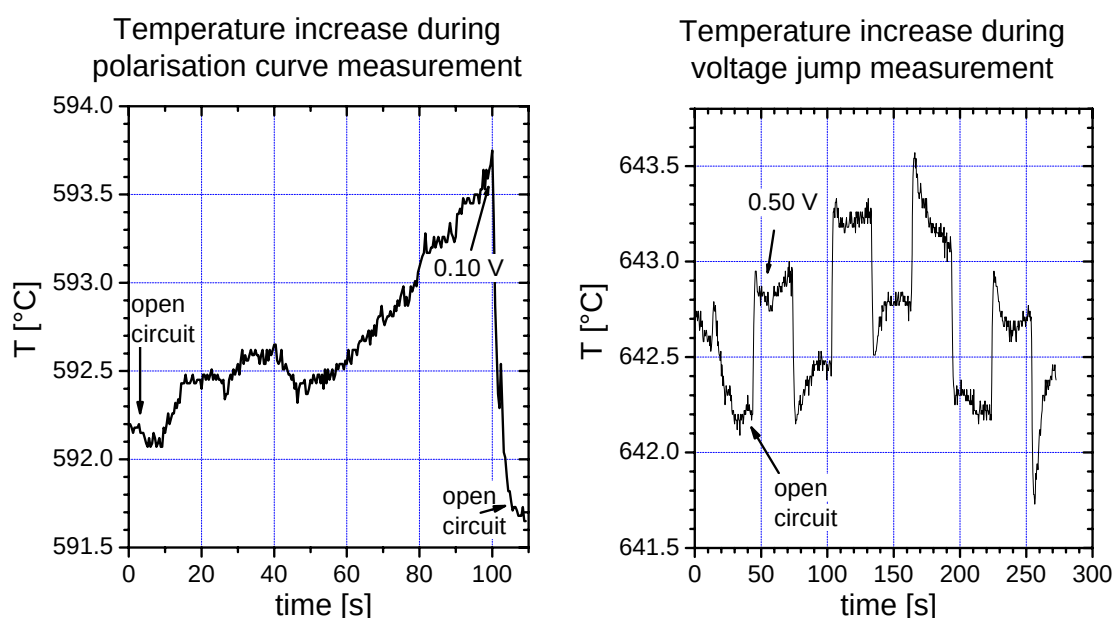


Figure 7 Measurement of temperature increase in the centre of the sample during polarisation measurements at 592 °C (left), and voltage jumps at 642 °C (right).

By averaging a series of temperature jumps after rapid voltage changes, sufficiently accurate measurements of the self-heating can be obtained. The results for the centre of

the cell are shown in Figure 8. Due to the higher power the effect at 642 °C is greater than at 592 °C.

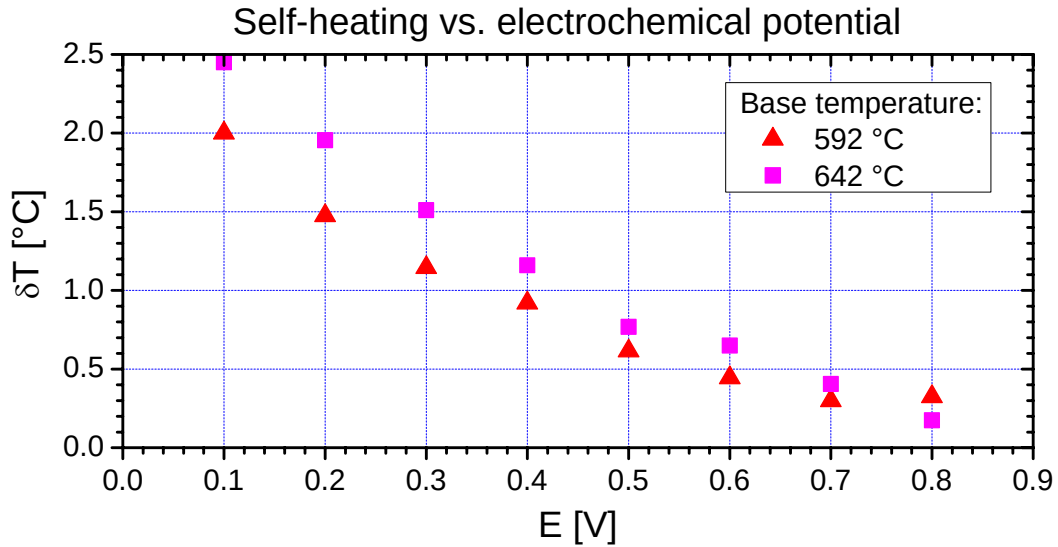


Figure 8 Temperature increase in the centre of SOFC sample P1 due to self-heating at two different base temperatures.

4.4. Redox cycling

The anodes of the pellet cells were subjected to repeated redox cycling by exposure to hydrogen and air. In an unknown moment during these experiments, sample cell P1 cracked, leading to fuel leakage across the electrolyte. The results of this experiment therefore do not allow for conclusive information on the anode behaviour. The data below show the results of sample P2. For the redox experiments, the cell is left open circuit and its voltage continuously monitored. The temperature of the cell is measured using the thermal camera and averaged over a 6 mm diameter spot in the centre. The furnace temperature is monitored with the thermocouple next to the pellet.

In the fully controlled oxidation experiments, a 50% hydrogen, 50% nitrogen gas mixture is initially supplied to the anode to keep it in the fully reduced state. To initiate the experiment, the hydrogen supply is switched off. The first arrow in Figure 9 indicates this point in an experiment at 550 °C. The nitrogen is allowed to continue flowing in order to purge hydrogen from the pipework and anode. After about 3 minutes, the OCV drops without a clear signature in the pellet temperature. This is taken as an indication of complete fuel purging, and air is then added to the nitrogen through a separate, much shorter tube. As a result, the pellet temperature rises by 5.8 °C within one second. Burning of fuel that was trapped inside the anode pores may contribute to this heating. Within a further 11 s the temperature drops to a minimum at 3.0 °C cooler than the background temperature. The pellet temperature then recovers towards its original value with a time constant of 2 minutes.

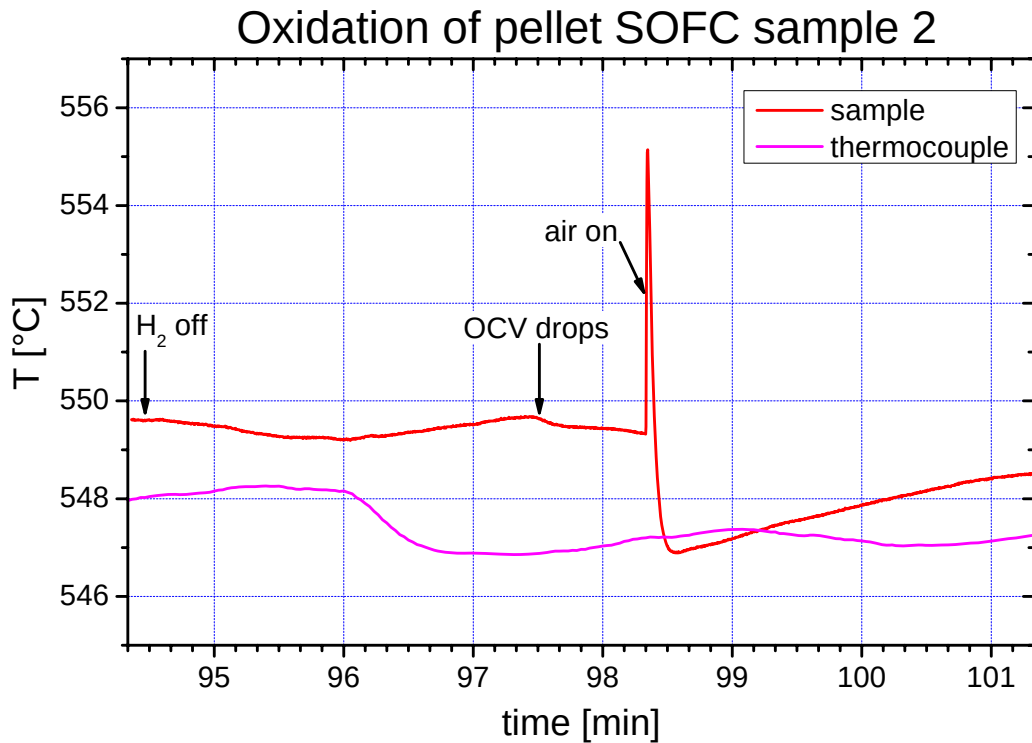


Figure 9 Oxidation of the anode of sample P2. For explanations see main text.

The thermal signature of a reduction is significantly smaller. Therefore, drift and oscillation due to insufficient temperature control prevent quantitative analysis of the data. Figure 10 illustrates the behaviour for three events. Due to its location outside the sample tube, the thermocouple follows neither the oscillation nor the drift exactly. This background time dependence is also too erratic to allow a subtraction. When the hydrogen gas reaches the anode, the sample temperature increases quickly by about 0.5 °C, as indicated by the arrows. In the case of Figure 10(a), and to a lesser extent Figure 10(b), a short temperature overshoot is visible. This has been avoided in Figure 10(c) by purging with nitrogen gas for a longer time (2½ minutes) and greatly reducing the hydrogen flow rate. After the step change in temperature, a relaxation to the original value would be expected. However, this relaxation is too slow and therefore masked by the furnace instability.

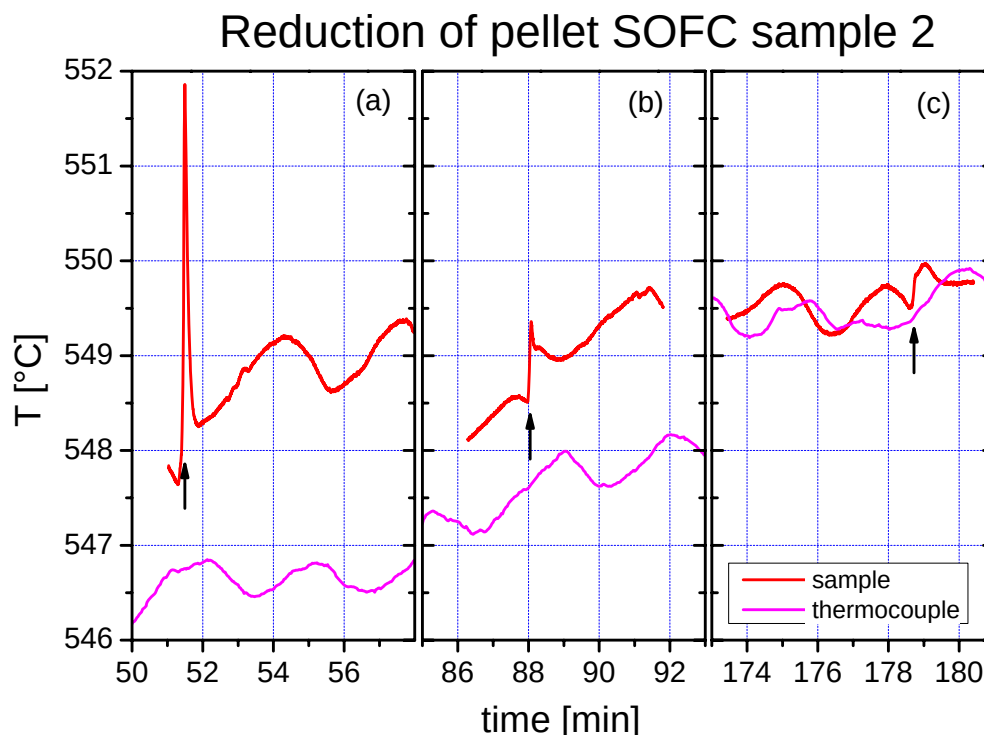


Figure 10 Reduction of the anode of sample P2. Three events are shown as graphs of the time dependence of temperature. Arrows indicate the times at which the reactions start. The instability of the furnace control can be seen by the background drift and oscillation.

In summary, anode oxidation leads to cooling by several °C and decays over minutes. Correspondingly, reduction heats the sample. This heating effect is however smaller in magnitude and lasts much longer. In addition, fast temperature increases can occur upon redox cycling due to fuel oxidation with trapped gas.

5. Thermal imaging for SOFC materials research

As pointed out in Chapter 1, thermal issues in SOFC often arise from properties of the materials used. Therefore, the thermal imaging technique is useful for analysis of SOFC materials in addition to in-situ measurements. Two examples are outlined below.

5.1. Thermal stress analysis

Stress in fuel cell materials can arise from temperature gradients and damage the cell. If the electrolyte cracks, fuel can leak across to the cathode and react directly with air without contributing to the generation of electricity. Also, due to differential thermal expansion of electrolyte and electrode materials, the electrodes can delaminate and interrupt the current path.

Thermal imaging of materials samples can test the failure conditions for materials used in SOFC. In the present study, three samples have been used to do this. Sample S1 is a 50 mm × 50 mm × 0.2 mm square plate of yttria-stabilised zirconia (YSZ), the most common electrolyte material for SOFC. Sample S2 is a similar plate of CGO. Sample S3 is a YSZ plate as in sample S1, which has electrodes printed onto it. The electrode areas are 40 mm × 40 mm wide. The experiment has been performed in the vertical

furnace. The sample is positioned at the low end of the hot zone on a vertical glass tube with inner diameter 44 mm. The infrared camera is directed towards the sample from below. A temperature gradient is created by flowing cold gas through a vertical tube onto the centre of the sample from above. The flow rate is electronically controlled. A type N thermocouple is placed in the gas stream at the end of the supply tube, about 5 mm above the sample. The set-up and samples are shown in Figure 1.

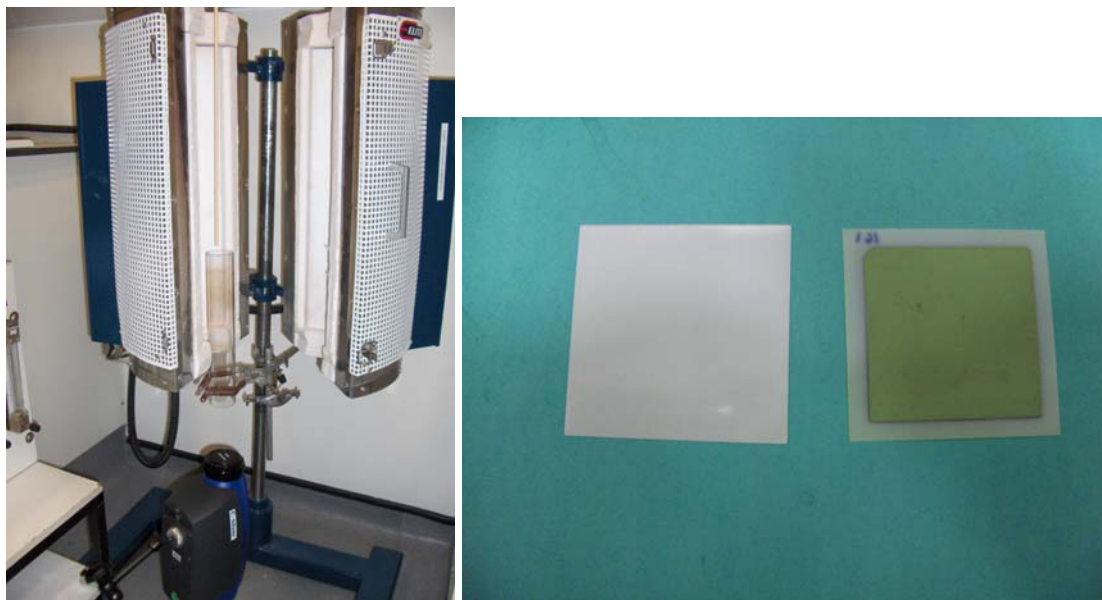


Figure 11 Samples and set-up for thermal stress analysis. Left: vertical split-case furnace with cylindrical glass sample holder, gas supply tube from above and thermal camera from below. Right: samples with and without electrodes.

Curiously, the plain electrolyte is almost transparent to infrared light: In Figure 12 the two electrolyte samples are shown at constant furnace temperature without gas flow. The circular shape of the image is due to the glass sample holder tube, which cuts off radiation from outside. The most obvious feature is the central cold spot. This spot is identified by moving the gas supply tube: It is the image of the tube, which acts as a light pipe between the back of the sample and the cold opposite end of the furnace.

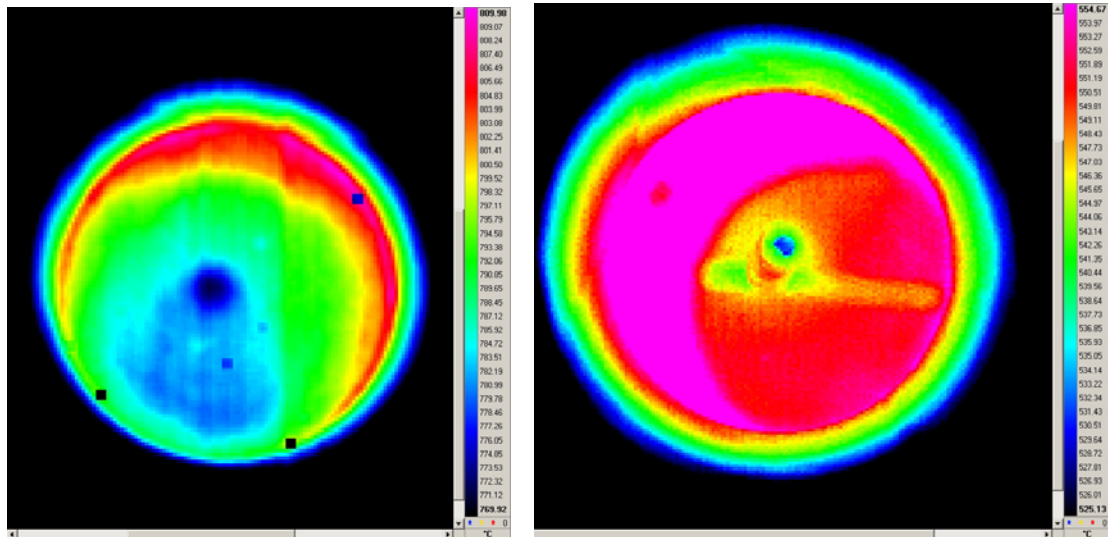


Figure 12 Infrared images of electrolyte material samples in the vertical furnace. Left image: sample S1 (YSZ) at 828 °C. Right image: sample S2 (CGO) at 535 °C.

The temperature readings from the camera also differ significantly from the thermocouple measurements: While the thermocouple reads 828 °C in the left panel of Figure 12, the camera determines only 790 °C for most of the YSZ sample. This means that there is less radiation reaching the detector from the direction of the sample than corresponds to a black body at 828 °C. Consequently, the sample cannot be optically thick. Combined with the presence of the gas tube image, partial infrared transparency of YSZ must be concluded.

In contrast, the image of the CGO sample at 535 °C (right panel of Figure 12) appears hotter than the thermocouple reading. The uniform part of the excess radiation can be explained by diffusely reflected radiation originating in other parts of the furnace. The hot crescent-shaped area on the left side of the image is a result of a slight camera misalignment. As a result, radiation from the hot furnace walls reaches the detector. Being far out of focus, their effect is spread out across a wider area of the image.

The main purpose of the thermal stress analysis is the investigation of the response of SOFC materials samples to temperature gradients. While firm quantitative statements are not easy to obtain due to transmission, reflection, and unknown emission of infrared light, the qualitative behaviour can still be obtained. To achieve this, the infrared image without gas cooling is subtracted from the image of the cooled sample.

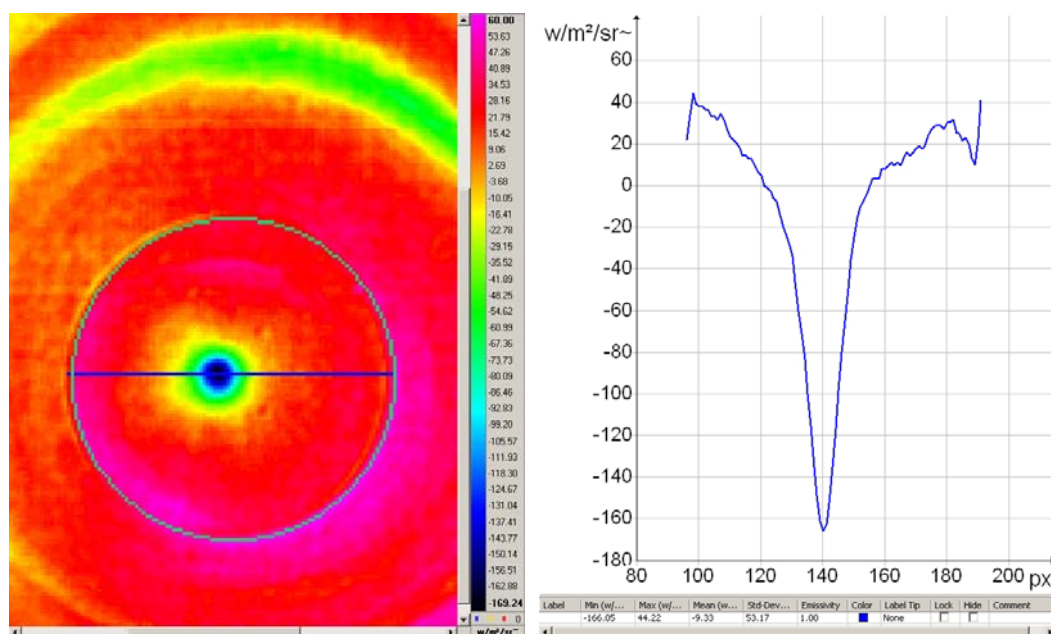


Figure 13 Thermal stress analysis of materials sample S1 (YSZ) at 831 °C and gas flow of 1.0 l/min nitrogen. Left: difference in radiance between gas cooled and uncooled sample, as detected by the camera. The green circle indicates the sample area. Right: differential radiance along the blue line in the left panel.

A measurement of sample S1 (YSZ) at 831 °C is shown in Figure 13. Without gas flow, the radiance detected from the sample area is around 4030 W/m²/sr. A snapshot of this radiance distribution is taken and subtracted from the image with 1.0 l/min nitrogen gas flow. Due to the cooling by the gas flow, the furnace controller increases the heating power in order to keep the temperature constant. As a consequence, the background radiation increases by about 30 W/m²/sr. The localised cooling at the end of the gas tube reduces the emitted radiation by 190 W/m²/sr. Neither the YSZ nor CGO samples suffer damage due to the temperature gradients created with electronically controlled gas flow. A maximum of 1.0 l/min was used with YSZ at 830 °C, and 32.0 l/min with CGO at 540 °C. However, the samples do break upon manually controlled application of higher gas flows with significant gas pressure onto the sample.

More detailed investigations are performed with sample S3, a complete, electrolyte-supported SOFC. The electrolyte material is YSZ and therefore the experiments are done at 850 °C, near its design operating temperature. Initially, a thermal image is taken at a stable temperature. The electrode area is clearly visible in Figure 14. The temperature of this measurement is 829 °C. For an emissivity of one, the radiance in the centre of the sample as detected by the infrared camera corresponds to a temperature of 805 °C. Adjusting the emissivity value for this calculation to 0.953 results in agreement with the thermocouple reading. This value is used for subsequent measurements. With this procedure, the same emissivity value is found for both anode and cathode materials.

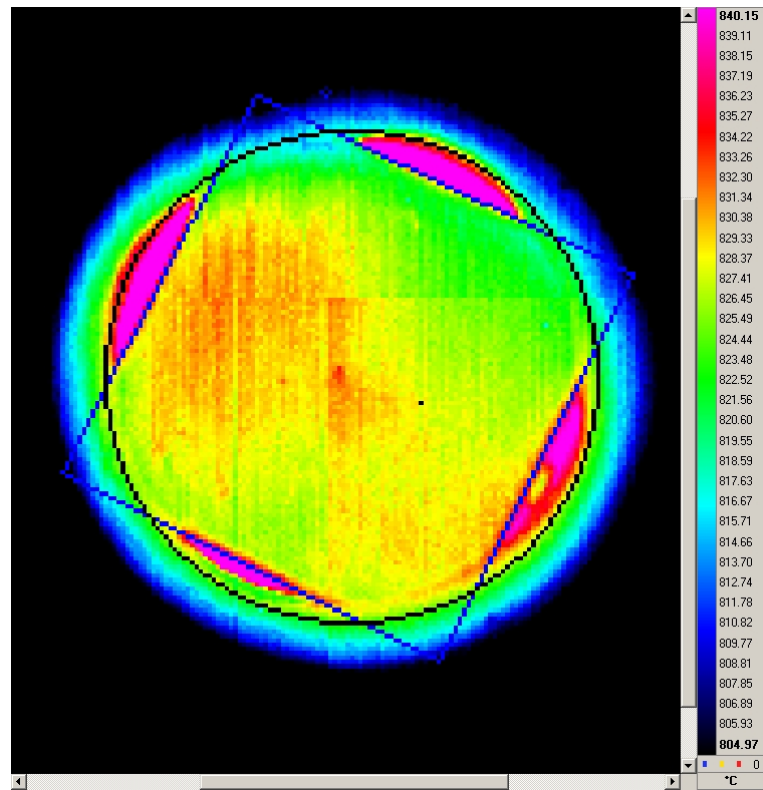


Figure 14 Infrared image of electrolyte-supported SOFC, sample S3, during thermal stress experiment. The blue square indicates the electrode area (40 mm × 40 mm), the black circle shows the glass tube.

Temperature gradients are again produced by blowing nitrogen gas onto the centre of the sample. On its way through the tube, the gas passes through the hot zone of the furnace and heats up. This heating depends on the dwell time and therefore the flow rate. The gas temperature therefore has been measured with a type N thermocouple inside the gas stream at the end of the tube, see Figure 15. At flow rates less than 4 l/min the gas stays in the hot zone long enough to heat above the furnace temperature at the end of the tube, which is at the low end of the hot zone. Up to 12 l/min a well-defined temperature reduction occurs up to 100 °C less than the sample temperature. At flow rates higher than 12 l/min the thermocouple starts to vibrate in and out of the gas stream and its temperature reading fluctuates by 5 °C. The temperature drop can reach almost 200 °C.

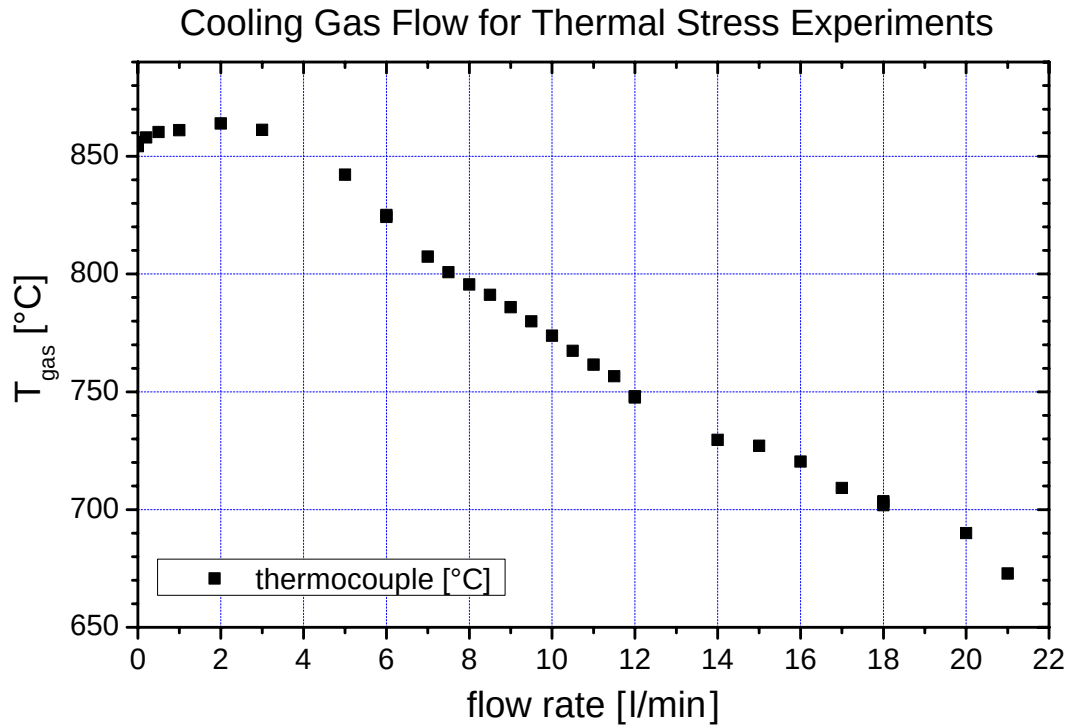


Figure 15 Flow rate dependence of the temperature of the cooling gas in thermal stress experiments. For explanations see text.

Applying this cold gas stream to the SOFC sample creates a temperature distribution as shown in Figure 16. The general behaviour is the same for anode and cathode, although the magnitude of the temperature non-uniformity seems to be higher when the gas is blown at the anode. The cold spot in the centre is directly in line with the gas tube. The profile around it is not symmetric and therefore indicates non-uniformity of the thermal conductivity of the sample. Asymmetries in the gas flow may also play a role as the gas tube is slightly off-centre. The outer ring of lower radiance indicates the sample holder tube. Four segments with high radiance can be identified outside the electrode area but inside the sample holder tube.

From this type of graph, temperature profiles along a section through the cold spot have been extracted. The results for nitrogen onto the cathode are shown in Figure 17. As expected from Figure 15, for low flow rates (2.0 l/min) the sample is locally heated. Flow rates up to 16.0 l/min cause increasingly stronger local cooling by up to 100 °C. Higher flow rates do not increase the cooling significantly. By numerical differentiation, temperature gradients can be determined. Maximum values of about 8 °C/mm are found in Figure 18 (higher values are mainly due to noise). Most of the temperature change occurs within 10 mm of the centre, or half the distance between centre and edge of the electrode.

Despite these large gradients, which have been applied repeatedly and rapidly, neither delamination nor cracking is observed. This result may facilitate improvement of SOFC models and relaxation of constraints on start-up and operating conditions.

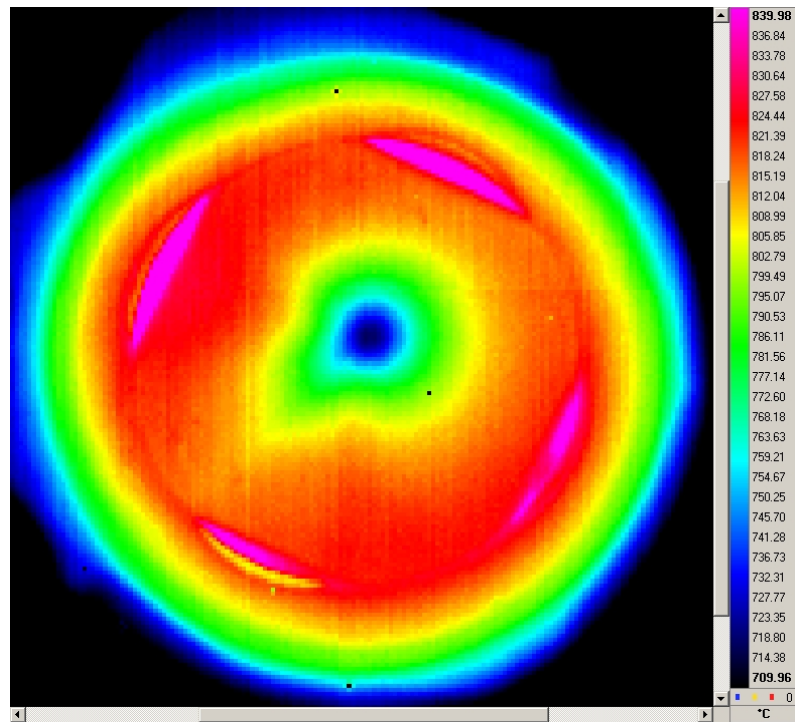


Figure 16 Temperature distribution in SOFC sample S3 under thermal stress. A view of the cathode is shown while nitrogen is blown onto the anode (6 l/min). The furnace temperature is 829 °C.

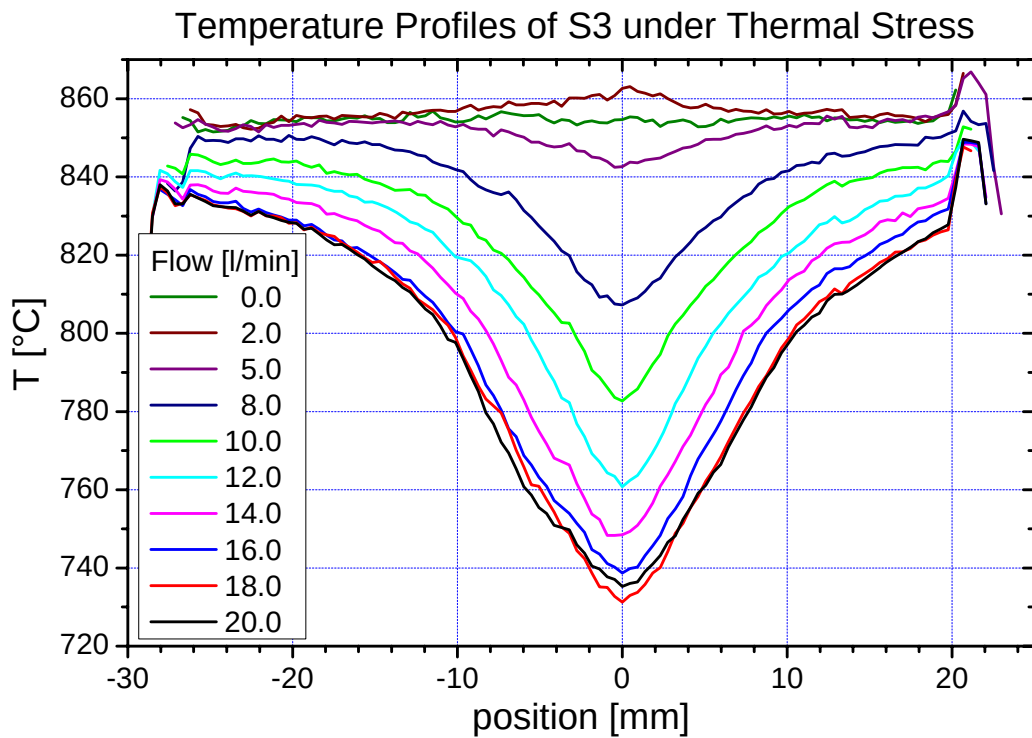


Figure 17 Temperature profiles of SOFC sample S3 under thermal stress. Nitrogen gas is blown onto the cathode at various rates.

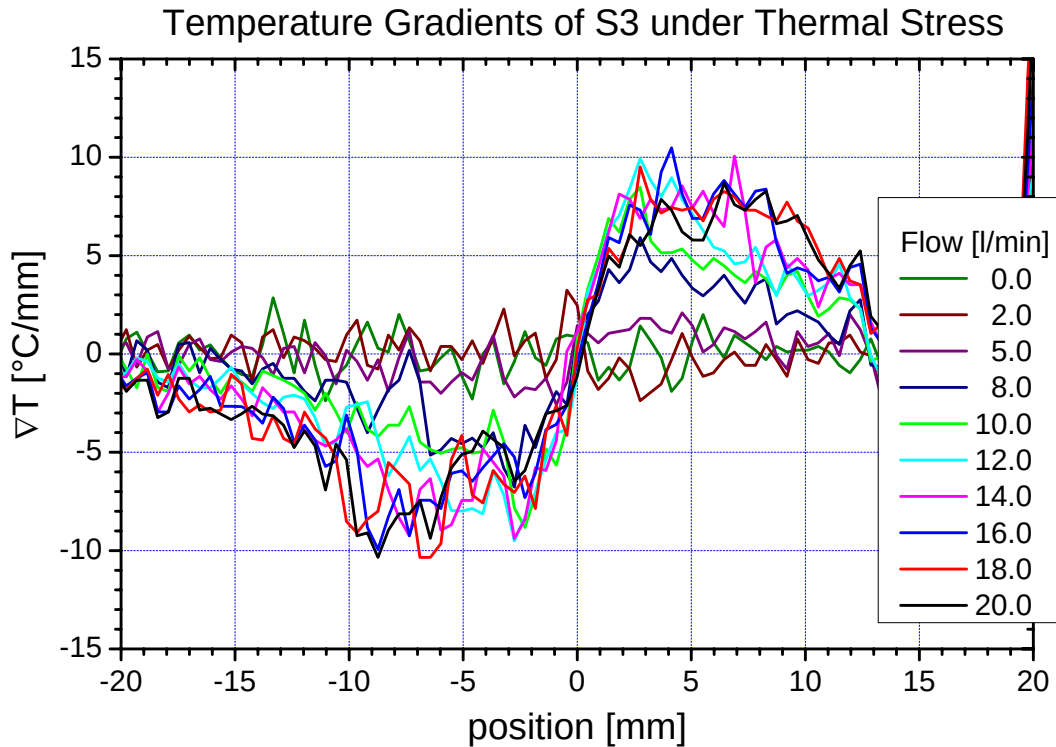


Figure 18 Temperature gradients of SOFC sample S3 under thermal stress, determined numerically from the data in Figure 17.

5.2. Combinatorial materials testing

The large number and variety of SOFC materials and their processing lead to very time-consuming and repetitive research activities. In principle, thermal imaging can help here, too. One essential piece of information for a new material is its oxidation temperature. The infrared camera can detect the thermal signature of the oxidation process. Samples of many different compositions can be in the field of view of the camera at the same time and allow fast combinatorial measurements.

Within this study, eleven dots of $\text{LaSrMn}_{1-x}\text{Co}_x$ have been deposited on an alumina plate. The dots are about 1 mm in diameter and differ in composition by the Co doping concentration, x . The samples are heated steadily from room temperature to 800 °C and continuously monitored by the thermal camera.

Some of these data are shown in Figure 19. There is a slight offset between the curves for the different samples. The reason is their different emissivity, which has not been corrected for. At 310 °C the warm-up curves display a kink, indicated by an arrow in Figure 19. This kink appears at exactly the same radiance level for each sample, but at different times or furnace temperatures. It must therefore be concluded that this is a measurement artefact, most likely due to the camera calibration function. A graph of the raw analog-digital converter signal versus time (not shown) displays smooth curves in this range. No other anomalies can be found in this measurement. The heat created by the oxidation is too small to be detected before being dissipated into the base plate. The use of larger samples would improve the sensitivity of this technique.

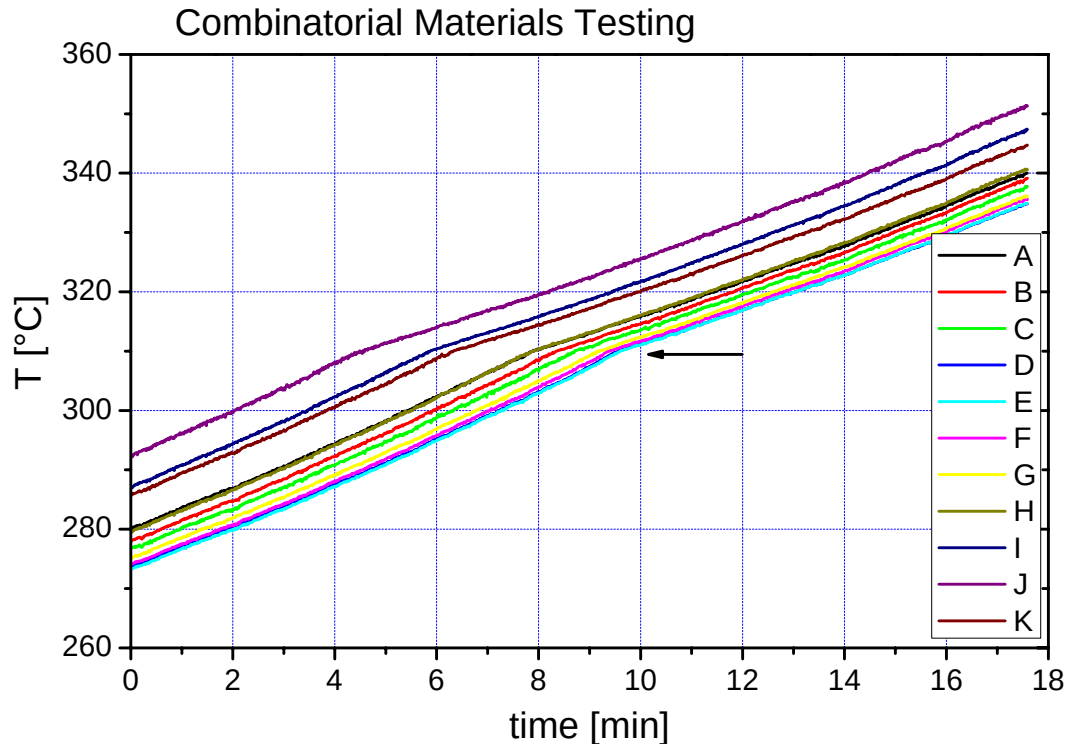


Figure 19 Heating of eleven materials samples in combinatorial experiment, monitored by the infrared camera. No emissivity correction is applied. The arrow indicates a kink in the warm-up as explained in the main text.

6. Conclusions

Thermal imaging has been successfully applied to the study of temperature distributions in operational solid oxide fuel cells. The technique has also been used to determine the tolerance of SOFC materials to thermal stress.

The results of the pellet SOFC measurements are a valuable input to modelling work, including that of fuel cell stacks. The information on the local temperature increase due to the electric current has wide ranging consequences, as the temperature increase feeds back into the ionic and electronic conductivity of the electrolyte. Therefore, the polarisation curves can behave qualitatively different from the conventional, isothermal models [1].

The detection of the non-uniformity of the temperature increase under operation (Figure 6) may be useful for investigation of problems in the materials preparation process, particularly for larger, industrial SOFC. These experiments should be repeated with larger samples.

The investigation of the redox dynamics is interesting because these reactions affect the delamination of the electrodes. Thermal imaging is well suited to measuring these effects in situ in an assembled cell, after sintering of the electrodes.

Thermal stress investigations are an active research field including a lot of modelling work. The data presented in Section 5.1 provide a valuable input for modelling of the long-term behaviour and failure mechanisms of SOFCs. Such thermal stress modelling work is already under way at Imperial College [1].

In the field of combinatorial research, the technique of imaging promises to help faster sample processing. However, larger samples are required in order to obtain a detectable effect.

In summary, thermal imaging proves to be a very useful technique in solid oxide fuel cell research. We expect the application areas listed above to be just the first of many.

7. Acknowledgements

This work has benefited substantially from the contributions of Prof. Nigel Brandon, Dr. Michael de Podesta and Dr. Gareth Hinds who helped plan the experiments and suggested possible applications. Rob Simpson helped setting up the experiment. Jeremy Rossiny suggested the combinatorial measurements and supplied the sample. All of the above as well as Dr. Patricia Aguiar and Ralph Clague provided fruitful discussions and interpretation of the results.

The project is funded by the Department of Trade and Industry under the Measurement for Emerging Technologies programme.

SS would also like to thank Imperial College London for its hospitality.

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