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Thermal effects of planar high temperature heat pipes in solid oxide cell stacks operated with internal methane reforming

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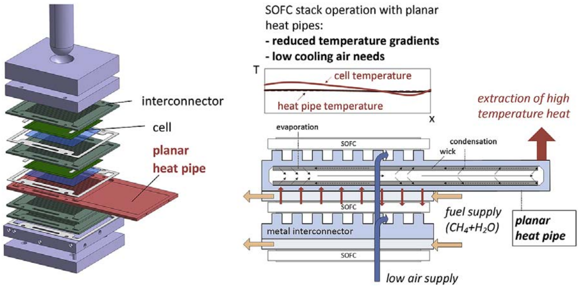
HIGHLIGHTS

- Integration of planar sodium heat pipes into SOFC stacks.
- CFD thermal modelling of stacks with planar heat pipe interconnectors.
- Thermal effects of direct internal methane steam reforming.
- Model validation with steady-state short stack measurements.
- Temperature distributions in stacks with respect to heat recycling and air ratios.

GRAPHICAL ABSTRACT



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ABSTRACT

The presented paper contributes to developing a new thermal control approach for solid oxide cell (SOC) stacks and systems. Integrating planar liquid metal heat pipes to the interconnector structure of the stacks targets a reduction of internal temperature gradients and an enhanced heat extraction from the stack. This work applies 3-D CFD-modelling to discuss the thermal effects of integrated heat pipes in solid oxide cell stacks, in order to evaluate the possible benefits in terms of temperature gradient reduction and heat removal as well as the resulting benefits for stacks and systems. The stack model set-up is described and its functioning is validated with experimental results from thermal short stack measurements with integrated heat pipe interconnectors. The simulation results are discussed with respect to the possible benefits for full-scale stacks of different cell size, in particular regarding internal heat recycling and the beneficial reduction of air ratios.

1. Introduction

Electric power generation systems will undergo fundamental changes in the coming decades. Striking indicators of this necessity are the negative price trends e.g. in Germany's electricity markets in conjunction with the strong increase of grid intervention costs. Centralized, steady Rankine-based thermal power plants will have to be replaced with flexible, decentralized systems that operate as back-up partner to highly volatile solar and wind driven power generation.

Solid oxide cells are compelling products for these upcoming business fields. Due to their modularity, fuel flexibility and reversibility they address markets both for distributed power and heat generation as well as surplus electricity storage. Operated as fuel cells (SOFC) they offer excellent part load behavior, highest electric efficiencies up to 60% even for very decentralized power generation and suitability for carbon monoxide, methane and yet higher hydrocarbons [1].

As reversed process water electrolysis is one of the common entry steps to most of chemical energy storage systems, solid oxide electrolysers (SOEC) target the production of a large variety of synthetic fuels [2]. Compared to low temperature electrolysis systems this high temperature technology benefits from very favourable thermodynamic conditions due to its increased temperature. Thus, SOEC systems may

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significantly decrease specific energy demand below 4.5 kWh/Nm^3 H_2, a value that state-of-the-art alkaline and PEM – electrolyzers reach today [3] (i.e. approx. 67% lower heating value (LHV) based efficiency), and comes close to hydrogen's LHV of 3.0 kWh/(Nm^3 H_2).

However, high competitiveness in the described markets requires simple, integrated and load flexible systems. Therefore, large scientific and technical advances have been made within the last years in particular regarding solid oxide cell materials and structure of the electrolyte and both electrodes. Despite this, for SOC systems the above named key features are inevitably interwoven with the question of thermal management and thermal integration of the stacks. In fuel cell operation, the thermodynamic enthalpy balance and electrochemical loss produce a significant amount of waste heat, typically in the range of 20–50% of fuel's LHV. The high power density of the planar stack structure and the limit to stack internal temperature gradients outreach the possible heat transfer by conduction within the stacks.

In steady operation, the thermal control is mostly realized by means of excess air cooling, considerably reducing thermal efficiencies. Typical air ratios λ (supplied air over fuel stoichiometric air demand) vary between 3.5 and 6 for systems that benefit from (partly) stack internal reforming of hydrocarbons [4]. SOFCs operated on pure hydrogen with high fuel uses require even higher cooling air and reach air ratios of up 4–10, depending on the power density [5]. These airflows far beyond stoichiometry cause further disadvantages on a system level, in particular a low thermal efficiency and high auxiliary power losses for blowers. Typical values for a 21.3 kW_{DC} stack operated on natural gas (50% steam pre-reforming) [6] and $\lambda = 5.5$ are a blower power of approx. 2.4 kW representing over 10% of the electric stack output.

Furthermore, a direct linking of solid oxide cell system (SOFC and SOEC) to volatile electricity sources leads to strong load gradients and consequently important changes in internal heat consumption/production rates. This implies alternating temperature distributions within the stacks that result in dynamic mechanical stress within the sensible ceramic cell and are a cause for micro cracking as well as delamination leading to a strong decline of cell performance and lifetime [7]. As a consequence, the need to prevent fracture of cell components is restricts the thermal dynamics of the stack and thus the theoretically fast electric load adaptation of SOCs.

Fig. 1 explains the concept and basic idea of the integration of planar heat pipes into the interconnector structure of a SOFC stack. This interconnector represents an almost isothermal body as the liquid metal working fluid enables highest latent heat transport due to an evaporation – condensation cycle inside the heat pipe. Thereby, the heat distribution within the stack is strongly improved and high temperature (HT) heat can be directly extracted from the stack. Stack internal temperature gradients including their negative effects on solid oxide cell long-term stack stability, as well as the high demand for cooling air shrinks. The proposed approach allows highest thermal system integration with pre-heaters and secondary (endothermal) processes such as fuel pre-reforming, dehydrogenation reactors [8], solid fuel gasification [9] and high temperature heat storages. In general, high system compactness and thermal integration of the entire solid oxide system (stack, off-gas burner, air pre-heater and pre-reformer) into stack modules are a major development objective [6] for SOFC systems. Similar approaches have been proposed by Supra [10] and Niemasz [11] for low temperature fuel cells applications (i.e. PEM or HT-PEM).

Previously published works describe the development of the required planar heat pipe interconnectors and their integration into the stack structure of a short stack based on electrolyte supported cells [12–14]. The planar heat pipe interconnectors with thicknesses between 3 and 6 mm are based on a sandwich design of metal wire screens and elementary sodium as working fluid. Within the possible operation range between 650 °C and 870 °C these planar heat spreaders (120 × 270 mm^2) demonstrate almost isothermal behavior (< 10 K temperature gradients in the active zone) in an experimental set-up comparable to heat extraction from a stack based on 100 × 100 mm^2 SOFCs. Heat transfer performance of the prototypes reached up to 1 kW in horizontal operation and good long-term stability was shown over 2000 h. While the developed heat pipe interconnectors have been integrated in short stacks with 2–3 cells in order to demonstrate their beneficial effects on temperature gradients within the stack structure, this paper provides a numerical extrapolation to full-scale stacks and some design guidelines.

In previous studies, mainy authors carried out research or reviews on modelling SOFCs based on thermo-fluid and or electrochemical processes including various CFD approaches [15–18]. In particular, Al-Masri et al. [19] developed a 3D computational model in the commercial CFD software FLUENT for predicting the temperature field in a lightweight SOFC stack. The model focuses on the transient heating up processes of the stack where important thermal stress is expected. Hosseini et al. [20] developed a CFD model of a methane fueled single cell SOFC stack for analyzing the combined effects of macro/micro structural parameters. They assessed for the effects of the reforming and

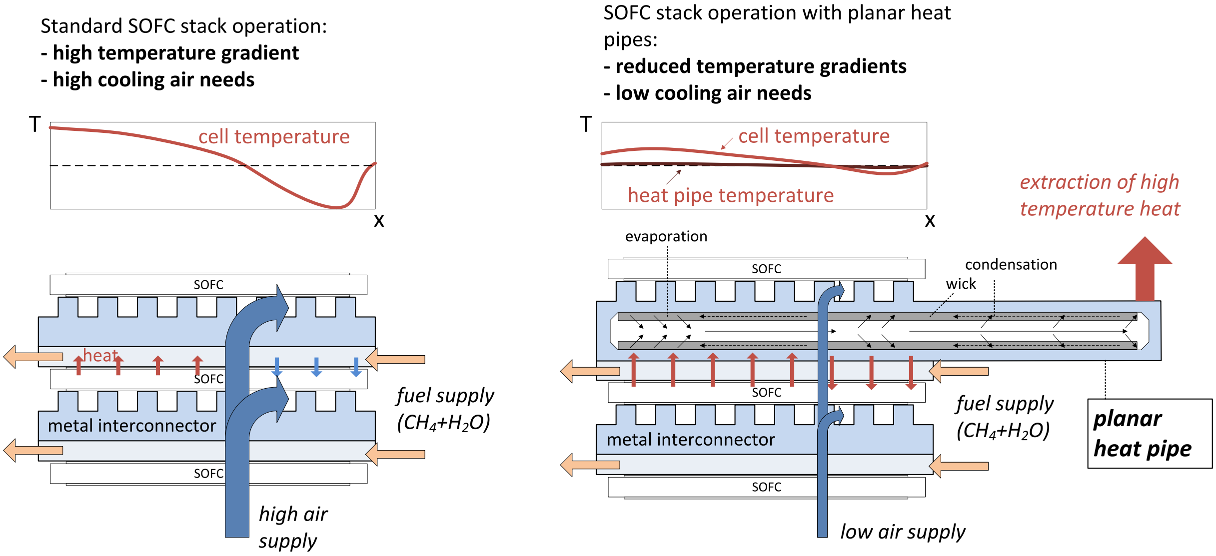

Fig. 1. Concept of solid oxide cell stacks with planar heat pipes integrated into the interconnector layers, targeting an internal temperature gradient reduction and improved heat removal from the stack structure.