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Model predictive control of the solid oxide fuel cell stack temperature with models based on experimental data

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HIGHLIGHTS

- Model predictive control is developed for SOFC stack temperature control.
- All models are identified from 10 kW SOFC system data.
- Temperature difference and thermal stress over the stack are reduced by MIMO control.
- Multi-input control enables improved response time compared to single-input control.

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ABSTRACT

Generalized predictive control (GPC) is applied to control the maximum temperature in a solid oxide fuel cell (SOFC) stack and the temperature difference over the stack. GPC is a model predictive control method and the models utilized in this work are ARX-type (autoregressive with extra input), multiple input-multiple output, polynomial models that were identified from experimental data obtained from experiments with a complete SOFC system. The proposed control is evaluated by simulation with various input–output combinations, with and without constraints. A comparison with conventional proportional-integral-derivative (PID) control is also made. It is shown that if only the stack maximum temperature is controlled, a standard PID controller can be used to obtain output performance comparable to that obtained with the significantly more complex model predictive controller. However, in order to control the temperature difference over the stack, both the stack minimum and the maximum temperature need to be controlled and this cannot be done with a single PID controller. In such a case the model predictive controller provides a feasible and effective solution.

1. Introduction

The solid oxide fuel cell (SOFC) technology enables the combined production of heat and power with a high electric efficiency and from a wide range of hydrocarbon fuels. The main obstacle for wide-spread utilization SOFC power systems is their high lifecycle cost, which in turn, is due to the high investment cost related to SOFC systems and the relatively short lifetime of the SOFC stack. The lifetime of a SOFC stack is effectively determined by the rate of the stack performance degradation which depends partly on to the inherent properties of the stack, such as structure and materials, but also on the conditions that stack is operated in. Automatic control can be used to optimize the operating conditions so that the part of stack performance degradation which depends on the operating conditions is minimized.

One significant factor affecting the SOFC stack performance and performance degradation rate is the temperature in which the stack is operated [1]. In particular, a too high operating temperature increases the stack degradation rate unnecessarily, and a too low operating temperature will decrease the stack voltage and its efficiency, especially when operated with hydrocarbon fuels instead of pure hydrogen. Also the spatial temperature variations inside the SOFC stack can be a cause for stack degradation [2,3]. The larger the temperature variations are, the bigger are the mechanical stresses posed on the stack structure due to mismatch of the stack materials' thermal expansion coefficients. Hence, both the absolute temperature as well as the temperature distribution inside a SOFC stack should be kept within desired boundaries during both steady-state and transient operation, and model predictive control, which

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incorporates operating constraints can be used to achieve this target.

Physical modeling of SOFCs and SOFC systems is today at a very advanced level. Good overviews of dynamic SOFC modeling and its status-quo are found in e.g. Refs. [4,5]. One typical application for dynamic models is using them to develop control for the modeled processes, and several efforts on SOFC system control have also been reported. These works can be roughly divided into two categories: (i) control aiming primarily for SOFC load following, e.g. Refs. [6–13] and (ii) SOFC temperature control, e.g. Refs. [14–18]. Avoiding fuel starvation is typically a part of the load-following control, but in Ref. [19] the control focus is also on avoiding carbon formation in the SOFC. Both the fuel starvation limit and the chance of forming solid carbon in the system pose relevant operating constraints on SOFCs and thus on their control.

The temperature control developments found in the literature include both simple decentralized, as well as complex advanced control approaches. In Refs. [14,17] the control is based on decentralized PI and PID controllers (proportional-integral-derivative), which are tuned by utilizing the model so to provide a desired SOFC stack temperature response. In both cases the air flow is used as the manipulated variable. Advanced control is used in Refs. [15,16,18] where the control is based on a variable structure control and H_∞ control, respectively. In Ref. [15] the air and fuel flow are considered as manipulated inputs, while in Ref. [16], the air flow and air temperature before the stack are the manipulated variables. In all the said cases the control development is based on a 0-, 1- or 2-dimensional physical SOFC model. For the purpose of advanced control development, such models need to be simplified somehow and the mathematical treatment of the control derivation becomes easily rather involved, which always raises the threshold for SOFC practitioners to apply these results in their work.

This paper aims to present a simple means for SOFC stack temperature regulation and control by applying the generalized predictive control (GPC) method [20], which is a variant of model predictive control (MPC). In contrast to other works, the model utilized in this work is a linear polynomial input–output model and is identified directly from experimental data [21], whereby an extensive part of physical modeling and/or model simplification is avoided. As first result, the obtained control algorithm is tested by simulation and various input–output combinations are examined in closed-loop. The behavior of the system controlled by GPC with and without typical practical constraints is analyzed and a comparison with PID control is made to clarify when the development of an advanced control algorithm is worthwhile. Attention is given to how the control handles the continuous rise of the SOFC stack temperature, induced by stack performance degradation.

The control problem tackled here is deliberately limited to stack temperature control for several reasons. The thermal inertia of the stack and the system effectively dominates the transient behavior of both the system temperatures and the stack voltage, assuming that fuel and air starvation are avoided. The stack temperature is a property that must and can be controlled actively by the adjustable system inputs, whereas the values of such properties as the fuel flow rate and anode off-gas recycle flow rate are often dictated by their feasible operating bounds and the maximal efficiency criterion together. Similarly, it is considered reasonable to assume that the system load current is a non-controllable input to the system as its value is dictated rather by the desired load output than by the control system. Finally, as there are several means to affect the stack temperature, it is considered essential to find that combination of these means which has least adverse effects to system operation in terms of e.g. efficiency. To summarize, the load current is assumed to be an external input and its value together with the maximal efficiency requirement and system specifications essentially dictate the minimal air and fuel flow rates. Therefore the control effort is focused on providing the SOFC stack with the best possible operating conditions in terms of stack temperature and stack temperature distribution.

There are several similarities between this and earlier works. In particular, the approach to the modeling and control development is analogous to that in Refs. [10,19], where also system identification, Kalman filtering and model predictive control were used. The control aim, however, was not temperature control and the control model was a set of linear parameter-varying models instead of a linear time-invariant (LTI) model which is used here. Model predictive control and system identification to obtain an LTI model for control purposes was also applied in Refs. [8,12], primarily for load-following control development, however. In all these works [8,10,12,19] the control model was identified from simulated data, whereas in this paper, models identified directly from experimental data are used.

Section 2 contains a brief overview of the experiments and the data treatment related to this work, but for a more detailed description of this part as well as hardware-related details, the reader is directed to [21] and the references therein. Model identification for control development purposes and the process of developing a generalized predictive control algorithm are described briefly in Section 3. GPC is then applied to the case problem in Section 4. Simulation results, with a brief discussion are given in Section 5. Together with [21] these papers describe a complete process from experiment design to model identification and model predictive control development for a full solid oxide fuel cell system.

2. Experimental and model identification work

The experiments, the model identification process and the development of a Kalman filter -based estimator for the stack temperatures are described fully in Ref. [21]. Therefore only a brief overview is given here.

2.1. Experiments and data pre-treatment

The case-system in this work is a complete 10 kW SOFC system with a single planar SOFC stack [22,23]. The data was obtained from designed experiments in which the system was operated in varying operating conditions, reached by manipulating four selected input variables: load current, air flow, air inlet temperature and natural gas feed (see Table 1). To collect relevant data over the full system operating range, a so-called fractional factorial experiment design was carried out twice, around two different central operating

Table 1
Considered system inputs and outputs.

	Symbol for physical variable	Unit	Nominal value	Symbol for variable after pre-treatment
Inputs				
Load current	I	A	160	u_1
Air flow	$\dot{V}_{\text{air}}$	dm^3 min^{-1}	1062	u_2
Air inlet temperature	$T_{\text{air,in}}$	°C	735	u_3
Fuel flow	$\dot{V}_{NG}$	dm^3 min^{-1}	27.90	u_4
Outputs				
Maximum temperature	$T_{\max}$	°C	773.3	y_1, $y_{1,\text{DT}}$
Minimum temperature	$T_{\min}$	°C	692.9	y_2, $y_{3,\text{DT}}$
Cathode outlet temperature	$T_{\text{cath,out}}$	°C	737.3	y_3, $y_{3,\text{DT}}$