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

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Abstract. The present paper reports the experimental study on the dynamic behavior of a solid oxide fuel cell (SOFC). The cell stack consists of planar type cells with standard power output 300W. A Major subject of the present study is characterization of the transient response to the electric current change, assuming load-following operation. The present studies particularly focus on fuel provision control to the load change. Optimized fuel provision improves power generation efficiency. However, the capability of SOFC must be restricted by a few operative parameters. Fuel utilization factor, which is defined as the ratio of the consumed fuel to the supplied fuel is adopted for a reference in the control scheme. The fuel flow rate was regulated to keep the fuel utilization at 50%, 60% and 70% during the current ramping. Lower voltage was observed with the higher fuel utilization, but achieved efficiency was higher. The appropriate mass flow control is required not to violate the voltage transient behavior. Appropriate fuel flow manipulation can contribute to moderate the overshoot on the voltage that may appear to the current change. The overshoot on the voltage response resulted from the gradual temperature behavior in the SOFC stack module.

1. Introduction
Solid oxide fuel cells (SOFCs) are anticipated electrochemical devises for distributed power generation. Its operating temperature (700 - 1000 [°C]) makes it possible to use carbon monoxide (CO) and hydrocarbon based-fuels. The high operating temperature integrates a SOFC into a hybrid system with a gas turbine. On the other hand, the high operating temperature is one of physical restrictions for SOFCs, since the thermal stress may crack the thin made cells, which are composite multilayer with anode and cathode electrodes and sandwiched thin-layer electrolyte that enables high conductivity of oxygen ion. Reduction of the thermal stress and the thermal expansion is an important issue [1]. It is needed to improve the durability of the SOFC to be adopted for the system in practical...
operation. The intermediate temperature SOFC (IT-SOFC) and the metal-supported SOFC (MS-SOFC) have been developed to avoid the disadvantage of high operating temperature [2-4]. Those alternatives are required to accomplish the competitive power density comparing to the conventional SOFC in order to break through the matter for commercialization. System design of the SOFC is also an important issue. The power generation process of the SOFC involves electron transport, heat and mass transfer. High operating temperature makes an experimental approach more difficult. In this viewpoint, numerical modeling is a practical tool for the SOFC development. Dynamic modeling is an effective approach to estimate the transient behavior of the SOFC system toward building control method. It is important for this approach to take into account the physical restriction against manipulated variables in a control system.

To be a competitive power system in the practical use, the load-following capability is highly required to diversify its variety of application. Previously, the dynamic behavior of the SOFC was discussed to predict the load-following performance, adopting the dynamic modeling [5-7]. At the same time, the control scheme was considered to optimize efficient operation under the load-following mode. A cell operating temperature, a fuel utilization factor ($U_f$) and a steam-to-carbon (S/C) ratio were referred to the optimization parameters of operation. The controls of the cell operating temperature and the fuel utilization factor improve the power generation efficiency under the part-load condition. Those controls can contribute toward improving the transient capability and avoiding the fuel starvation occurrence. The reasonability of the control was previously studied with the numerical analyses [8, 9].

Conventionally, the fuel utilization factor is employed for evaluating fuel provision capability. In the other prospect, if the $U_f$ reaches 100%, the fuel starvation may occur. It can bring mechanical failure in the thin anode electrode layer [10-12]. Monitoring the fuel utilization factor prevents crucial situations. However, the experimental study on the control of the fuel utilization factor is insufficient to find an adequate operation method. Previously, Takahashi et al, conducted experimental investigation on the fuel utilization control by the single tubular cell test [13]. They observed the response lag on voltage output due to the flow rate manipulation to keep the fuel utilization constant under ramping current. They concluded that the lag and the amplitude of the overshoot observed on the transient behavior of the voltage may depend on the cell geometry and the system configuration.

In this paper, the SOFC transient capability was investigated by using the 300W class planar type SOFC cell stack, particularly the fuel utilization control was discussed as a main topic.

2. Experimental set-up

2.1. SOFC Modular Stack Test Bench (MSTB)
The SOFC test module demonstrated in the present study, it was designed and fabricated by the SOFCPOWER S. p. A.. A scale of the SOFC stack test module, so called Modular Stack Test Bench (MSTB), is anticipated to perform 300W power output. Most of the technical information about the SOFC is under the intellectual property right and therefore confidentially protected. Presented specification of the SOFC cell stack is based on public accessible data [14]. The SOFC has anode supported structure, adopting Nickel (Ni) and 8mol% Yttria-Stabilized Zirconia (8YSZ). 8mol% Yttria-Stabilized Zirconia (8YSZ) is adopted for the thin film electrolyte which is sandwiched by the two electrodes, a porous perovskite cathode and the relatively dense anode. Gadolinium Doped Ceria (GDC) is adopted for the barrier layer cathode configuration with the Lanthanum Strontium Cobalt Ferrite (LSCF) anode. The GDC layer separates the thin film electrolyte and the LSCF cathode layer for the mechanical issue occurring in case of low operating temperature [14]. The properties and specification of the SOFC cell are shown in Table 1, referring to the data published [14].

A planar geometry is adopted for the SOFC cell. The design of a cell, serialized as the S-Design in the SOFCPOWER product variety. Footprint of a cell is 152 × 70 [mm × mm]. The active cell area available for the reaction is 50 [cm²]. The cell performs fuel utilization of up to 75% and can achieve high power density larger than 1 [W cm⁻²].
Table 1. Composition and thickness of a planar type SOFC cell.

| Layer                        | Composition  | Thickness [µm] |
|------------------------------|--------------|----------------|
| Anode electrode              | Ni/8YSZ      | 240 ± 20       |
| Electrolyte                  | 8YSZ         | 8 ± 2          |
| Bilayer cathode electrode    | GDC + LSCF   | 50 ± 10        |

The MSTB includes a cell stack divided into 3 clusters for the present set-up. Each cluster owns 6 single planar cells, and all the cells are connected in the series circuit. The image of the cell stack is shown in Figure 1. The cell stack is located on the top of the test bench and then covered with the electric furnace. An exterior of the test bench is shown in Figure 2. The bench has control tools of the heaters and mass flow controllers and the electronic load. System configuration of the MSTB is also shown in Figure 3. The detailed explanation for the MSTB is following: First, compressed air in gas cylinder is regulated to 5 [bar] and fed to the cathode channel after preheating. A part of oxygen in the fed air is consumed in the electrochemical reaction. At the same time, the air is used to remove the heat from the cell stack. Then the air is fed to the afterburner to combust unused fuel from the anode channel. On the other side of the air processing, the compressed fuel, i.e. hydrogen (H₂) and nitrogen...
(N₂) mixture, is regulated to 3 [bar] and fed to the anode channel after preheating. The residual fuel is oxidized in the afterburner. After the combustion process, the gas is cooled down and the condensed water is separated and the dry gas is finally exhausted to the ambient.

2.2. Evaluation of performance

2.2.1. Fuel utilization factor
The fuel utilization factor must be calculated to manipulate fuel flow rate during the experiment. Reaction formula in the SOFC, which is fueled with H₂, can be described as follows:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$  \hspace{1cm} (1)

When 1 [mol] of H₂ reacts, 2 [mol] of the electron is emitted. Hence, $U_f$ is defined as the molar flow rate ratio of the consumed H₂ and the provided H₂. The electric current is estimated from the molar flow rate of the consumed H₂. Finally, the $U_f$ is expressed as follows:

$$U_f = \frac{n_{H_2,\text{consumed}}}{n_{H_2,\text{provided}}} = \frac{I}{2Fn_{H_2,\text{provided}}}$$  \hspace{1cm} (2)

where, $F$ indicates the Faraday constant and is referred to 96,845 [C mol⁻¹].

2.2.2. SOFC electrical efficiency
For the evaluation of the power generation characteristics of the SOFC, electrical efficiency was chosen. Electrical power output in Direct Current (DC) is calculated with the current and stack potential under the polarized condition summarized for all the cells located in the stack as follows:

$$P_{\text{SOFC}} = IV_{\text{cell}}N_{\text{cell}}$$  \hspace{1cm} (3)

where, $V_{\text{cell}}$ is the cell voltage. During the measurement, all the potentials for each cell stack are monitored, and then those are averaged to the voltage per single cell. The DC electrical efficiency is evaluated as a function of the electrical output and the chemical input of the fuel.

$$\eta_{\text{DC}} = \frac{P_{\text{SOFC}}}{n_{H_2,\text{provided}}LHV}$$  \hspace{1cm} (4)

where, the constant $LHV$ indicates Lower Heating Value (LHV) in the reaction (1), which is referred to 241.826 [kJ mol⁻¹].

3. Experimental results and discussion
Experiment was performed at Department of Fundamental Research in Energy Engineering, AGH - University of Science and Technology, Poland, in most of the cases under the nominal conditions. The nominal conditions were determined and are indicated in Table 2.

| Variable                            | Value           |
|------------------------------------|-----------------|
| Hydrogen flow rate                 | 5.4 [L min⁻¹]   |
| Nitrogen flow rate                 | 3.6 [L min⁻¹]   |
| Air flow rate                      | 45.0 [L min⁻¹]  |
| Cell stack electric furnace temper| 750 [°C]        |
| Air inlet channel electric heater  | 630 [°C]        |
| Fuel inlet channel electric heater | 550 [°C]        |
3.1. Effect of cell operating temperature and fuel concentration

The stack furnace temperature was set at 700, 725 and 750 [°C]. The current was manipulated to obtain the current-voltage (I-V) curve in the range from 0 up to 24[A]. At the operating point of 24 [A], the fuel utilization factor reached 61% with the H₂ flow rate as indicated in Table 2. It is noted that the obtained terminal voltages for each cell stack were averaged into the voltage per single cell. The result is shown in Figure 4. At the point where the current of 24 [A] was applied, the DC power output of 320.9 [W] and the DC efficiency of 37.5% (LHV) were achieved under the stack furnace temperature of 750 [°C]. The current density reached about 4800 [A m⁻²].

In case of 700 and 725 [°C], the cell voltage was not drawn over the current of 18 [A] and of 23 [A], respectively, as it is shown in Figure 4. The limitation was set at 700 [mV] for the current manipulation in the present study, in order to keep a safe operating condition for the stack capability by avoiding high local heat production rate [1, 6, 7]. At the current of 18 [A], the difference of the voltage is about 0.05 [V] and it leads to 15.6 [W] of the performance for the stack among all three cases.

Effect of the fuel concentration was also studied as indicated in Figure 5. The H₂ concentration was varied from 50% to 70%. In these experiments, the volume flow rate values of H₂ and N₂ were regulated to keep the residential time of the gas in the cell stack at constant. The higher H₂ concentration leads to higher voltage. The observed difference on voltage was about 0.03 [V] maximally between 50% and 70% of the H₂ concentration and the difference of 12.6 [W] was found in the power which was obtained at the applied current of 24 [A].

![Figure 4. Current-Voltage (I-V) characteristic under various stack furnace temperatures (Voltage is averaged for single cell).](image1)

![Figure 5. I-V characteristic under various fuel gas compositions (stack furnace temperature is 750 [°C] for all cases).](image2)

3.2. Transient characterization to fuel utilization control

3.2.1. Transient characterization to the current change

The measurement of the transient response to the ramped current manipulation was attempted under the condition represented in Table 2. The current was ramped at the rate of 1 [A min⁻¹]. The manipulation was conducted from 20 to 18 [A], from 20 to 15 [A] and from 20 to 5 [A], respectively. The measured results were shown in Figure 6. The voltage responds linearly to the ramping current. The operating temperature is almost constant during the current change. Hence, the voltage increase is affected solely by the current decrease. After the current change, the cell voltage decreased in all cases. All those behavior on the voltage may be related to the thermal behavior in the cell stack. The temperatures, which were measured at stack top and bottom, are averaged and shown in Figure 7. The cell stack was heated in the electric furnace. However, the stack temperature may be dominated by the
current decrease, which causes to decrease the heat generation within the cell stack. Thus, the drop of the temperature was observed after the decreased current change. The temperature responds slowly to the relatively quick current manipulation because of the large heat capacity of the cell stack. The amplitude of the observed overshoot on the voltage may be related to the amount of the current manipulation that magnifies the drop of the stack temperature. Focusing on the transient time of the voltage response, the transient behavior of operating temperature strongly dominates the dynamic performance.

Figure 6. Current manipulation and transient response of cell voltage.

3.2.2. Fuel utilization control

The fuel flow rate manipulation was conducted to keep the fuel utilization factor constant. Figure 8 shows the flow rates manipulation and the change of the $U_f$ to the ramping current down to 15 from 20 [A] with ramps at the rate of 1 [A min^{-1}]. The current change is illustrated in Figure 9 with the transient response of the cell voltage. The $U_f$ was leveled at 50, 60 and 70% respectively as it is presented in Figure 8. For a reference, the measured result without the flow rate manipulation was also shown in Figure 8 A). The $U_f$ changes visibly with the current manipulation in Figure 8 A). Adopting the fuel flow rate manipulation, the $U_f$ is leveled at almost constant level, though small variations are found in the transient response of the $U_f$. Before the current change, the corresponding cell voltages under polarized condition at 20 [A] were 0.817, 0.801 and 0.787 [V] for the $U_f$ at 50, 60 and 70%, respectively. After the transient manipulations, these voltages reached 0.832, 0.814 and 0.801 [V] in the steady state condition. From Figure 9, it was found that the equivalent thermodynamic time constants in all case are almost same. The change of the H₂ concentration due to the fuel flow rate manipulation, it is also noted in Figure 9. In the case of high fuel utilization, the H₂ concentration change becomes smaller and the voltage change also becomes smaller. Compared to the case without the $U_f$ leveling, the rates of the voltage increase during the current manipulation are moderated due to the lower H₂ concentration, which is caused by the fuel flow rate manipulation. The characteristics of voltage response, i.e. amplitude of the overshoot and transient time, are almost same among all the cases in Figure 9, for reasons of the almost same temperature responses in all the cases as presented in Figure 10.

Throughout the above mentioned investigation, the $U_f$ control does not have the malign influence upon the transient behavior of the cell stack. Figure 11 and Figure 12 show the DC power output and the DC efficiency. Because of the lower voltage at the higher $U_f$, the voltage differences are found before the current change. The power output decreases linearly during the current change. After the current manipulation conducted, since the cell operating temperature responds slowly as shown in Figure 10, the power output decreases gradually in spite of the nearly constant current. In steady states, the smaller $U_f$ leads the larger power output. Regarding the DC efficiency, the reduced H₂ flow rate makes it higher to the applied current. Before the current manipulation conducted, the obtained
efficiency was 34.4%, 39.6% and 46.1% to the $U_f$ at 50%, 60% and 70%, respectively with the current at 20 [A]. These efficiencies reach 34.8%, 41.1% and 47.4% to the $U_f$ at 50%, 60% and 70%, respectively after the current manipulation conducted to 15 from 20 [A]. It was found that the $U_f$ control is highly effective to improve the performance especially under the part-load condition.

Figure 8. Flow rates manipulation and transient response of fuel utilization factor. A) constant supply of H$_2$ and N$_2$ flow rates, B) H$_2$ and N$_2$ flow rates manipulation to keep $U_f$ at 50% at the rate of 17 [lpm h$^{-1}$], C) H$_2$ and N$_2$ flow rates manipulation to keep $U_f$ at 60% at the rate of 14 [lpm h$^{-1}$], D) H$_2$ and N$_2$ flow rates manipulation to keep $U_f$ at 70% at the rate of 12 [lpm h$^{-1}$] (Unit lpm h is a abbreviation of L min$^{-1}$).

Figure 9. Current manipulation from 20 to 15 [A] and transient response of cell voltage.

Figure 10. Transient response of cell stack average temperature during $U_f$ control.
4. Conclusions
The present paper investigated the transient characteristics of the 300W class planar type solid oxide fuel cell stack. The major subject was on the appropriate fuel provision for the load-following operation. The transient capability of the cell performance was evaluated with the different H2 concentration and the different fuel utilization factors. The effect of the cell operating temperature on the cell performance was remarkable. The present result shows the reasonability of the fuel flow rate manipulation for the control of the fuel utilization factor. The fuel provision control contributes the performance improvement under the part-load conditions.

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Figure 11. DC Power output.  
Figure 12. DC efficiency.