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The effect of applied control strategy on the current-voltage correlation of a solid oxide fuel cell stack during dynamic operation

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Abstract This paper discusses the transient characteristics of the planar type SOFC cell stack, of which the standard output is 300 W. The transient response of the voltage to the manipulation of an electric current was investigated. The effects of the response and of the operating condition determined by the operating temperature of the stack were studied by mapping a current-voltage (I-V) correlation. The current-based fuel control (CBFC) was adopted for keeping the fuel utilization factor at constant while the value of the electric current was ramped at the constant rate. The present experimental study shows that the transient characteristics of the cell voltage are determined by primarily the operating temperature caused by the manipulation of the current. Particularly, the slope of the I-V curve and the overshoot found on the voltage was remarkably influenced by the operating temperature. The different values of the fuel utilization factor influence the height of the settled voltages. The CBFC has significance in determining the slope of the I-V characteristic, but the different values of

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the fuel utilization factor does not affect the slope as the operating temperature does. The CBFC essentially does not alter the amplitude of the overshoot on the voltage response, since this is dominated by the operating temperature and its change is caused by manipulating the current.

Keywords: Solid oxide fuel cells; Stack operation; Dynamic operation; Current-based fuel control; Fuel utilization factor

1 Introduction

Solid oxide fuel cells (SOFCs), is a promising technology for the efficient use of fuel by converting its chemical potential directly into electricity with the highest conversion rate among the available line-ups of fuel cells. Their high operating temperature (600–1000 °C), allows oxygen ion to be transported through the nonstoichiometric crystal network of solid oxide electrolytes to the anode side. This characteristic is very important because since it is oxygen that comes to the anode side, a wide range of fuels can be utilized. A high operating temperature also enables further cascade use of thermal energy for its mechanical or thermal recuperation; the hybrid integration of the SOFCs with thermal cycles and/or the use of the SOFCs for the combined heat and power (CHP) generation regarding the electrochemical mechanism that the SOFCs possess [1–5].

Among the divergent utilizations of the SOFCs, in particular as power sources, load operation leads to more significant problems. There are usually two distinctions: a large scale base-load application in grid or an application in a rather small-scale distributed network which requires the flexible operation of a power source to demands instantly fluctuating. The latter application, the use of a SOFC in a distributed network, may require load-following performance. With the characteristics of high operating temperature, in building operating scheme for direct-current systems, the current-voltage (I-V) characteristic plays a significant role over the wide range of load conditions. Thus, settling operating conditions, choosing a control strategy and designing the entire system configuration is the advanced stage of the development for the commercialization of SOFC. The most often considered operation strategies are, of course the management of operating temperature and the appropriate fuel supply [6–8]. These two parameters must be the most considered ones for improving performance and demonstrating safe operation. This paper is presented to understand the transient characteristics of the I-V correlation, which is a result from the transition of the operating conditions due to control strategies. Carefully interpreting the I–V characteristics over operating conditions will be useful and practical to design the control process of the SOFC.

2 Experimental procedure of the SOFC cell stack

The SOFC test module demonstrated in the present study was designed and produced by SOFCPOWER. The SOFC cell stack test module, the so-called modular stack test bench (MSTB), is installed with a cell stack designed to perform a power output of 300 W. The SOFC has an anode supported structure, adopting nickel (Ni) and 8 mol% yttria-stabilized zirconia (8YSZ). 8YSZ is adopted for the thin-film electrolyte which is sandwiched by the two electrodes, a porous perovskite cathode and a dense anode. Gadolinium doped ceria (GDC) is adopted for the barrier layer cathode configuration with the lanthanum strontium cobalt ferrite (LSCF) cathode. The GDC layer separates the thin-film electrolyte and the LSCF cathode layer for mechanical issues occurring in the case of a low operating temperature [9]. A planar geometry is adopted for the SOFC cell (see Figs. 1A and 1B). The dimensions of the cell are 152 mm×70 mm. The active cell area available for the reaction is 50 cm^2.

The MSTB includes a cell stack divided into 3 clusters for the present set-up. Each cluster comprises of 6 single planar cells, and all the cells are connected in a series circuit. An image of the cell stack is shown in Fig. 1C. The cell stack is located at the top of the test bench and then covered with the electric furnace. The bench has control tools for the heaters, the mass flow controllers and the electronic load. The system configuration of the MSTB is also shown in Fig. 1D. The following is a detailed explanation of the MSTB: First, compressed air in the gas cylinder is regulated to 500 kPa and fed to the cathode channel after preheating. Part of the oxygen in the fed air is consumed in the electrochemical reaction. At the same time, the air is used to remove heat from the cell stack. Then, the air is fed to the afterburner to combust the unused fuel from the anode channel. On the other side, the compressed fuel, i.e., the hydrogen (H_2) and nitrogen (N_2) mixture, is regulated to 300 kPa and fed to the anode channel after preheating. The residual fuel, unused in the electrochemical reaction, is oxidized in the afterburner. After the combustion process, the gas is cooled down, the condensed water is separated and the dry gas is finally released to the ambient air. The temperature of an electric furnace for the cell stack is set constant, usually at 750 °C, to heat up the SOFC cell stack during measurements. Note that the operating temperature of the SOFC cell stack is indirectly controlled by setting the temperature of the electric furnace. However, there are always gaps found in the local temperature distribution adjacent of the cell stack. Thus, temperatures at the stack top and bottom are measured to know the local temperature difference in the installed cell stack.

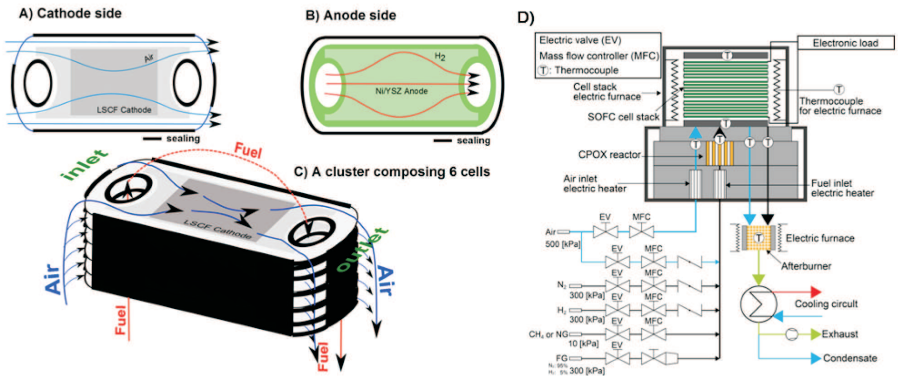

Figure 1: Schema of the planar cell from: cathode side A) anode side and B), C) composing a cluster from 6 cells, D) the configuration of the experimental set-up.

3 Results and discussion

3.1 Preliminary

Most of the cases presented in this paper were demonstrated under nominal conditions. The nominal conditions are determined and indicated in Tab. 1.

In addition, the following considerations were taken during the experiments:

- The air flow rate cannot be changed since reducing the air flow rate magnifies the temperature gradient in the cell stack. Additionally, it results in a violation of off-gas regulations.
- Minimum cell voltage must not go below 0.7 V, in the present study, under polarized conditions, in order to keep a safe operating condition for the stack capability by avoiding a high local heat production rate [6,7,10].

Table 1: Nominal experimental conditions.

Variable	Value
Hydrogen flow rate	5.4 l/min
Nitrogen flow rate	3.6 l/min
Air flow rate	45.0 l/min
Set-point temperature for the cell stack electric furnace	750 °C
Set-point for the air inlet electric heater	630 °C
Set-point for the fuel inlet electric heater	550 °C

- The manipulation of the electric current cannot be faster than the rate of 1 A/min aiming of the safe operation with the cell stack. This may, also, ensure the reproducibility of measurements.

The operation with the open fuel utilization factor (open U_f), in which the flow rates are fixed to be constant during the current manipulation, was examined as the reference. In the experimentation with the open fuel utilization factor, the response of the voltage output is correlated to the current setting from 20 A and 18 A, 15 A or 5 A, and from 18 A, 15 A or 5 A to 20 A. The effect of the transient thermal conditions is shown in the reference case by manipulating the stack furnace temperature together with the electric current. The stack temperature was manipulated to simulate the large temperature drop possibly caused by the current change. The set-point of the stack furnace was in the range from 750 to 740 °C and from 750 to 730 °C with the constant rate of 100 °C/h.

The current-based fuel control (CBFC) was applied in the present study for discussing the transient characteristics of the SOFC. In this solution the fuel flow rate was manipulated to control the fuel utilization factor in accordance with the current operations. Figure 2 shows the example of the CBFC implementation during the load operation determined by the current. The fuel utilization was kept at 50, 60, and 70% to the ramping current in the range between 15 and 20 A at the rate of 1 A/min. The fuel utilization factor in Fig. 2 was evaluated from the measured H_2 flow rate and actual current applied in the measurement. The set-point of the cell stack furnace was aimed to keep the nominal condition, 750 °C. Additionally, the different operating condition was examined by applying the stack furnace temperature at 730 °C during the current setting.

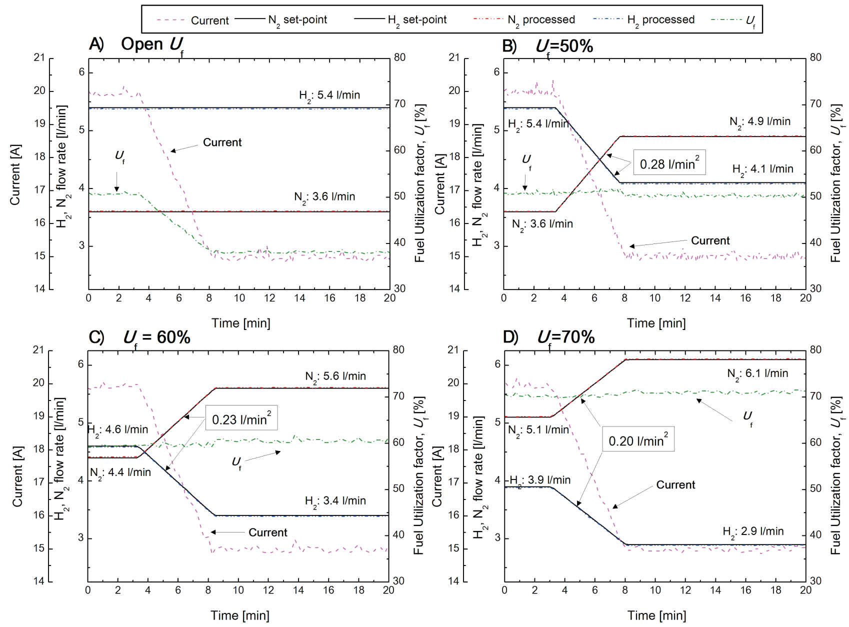

Figure 2: Manipulation of fuel flow rate in order to keep the fuel utilization factor: A) fixed (the so-called open fuel utilization factor), B) 50%, C) at 60% and D) at 70% during the current changed from 20 to 15 A at a rate of 1 A/min.

3.2 The effect of an open fuel utilization factor on voltage characteristics

The transient characteristics of the SOFC with an open fuel utilization factor are first discussed. Figure 3 shows the transient response of voltages and the stack temperature. The stack temperature is expressed as the mean of temperatures measured at the stack top and at the bottom. More detailed discussion on the temperature behaviour of the stack can be found in the previous work [11,12]. The response of the voltage is the almost linear to the setting of the current. The temperature response is gradual to the current change, thus the gradual temperature response influences the voltage response after manipulating the current and then leaves the overshoot on the voltage response. However, note that the case, when the current manipulated between 20 and 5 A, indicates that the voltage response during the ramping current has been influenced by the response of the stack temperature.

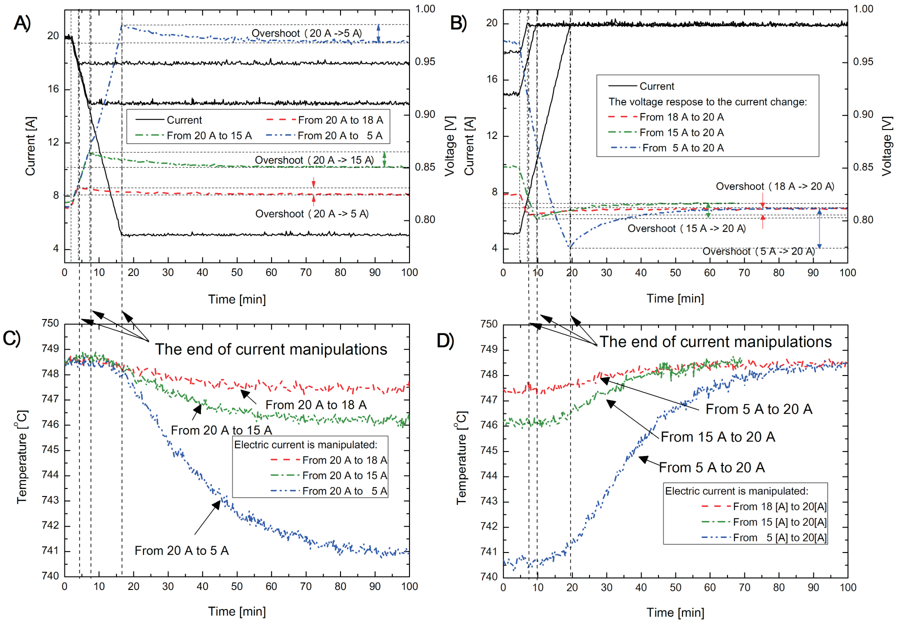

Figure 3: Transient response of the cell voltage and averaged stack temperature A), C) to the increasing current, and B), D) to the decreasing current at the open fuel utilization factor condition.

The behaviour of the voltage along the current operation is also expressed as current-voltage (I-V) characteristic curves and presented in Fig. 4. Drawing the I-V curve is usually adopted for the evaluation of steady-state performance of a cell. In this paper, it is used to describe the process of voltage observed during the dynamic operation. In the cases of decreasing the current from 20 to 18, 15 and then 5 A, paths of voltage along the current are presented as the linear curves, of which the slope is determined only by the operating temperature at the initial state of 20 A (since the fuel flow rates are the same and kept constant during the operation). The change of the stack temperature is a result of heat generation by electrochemical reaction when the current increases. Note that the case of ramping down the current from 20 to 5 A rather does not look close 'linear curve'; the gradual response of the operating temperature influences and bends 'the linearity' of what can be resulted from a simple correlation between the current and voltage observed over the given constant temperature. After the current ramping stops, the voltage is settled only by the temperature drop in the cell stack,

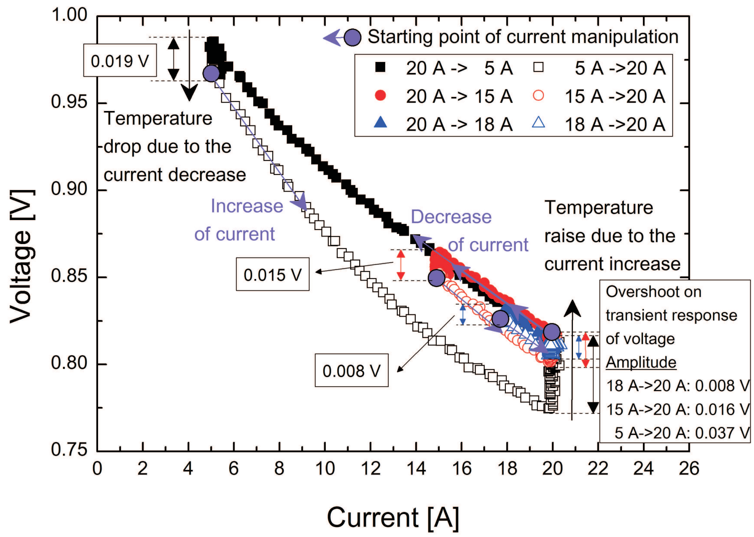

Figure 4: Transient current-voltage (I-V) characteristic with a variety of current changes at the open fuel utilization factor condition.

which is caused by the current operation. This behaviour was stated to be 'overshoot' on the transient response of the voltage, as described in the previous paragraph. The length of the vertical change in the voltage, here namely the amplitude of the overshoot, is determined by the extension of the drop in the operating temperature. When the voltage is settled at states with lower current (for instance at 15 A and at 5 A compared to the one at 18 A), the temperature drops become larger and the vertical change in the voltage is elongated. This also results in a similar correlation between the amplitude of the voltage overshoot and the range of the current manipulation.

Ramping up the current to 20 A is conducted from the state with lower operating temperature. The I-V characteristics are not identical between the processes of decreasing and increasing the current (see Fig. 4). The operating temperature determines the slope of the curves, which becomes steeper in the case of increasing the current due to the internal resistance increased by the low setting of the operating temperature settled at the current of 18, 15 or 5 A. After ramping up the current, the voltages are settled by the temperature raise. The vertical change of voltage, 'the overshoot', goes back to the initial point where the decreasing current was started from

20 A. The vertical change of voltage becomes larger than that observed at the cases of decreasing the current. The operating temperature affects the internal resistance, which limits the rate of voltage change along the temperature. The drop of the temperature decreases the rate, meanwhile the raise of the temperature increases the rate. This differs the amplitude of overshoot observed in increasing the current and in decreasing the current. The tendency becomes more visible when the range of manipulating the current is wider.

The process of manipulating the current between two points (in particular, between 20 and 18 A, between 20 and 15 A as well as between 20 and 5 A in the presented cases) creates closed cycles surrounded by bounds: vertical change of the voltage and the voltage change by manipulating the current. The characterizations of both types of bounds are strongly influenced by the operating temperature. The operating temperature is the influential factor determining the process that can be observed by the shape of the cycle on the I-V map.

The influence of the operating temperature significantly appears on this cycle and determines its shape. This is seen in Fig. 5 in which the cycle was described by manipulating the set-point of the electric furnace up and down, in the range between 750 and 740 °C and between 750 and 730 °C at the rate of 100 °C/h, together with ramping the current up and down between 20 and 15 A at the rate 1 A/min. The measured stack average temperature, the amplitude of the overshoot and the incline of the I-V, in mV/A, is indicated in Fig. 5. The stack average temperature described in Fig. 5 is the value from the steady-state condition at the current of 15 A and of 20 A. In decreasing the current from 20 to 15 A for both with and without the ramping furnace set-point temperature, the incline of the I-V is the same for all the cases. The process of decreasing the current from 20 to 15 A is almost the same for all the presented cases, since the effect of dropping the stack furnace temperature insufficiently affects the voltage output in the duration of ramping the current; it rather comes after ramping the current down to 15 A. In this process, the influence of manipulating the furnace temperature remarkably appears on the overshoot of the voltage (the vertical change in voltage), which was resulted from the stabilization of the temperature. The other process of increasing the current up to 20 A together with the increase of the furnace temperature starts from the state (at which the operating temperature settled at the current of 15 A), and results in steeper I-V characteristics. This becomes more recognizable when the stack average temperature is lower (see the inclines denoted in Fig. 5). In the process of increasing the current, the raise of the stack average temperature is enhanced by changing the set-point of the furnace temperature from 730 to 750 °C or from 740 to 750 °C. Thus, the overshoot becomes larger to the larger raise of the stack average temperature. The overshoot observed after increasing the current with the raise of the stack furnace temperature is enhanced compared to the one observed after decreasing the current with the dropping of the stack furnace temperature. The large drop of operating temperature enlarges the area of the cycle of voltage change drawn by the current operation and by the temperature stabilization.

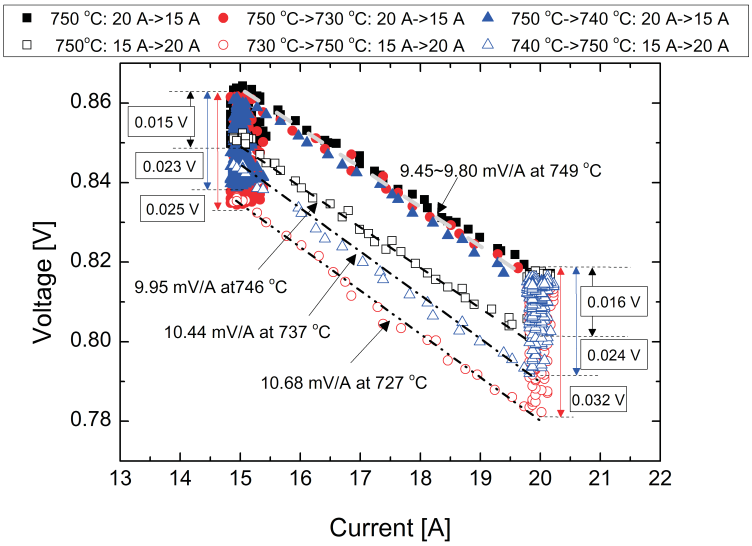

Figure 5: Current-voltage characteristic at the conditions when the stack furnace temperature manipulated between 750 and 740 °C and between 750 and 730 °C at a rate of 100 °C/h together with the electric current ramping at the rate of 1 A/min.

3.3 The effect of current-based fuel control on voltage characteristic

Figure 6 shows the transient response of the cell voltage and averaged stack temperature to the increasing current and to the decreasing current when the CBFC is employed to level the fuel utilization factor at 50, 60 and 70%. For the present setup, the fuel utilization factor does not influence the response of the temperature as it was shown in Figs. 6C and 6D. The slope of the voltage changes over instance are the equivalent for all the cases when the CBFC was adopted for the current manipulation.

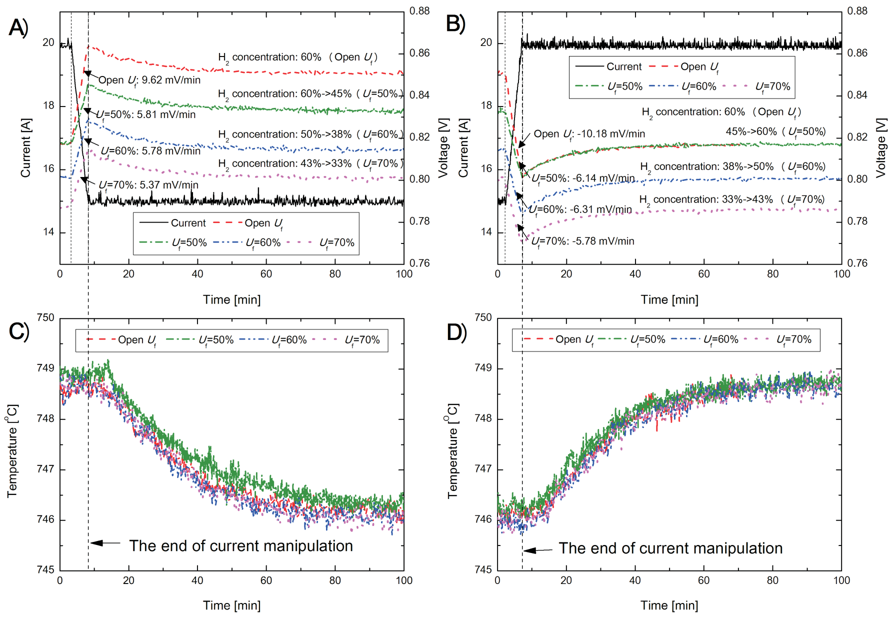

Figure 6: Transient response of the cell voltage and averaged stack temperature: A), C) to the increasing current and B), D) to the decreasing current when the CBFC is employed to level the fuel utilization factor at 50, 60 and 70%.

Figure 7 shows the transient response of the voltage drawn on the I-V map. The case with the 'open U_f' is shown as a reference. The amplitude of the overshoot to the current change and the slope of the I-V curves are also denoted in Fig. 7. The slope of curves becomes smaller than the 'open U_f' case, though the temperature behaviour is the equivalent. This is thus stated as the effect of the CBFC on the I-V characteristics. The overshoots of the voltage are the same for all the presented cases when both 'open U_f' and the CBFC control is applied. The amplitude of the overshoot seems to be determined by the voltage change caused by the stabilization of the operating temperature after the change in the electric current. A similar observation is also found in the case of ramping up the current from 15 to 20 A. The different set-points of the fuel utilization factor show the different height of voltage. It does alter neither the incline of the I-V correlation nor the amplitude of the overshoot.

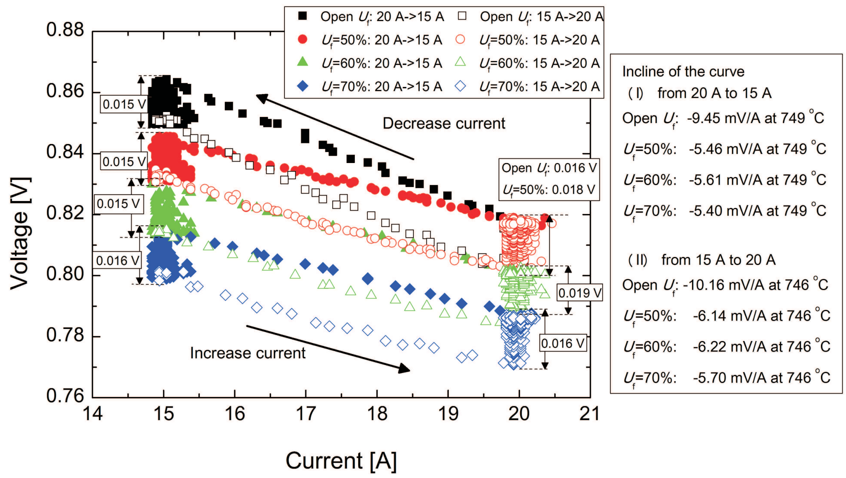

Figure 7: The current-voltage characteristic curves when the current changes from 20 to 15 A and from 15 to 20 A while the fuel utilization factor is kept at 50, 60 and 70%.

The influence of the operating temperature to the I-V correlation was examined while the CBFC is applied for the fuel flow control corresponding to the manipulation of the current. Figure 8 shows the process of the transient voltage response to the current change on the I-V map in different operating temperatures when the CBFC is applied. The process of ramping the current from 20 to 15 A and from 15 to 20 A, is conducted at furnace temperatures set at 750 and 730 °C, while the flow rate is operated to keep the fuel utilization factor at 50, 60 and 70%. There is also a case, in which the cycle is drawn by the current operation between 20 and 18 A at the stack furnace temperature of 730 °C, illustrated in Fig. 8. The slope of the I-V curve and the amplitude of the overshoot observed after changing the current noticeably influenced by the operating temperature determined with the manipulation of electric current in this study. This can be seen in the shape of the cycle in different operating temperatures.

Considering the parametric studies conducted in the present paper, the CBFC does have certain significance to determine the slope of the I–V curve; though the value of the fuel utilization factor, by regulating the supplied flow rate of fuel to the corresponding electric current, does not influence the slope in this range of the current. The CBFC itself may not be counted as the factor determining the amplitude of the overshoot on the voltage response. However, note that the value of the fuel utilization factor

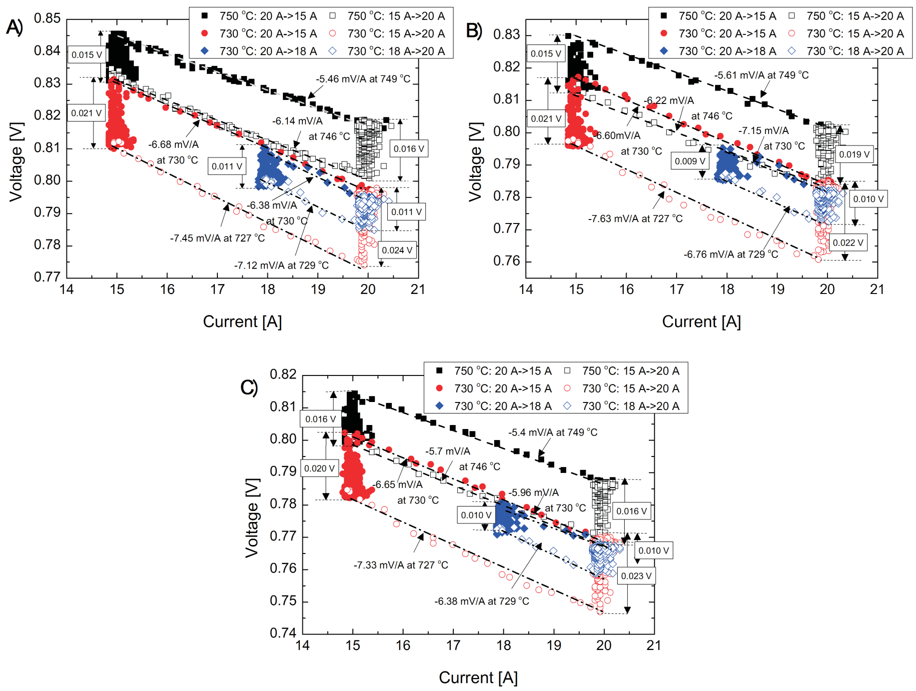

Figure 8: The effect of the CBFC on I-V characteristic with the various operating temperatures at 750 and 730 °C for keeping the fuel utilization factor at: A) 50%, B) 60% and C) 70%.

is dependent on the settled voltage level itself. The operating temperature and its change caused by the current manipulation seem to be the influential factor in determining both the slope of the I-V curve and the amplitude of the overshoot on the voltage response.

4 Conclusions

This paper presents an experimental study on the transient characteristics of the planar type SOFC cell stack with the standard power output of 300 W. The transient response of the voltage, averaged per a cell, under the CBFC and under the 'open U_f' conditions was shown over the instance. The present study particularly focuses on the I-V correlation during the dynamic operations of the SOFC. Additionally, the effects of the operating temperature and the adopted control strategy were studied. The transient response of the voltage to the ramping current was described on the I-V map, which is often used for evaluation of the steady-state performance of a cell. Drawing the transient response on the I-V characteristic curve clearly reveals the mechanism of changing the current and its effect on the voltage response. This approach also contributes to clarifying the effect of the operating condition on the I-V characteristic during the dynamic operations, specifically for the processed parameters of the operating temperature and the fuel utilization factor in this study. The operating temperature is the major significance in choosing the operating condition, especially for increasing the current. The overshoot of the voltage and the steepness of the I-V curve were the results of the change in the operating temperature, which is a consequence of heat generated by the electric current. The CBFC does have a certain significance to determine the slope of the I-V curve, though the different set-points of the fuel utilization factor do not influence the slope. The CBFC does not affect the amplitude of the overshoot on the voltage response. The dynamic operation with the CBFC in the different operating temperatures confirms the latter statement; the height and its change of the operating temperature caused by the extensiveness of the current manipulation seem to be dominant in determining the incline of the I-V curve and the amplitude of the overshoot on the voltage response.

The I-V mapping is beneficial and practical to evaluate both the steady-state performance and the transient characterization of the SOFC. This approach enables analysing the effect of operating conditions as conducted in the presented work. The authors believe that I-V mapping will also enable the evaluation of the control strategy and optimize the process of control.

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References

[1] Harvey S.P., Richter H.J.: *Gas turbine cycles with solid oxide fuel cells part I: Improved gas turbine power plant efficiency by use of recycled exhaust gases and fuel cell technology.* T. ASME J. Energy Resour. Technol. **116**(1994), 305–311.

[2] Harvey S.P., Richter H.J.: *Gas turbine cycles with solid oxide fuel cells part II: A detailed study of a gas turbine cycle with an integrated internal reforming solid oxide fuel cell.* ASME J. Energy Resour. Technol. **116**(1994), 312–318.

[3] Bakalis D.P., Stamatis A.G.: *Incorporating available micro gas turbines and fuel cell: Matching considerations and performance evaluation.* Appl. Energy **103**(2013), 607–617.

[4] Bianchi M., De Pascale a., Melino F.: *Performance analysis of an integrated CHP system with thermal and Electric Energy Storage for residential application.* Appl. Energy **112**(2013), 928–938.

[5] Kupecki J., Badyda K.: *SOFC-based micro-CHP system as an example of efficient power generation unit.* Arch. Thermodyn. **32**(2011), 33–43.

[6] Mueller F., Jabbari F., Gaynor R., Brouwer J.: *Novel solid oxide fuel cell system controller for rapid load following.* J. Power Sources **172**(2007), 308–323.

[7] Stiller C., Thorud B., Bolland O., Kandepu R., Imsland L.: *Control strategy for a solid oxide fuel cell and gas turbine hybrid system.* J. Power Sources **158**(2006), 303–315.

[8] Komatsu Y., Kimijima S., Szmyd J.S.: *Numerical analysis on dynamic behavior of solid oxide fuel cell with power output control scheme.* J. Power Sources **223**(2013), 232–245.

[9] SOFCPOWER S.p.A.: http://www.sofcpower.com. (accessed, November, 2010).

[10] Selimovic A., Kemm M., Torisson T., Assadi M.: *Steady state and transient thermal stress analysis in planar solid oxide fuel cells.* J. Power Sources **145**(2005), 463–469.

[11] Komatsu Y., Brus G., Kimijima S., Szmyd J.S.: *Experimental study on the 300W class planar type solid oxide fuel cell stack: Investigation for appropriate fuel provision control and the transient capability of the cell performance.* J. Phys. Conf. Ser. **395**(2012), 012162.

[12] Komatsu Y., Brus G., Kimijima S., Szmyd J.S.: *The effect of overpotentials on the transient response of the 300W SOFC cell stack voltage.* Appl. Energy **115**(2014), 352–359.