OPTIMAL DESIGN AND OPERATION OF SOFC SYSTEM FOR RAPID START-UP

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Abstract

The simultaneous optimization approach is applied to the dynamic optimization problem of the SOFC system. This method can handle complex constraints on the state variables, such as heating-up rate of the SOFC membrane, while the number of optimization variables becomes large. The dynamic model of the SOFC system is simplified so as to reduce the computational time. The preliminary initializing method is also proposed to derive the feasible initial operation profiles which are supplied to the dynamic optimization problem. A design parameter such as the size of the intake air cooler, which has the largest heat capacity in the SOFC system, is also optimized to realize the theoretical minimum start-up time calculated from the maximum heat-up rate constraints.

Keywords

Optimal start-up operation, Solid oxide fuel cell, Sequential approach

Introduction

The Solid Oxide Fuel Cell (SOFC), with its high operating temperature, is considered to be more energy efficient than other commercialized fuel cells. On the other hand, there are many operational constraints, such as a maximum heat-up rate of the SOFC membrane to avoid membrane destruction. In the SOFC system, frequent start-up, shutdown and load change operations are required because it is generally operated on-demand. Therefore, it is very important, for the SOFC system, to derive the optimal design parameters and dynamic operation profiles which satisfy those operational constraints.

In the last decade, many researchers have discussed the dynamical behavior of the SOFC system. Achenbach (1995) analyzed the transitional responses of temperature and pressure of the SOFC membrane using a three dimensional physical model. Padulles et al. (2000) proposed a simplified dynamic model of SOFC, which was modeled as a CSTR, in order to analyze the dynamic response of the SOFC system. Robert (2002) discussed the operation of the SOFC system which includes burners and heat exchangers. However, this study focused only on the operation from the end of the start-up, called hot standby, to the electricity generation.

The SOFC system discussed in this research has been under development by Mitsubishi Heavy Industries Co. Ltd. for future commercialization. The basic structure of this system was designed based on steady state operation. The start-up operation, which realizes required start-up time, has not been established yet. Therefore, in this study, the optimal start-up operation, which heats up the SOFC system including heat exchangers and combustion chambers from the room temperature (cold standby) to the temperature for generation (hot standby), is derived under operational constraints. The design parameters are also optimized in order to understand their influence on the system performance for future modification.

Basic Structure of SOFC System

The SOFC system discussed in this study mainly consists of a fuel cell, two combustion chambers and four heat exchangers, as shown in Fig. 1. The following chemical reactions are assumed to occur in the planar SOFC (Fig. 2) operated with air and methane during the electricity generation.

Methane steam reforming reaction:

$CH_4 + H_2O \text{ -> } CO + 3H_2$

CO shift reaction:

$CO + H_2O \text{ -> } CO_2 + H_2$

Electrochemical reaction at cathode:

$O_2 + 4e^- \text{ -> } 2O^{2-}$

Electrochemical reaction at anode:

$H_2 + O^{2-} \text{ -> } H_2O + 2e^-$

The major manipulated variables in this system are flow rates of main fuel (MF) and main air (MA). MF and MA are heated up by heat exchangers and combustors and fed to the SOFC membrane. Unreacted MF and MA from SOFC are burned in the main combustor with auxiliary fuel (SF) and the combustion heat is supplied to the heat exchangers as a source of heat. Flow rates of auxiliary fuel (SF) and air (SA) are also manipulated variables in this system. A certain amount of the combustion gas from the main combustor is recycled to the system directly for heat recovery.

As mentioned in the previous section, there many operational constraints related to the SOFC membrane during the start-up. One such constraint is the maximum

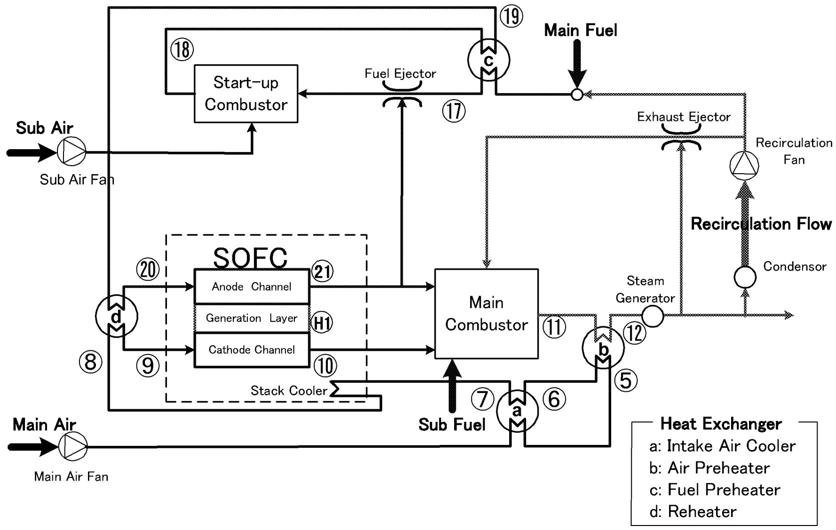

Fig. 1 SOFC system

heating-up rate of the SOFC membrane which must be less than RT_{max}. Therefore, the theoretical minimum start-up time t_{min} is calculated by Equation (1) in advance.

$$t_{min} = (T_f - T_{ini}) / RT_{max} \qquad (1)$$

Here, T_f and T_{ini} are the final and initial temperatures of the SOFC membrane.

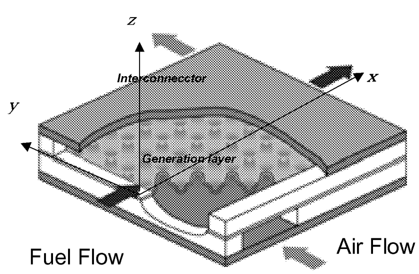

Fig. 2 Structure of planar SOFC

There are two objectives in this research. The first is to derive the optimal operation profiles which satisfy the operational constraints, since the regular start-up procedure is not established yet. The second is to improve the existing system in order to realize the theoretical minimum start-up time t_{min}. In the SOFC system, the heat capacity of the equipment is so large as to influence the start-up operation. For that reason, a design parameter such as the weight of a heat exchanger and manipulated variables are optimized simultaneously. In this research, values of some variables are normalized for keeping industrial secrets.

Mathematical Model and Optimization Method

In this research, a simultaneous approach (Alkaya et al., 1999) is applied to the optimization problem, since this approach can handle the complex constraints on the state variables. The dynamic model of the SOFC system, which consists of DAEs, is converted to a set of algebraic equations by using orthogonal collocation on finite elements. Then, the problem of finding the optimal operation profiles is formulated as a nonlinear programming problem with inequality constraints on state and manipulated variables. The resulting nonlinear programming problem is solved by using the rSQP technique. However, the number of optimization variables increases drastically when a rigorous dynamic model is used in the problem. Therefore, the following assumptions are introduced to the dynamic model of the SOFC system proposed by Ono et al. (2003).

(1) Static models for material balances.
(2) Negligible heat capacities of gases.
(3) CSTR model for combustors.
(4) No reactions in SOFC during start-up operation.
(5) Compartments model for heat exchangers.

By introducing these assumptions, the number of variables and equations is decreased to 26 state variables, 5 operation variables and 26 differential equations. The optimal operation problem of SOFC system is formulated as follows.

[DOPT]

$$\min_{\mathbf{u}(t)} \; t_f$$

$$\begin{aligned} \text{s. t.} \quad & \dot{\mathbf{x}}(t) = \mathbf{h}(\mathbf{x}(t), \mathbf{u}(t)) \\ & \mathbf{g}(\mathbf{x}(t), \mathbf{u}(t)) \geq \mathbf{0} \\ & \mathbf{x}(t) = [T_1, T_2, \ldots, T_{26}]^T, \quad \mathbf{x}_{\min} \leq \mathbf{x}(t) \leq \mathbf{x}_{\max} \\ & \mathbf{u}(t) = [F_{MA}, F_{MF}, F_{SA}, F_{SF}, F_{RF}]^T, \mathbf{u}_{\min} \leq \mathbf{u}(t) \leq \mathbf{u}_{\max} \end{aligned}$$

Here, $\mathbf{h}$ is the dynamic model and $\mathbf{g}$ is the inequality constraints of the SOFC system. In a simultaneous approach, the dynamic optimization problem is converted to an NLP problem by transforming operation variables $\mathbf{u}(t)$ and state variables $\mathbf{x}(t)$ to the discrete variables.

Initialization of Optimization Problem

Feasible operation profiles need to be supplied to the optimization problem as an initial solution to achieve the optimal solution in the limited computational time. However, there are no established start-up strategies satisfying the operational constraints. Therefore, in this study, an additional optimization problem called SOPT is formulated and solved to derive the feasible operation profiles. Although not optimal, these profiles do satisfy the operational constraints.

The SOPT is not a dynamic optimization problem (DOPT) but a static optimization problem. The minimum total flow rates of main air (MA) and auxiliary air (SA) are derived for 17 set-points of the SOFC inlet temperature, because lower flow rates seem to be preferable for rapid start-up operation. The SOPT is formulated as follows:

[SOPT]

$$\min_{u\in\Re^5} \quad F_{MA} + F_{SA}$$

$$\text{s. t.} \quad \dot{\mathbf{x}} = \mathbf{h}(\mathbf{x},\mathbf{u}) = \mathbf{0}$$

$$\mathbf{x}_{\min} \le \mathbf{x}(t) \le \mathbf{x}_{\max}, \quad \mathbf{u}_{\min} \le \mathbf{u}(t) \le \mathbf{u}_{\max}$$

$$|T_{set} - T_9| \le \Delta T_{\max}, \quad |T_{set} - T_{20}| \le \Delta T_{\max}, \quad T_i \le T_{\max}$$

$$|P_9(T_9) - P_{20}(T_{20})| \le \Delta P_{\max}$$

where $T_{\max}$ is the allowable maximum temperature, T_{set} is the set point of SOFC inlet temperature which lies between 373K to 1223K, ΔT_{max} and ΔP_{max} is the maximum temperature and pressure difference between the fuel and air inlet flows. The subscript indicates the stream number in Fig. 1.

Figures 3 and 4 illustrate the optimization results of SOPT. The x axis indicates the temperature set points of inlet flows. The following results are obtained through the simulation.

(1) F_{MA} and F_{SA} decrease when T_{set} increases.
(2) F_{MF} and F_{FR} increase when T_{set} increases.
(3) No correlation between F_{MA} and T_{set}.
(4) The temperature of stream 18 is the highest in the SOFC system and can be kept below the allowable maximum temperature $T_{\max}$.

These results give a snapshot of solutions of DOPT. In the next section, the obtained results are supplied to DOPT as an initial solution.

Optimal Operation of SOFC System

In this section, DOPT is solved by using the simultaneous optimization approach. Taking into account the results in the previous section, the following constraints during the start-up operation are newly introduced to DOPT to accelerate the convergence of the optimization. These constraints enforce the operation profiles to utilize F_{SF} and F_{SA} at the beginning of start-up operation mainly.

(1) F_{MF} and F_{RF} increase monotonically
(2) F_{SF} and F_{SA} decrease monotonically

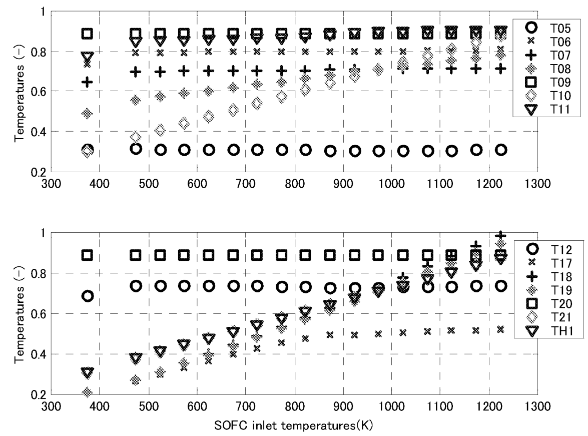

Fig.3 Results of SOPT (Temperature)

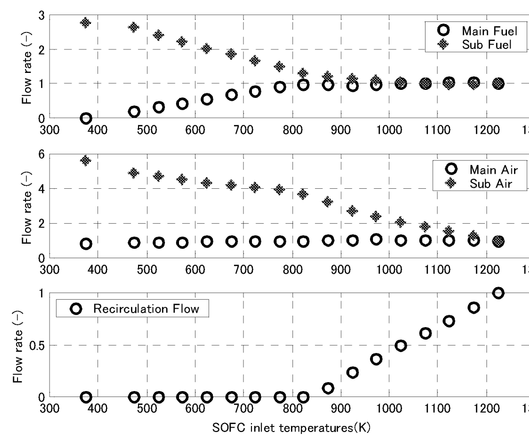

Fig.4 Results of SOPT (Manipulated variables)

Figures 5 and 6 show the optimization results obtained. In Fig. 5, the values of manipulated variables are normalized by dividing the values of the manipulated variables at the steady state operation. The y axes in Fig. 6 are also normalized with the maximum temperature difference ΔT_c, the maximum temperature in the system $T_{\max}$, the maximum pressure drop ΔP_{max} and the maximum heat-up rate of SOFC membrane ΔT. In Fig. 6, ΔT_9 and ΔT_{20} indicate the temperature change rates. The x axis is also normalized with the theoretical minimum start-up time defined by Eq.(1). Through the simulation, the following results are obtained.

(1) The existing SOFC system can be started up without violating any operational constraints by changing the manipulated variables optimally.
(2) The minimum start-up time is 1.2 times longer than the theoretical minimum start-up time.
(3) Recirculation flow need not be recycled to the SOFC system due to its low temperature.
(4) At the beginning of the start-up operation, the flow rate of SF is eight times larger than that of the MF at the static operation.

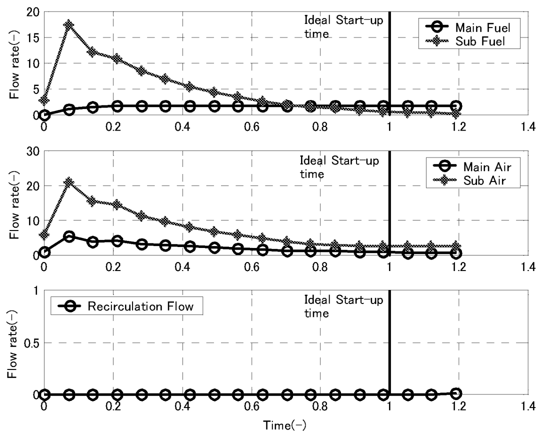

Fig.5 Optimization results (*Manipulated variables*)

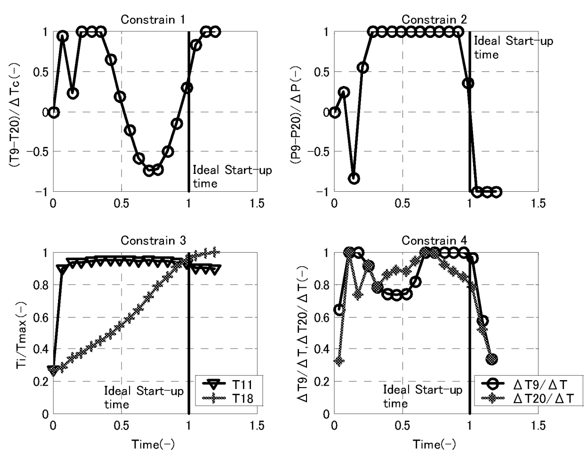

Fig.6 Optimization results (*Constraints*)

Optimization of Design Parameters

In the previous section, the optimal start-up time is longer than the minimum theoretical start-up time, since a certain amount of heat supplied to the SOFC system is used for heating up the heat exchangers. The simultaneous approach can optimize the manipulated variables and the design specifications at the same time. Therefore, the weight of the intake air cooler indicated as the heat exchanger (a) in Fig. 1 is newly added to DOPT as an optimization variable to realize the theoretical minimum start-up time, since it is the heaviest device in the existing SOFC system. The heat transfer area of the intake air cooler is assumed to be proportional to its weight.

The optimization result shows that the SOFC system can be started up in the theoretical minimum start-up time when the weight of the intake air cooler is decreased to 57% of the weight of the existing device. Figure 7 illustrates the inlet temperature changes of SOFC. The inlet temperature of SOFC increases to 1200K at the maximum heat-up rate of SOFC membrane when the weight of the intake air cooler is optimized. This result gives us the strategy for the process modification.

Conclusion

In this paper, the optimal operation profiles and the design parameter of the SOFC system are derived under the operational constraints, which arise from the physical characteristics of the SOFC membrane, using the simultaneous optimization approach. The following results of the optimal design and operation of the SOFC system are obtained through the simulation.

(1) Operation which satisfies all the operational constraints is possible when the feed flow rates are optimized as functions of time.
(2) The recirculation flow in the existing system is unnecessary for rapid start-up operation.
(3) The operation in the theoretical minimum start-up time is possible when the design specification of the device is optimized.

The obtained results will be applied to the pilot scale SOFC system and evaluated through the experiments for commercialization.

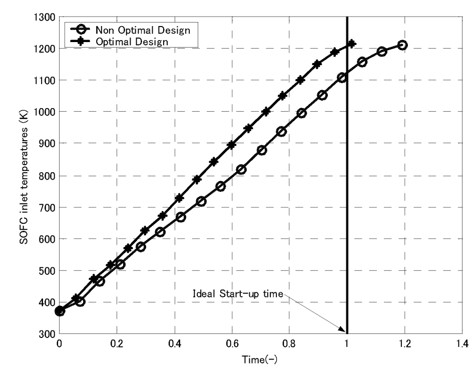

Fig. 7 SOFC inlet temperature change

Nomenclature

T = temperature, K
F = molar flow rate, mol/s
P = pressure, Pa

Subscripts

MA = main air
MF = main fuel
SA = sub air
SF = sub fuel
RF = recycle flow

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