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Anode-supported intermediate-temperature direct internal reforming solid oxide fuel cell

II. Model-based dynamic performance and control

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Abstract

In operation, solid oxide fuel cells (SOFCs) can be subjected to frequent load changes due to variable power demand. Knowledge of their dynamic behaviour is thus important when looking for suitable control strategies. The present work investigates the open and closed-loop transient response of a co-flow planar anode-supported intermediate-temperature direct internal reforming solid oxide fuel cell to load step-changes. A previously developed dynamic SOFC model, which consists of mass and energy balances and an electrochemical model that relates the fuel and air gas compositions and temperature to voltage, current density, and other relevant fuel cell variables, is used. A master controller that imposes a current density disturbance representing a change in power demand and sets the fuel and air flow rates proportional to that current (keeping the fuel utilisation and air ratio constant) and a typical feedback PID temperature controller that, given the outlet fuel temperature, responds by changing the air ratio around the default set by the master controller, have been implemented. Two distinct control approaches are considered. In the first case, the controller responds to a fixed temperature set-point, while in the second one the set-point is an adjustable parameter that depends on the magnitude of the load change introduced. Open-loop dynamic simulations show that, after a positive/negative load step-change, the overall SOFC temperature increases/decreases and the intermediate period between the disturbance imposed and the new steady-state is characterised by an undershoot/overshoot of the cell potential. Closed-loop simulations when load step-changes from 0.5 to 0.3, 0.4, 0.6, and 0.7 A cm^{-2} are imposed show that the proposed fixed set-point PID controller can successfully take the outlet fuel temperature to the desired set-point. However, it is also shown that for load changes of higher magnitude, an adjustable set-point control strategy is more effective in avoiding oscillatory control action, which can often lead to operation failure, as well as in preventing potentially damaging temperature gradients that can cause excessive stresses within the SOFC components and lead to cell breakdown.

Keywords: Anode-supported; Intermediate-temperature; DIR; SOFC; Dynamic simulation; Control strategy

1. Introduction

Solid oxide fuel cells (SOFCs) are energy conversion devices that produce electricity and heat directly from a gaseous or gasified fuel by electrochemical combination of that fuel with an oxidant. A SOFC consists of an interconnect structure and a three-layer region (often referred to as the PEN—positive-electrode/electrolyte/negative-electrode) composed of two ceramic electrodes, anode and cathode, separated by a dense ceramic electrolyte. SOFCs operate at high temperatures and atmospheric or elevated pressures, and can use hydrogen, carbon monoxide, and hydrocarbons as fuel, and air (or oxygen) as oxidant. In the cell, the oxygen ions formed at the cathode migrate through the ion-conducting electrolyte to the anode/electrolyte interface where they react with the hydrogen and carbon monoxide contained in (and/or produced by) the fuel, producing water and carbon dioxide while releasing electrons that flow via an external circuit to the cathode/electrolyte interface [1].

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Nomenclature

F	Faraday's constant ($\mathrm{C\,mol^{-1}}$)
F_{air}	molar flow rate of the air stream ($\mathrm{mol\,s^{-1}}$)
F_{fuel}	molar flow rate of the fuel stream ($\mathrm{mol\,s^{-1}}$)
$\bar{j}$	average current density ($\mathrm{A\,m^{-2}}$)
L	system length (m)
L_{cell}	cell length (m)
LHV_i^0	lower heating value of component i ($\mathrm{kJ\,mol^{-1}}$)
P_{SOFC}	power density ($\mathrm{W\,m^{-2}}$)
T	temperature (K)
U	potential (V)
U_{fuel}	fuel utilisation factor
w_{cell}	cell width (m)
W	system width (m)
x	axial coordinate (m)
y_i	molar fraction of component i
y_i^0	molar fraction of component i at inlet

Greek letters

α	coefficient of thermal expansion ($\mathrm{K^{-1}}$)
ε	sustainable stress-induced strain
η_{SOFC}	fuel cell efficiency
λ_{air}	air ratio

Superscripts

0	feed conditions (fuel and air channel inlet)

Subscripts

i	component, $i \in \{\mathrm{CH_4}, \mathrm{H_2}, \mathrm{CO}, \mathrm{O_2}\}$
max	maximum
PEN	PEN structure

While conventional high-temperature SOFCs generally operate between 1073 and 1273 K, a number of research groups are presently focusing on intermediate-temperature solid oxide fuel cells (IT-SOFCs). These typically operate between 823 and 1073 K, allowing for a wider range of materials and more cost-effective SOFC fabrication, particularly in relation to the interconnections and balance of plant (BoP). High-temperature SOFCs are generally all ceramic while IT-SOFCs are metal–ceramic and use stainless steel interconnects instead of more expensive high-chrome alloys or oxides. A typical SOFC electrolyte is yttria stabilised zirconia (YSZ), an oxide ion conductor at elevated temperatures. The anode is usually a nickel/zirconia cermet, which provides high electrochemical performance, good chemical stability, and low cost, and the cathode a perovskite material, such as strontium doped lanthanum manganite, often mixed with YSZ in the form of a composite [2,3]. Two main SOFC designs are the electrolyte-supported and electrode-supported SOFC. In the former design, the electrolyte is the thickest component and works as the support structure. Electrolyte-supported cells are only suitable for high-temperature operation where the, often large, ohmic losses can be reduced. Electrode-supported SOFCs have been developed in an attempt to minimise such ohmic losses under lower temperature operation, as in the case of IT-SOFCs. In these cells, one of the two electrodes is the thickest component and support structure, while the electrolyte is required to have high ionic conductivity and/or small thickness. However, it is usually observed that, despite a low ohmic contribution, the area specific resistance of IT-SOFCs may be larger than high-temperature SOFCs. This is due to activation and perhaps concentration overpotentials, which can often outweigh the ohmic contribution. Thus, many of the recent efforts in fuel cell technology development have been devoted to reducing the thickness of critical cell components while improving their structures, with the aim of obtaining a higher and more stable performance with a lower cost [4–6].

Most fuel cells need to convert a hydrocarbon primary fuel into a hydrogen-rich gas required for the electrochemical reaction on the anode side. One option is to process the fuel indirectly in an external catalytic steam reformer or partial oxidation reactor [7]. In the most common case of a reformer, heat needs to be available to drive the endothermic steam reforming reaction. One method of achieving this is to feed the exhaust cell gases into a burner, where the excess fuel is combusted, and the heat generated used to preheat the steam and the fuel and to provide the heat needed in the reformer. However, a more elegant and efficient method of providing heat for the reforming reaction in SOFCs is to carry out the reforming, partially or totally, within the cell stack [8,9]. Internal reforming SOFCs (IR-SOFCs) can eliminate the requirement for a separate fuel reformer and significantly reduce the requirement for cell cooling, usually achieved by flowing excess air through the cathode [10,11]. One approach to IR is direct internal reforming (DIR), where the methane is fed directly into the cell and the reforming takes place directly on the anode [8]. A problem, mostly related to high-temperature SOFCs, is the strong cooling effect caused by the highly endothermic reforming reaction that can generate large temperature gradients across the cell and limit the amount of IR allowed in practice. It has been shown that in high-temperature IR-SOFCs, all the methane is usually completely reformed within a small distance from the anode entrance [12–15]. IT-SOFCs offer significant advantages in terms of internally reforming methane, as the lower temperature naturally reduces the reforming reaction rate [16].

1.1. Complete fuel cell system

For operation, a SOFC must be embedded within a SOFC system incorporating a balance of plant to supply air and clean fuel, convert the direct current (dc) to alternate current (ac), and remove or process the depleted reactants, products, and heat [17–19]. A complete SOFC system is generally composed of five main sub-systems: fuel processing, fuel cell stack, power conditioning, heat recovery and/or further power generation using integrated gas and steam turbines, and plant control. Fig. 1 presents a schematic of such sub-systems. For