Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Power Sources 156 (2006) 321–333

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Techno-economic modelling of a solid oxide fuel cell stack for micro combined heat and power

A.D. Hawkes [a,*], P. Aguiar [b], C.A. Hernandez-Aramburo [c], M.A. Leach [a], N.P. Brandon [b], T.C. Green [c], C.S. Adjiman [b,d]

[a] *Centre for Energy Policy and Technology, Imperial College London, London SW7 2AZ, UK*
[b] *Department of Chemical Engineering and Chemical Technology, Imperial College London, London SW7 2AZ, UK*
[c] *Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, UK*
[d] *Centre for Process Systems Engineering, Imperial College London, London SW7 2AZ, UK*

Received 23 November 2004; received in revised form 9 May 2005; accepted 16 May 2005
Available online 19 July 2005

Abstract

Solid oxide fuel cell combined heat and power (CHP) is a promising technology to serve electricity and heat demands. In order to analyse the potential of the technology, a detailed techno-economic energy-cost minimisation model of a micro-CHP system is developed drawing on steady-state and dynamic SOFC stack models and power converter design. This model is applied it to identify minimum costs and optimum stack capacities under various current density change constraints. Firstly, a characterisation of the system electrical efficiency is developed through the combination of stack efficiency profiles and power converter efficiency profiles. Optimisation model constraints are then developed, including a limitation in the change of current density ($A\,cm^{-2}$) per minute in the stack. The optimisation model is then presented and further expanded to account for the inability of a stack to respond instantaneously to load changes, resulting in a penalty function being applied to the objective function proportional to the size of load changes being serviced by the stack. Finally, the optimisation model is applied to examine the relative importance, in terms of minimum cost and optimum stack maximum electrical power output capacity, of the limitation on rate of current density change for a UK residential micro-CHP application. It is found that constraints on the rate of change in current density are not an important design parameter from an economic perspective.

Keywords: Solid oxide fuel cell; Power converter; Cost optimisation; Micro-CHP

1. Introduction

Efficient technologies, such as solid oxide fuel cells are an important link in achieving a low-carbon economy as presented by the UK Government in the Energy White Paper [1]. The White Paper suggests a 60% carbon reduction target by 2050. This is a challenging aspiration, only achievable through a variety of measures including some relating to energy efficiency. In addition to low-carbon aspirations, a substantial complementary effort is being directed at moving towards more decentralised electricity generation. A part of the potential decentralised energy markets is the residential sector, which is a large consumer of both electricity and heat, and could benefit from consolidation to meet these demands via combined heat and power (CHP). Bringing all these points together, this paper develops a techno-economic model for meeting energy demand with micro-CHP using SOFC technology, and applies it to a residential situation.

Appropriate techno-economic characterisation of solid oxide fuel cell micro-CHP technology can provide a useful tool to direct research to improve this technology, and give manufacturers a guide for suitable system design. In this paper, steady-state and dynamic SOFC stack models are used along with a detailed power converter model to develop an accurate high-level characterisation of SOFC-based micro-CHP in the 0–5 kW_e range. This information

---

[*] Corresponding author. Tel.: +44 207 594 7312; fax: +44 207 594 9334.
E-mail address: a.hawkes@imperial.ac.uk (A.D. Hawkes).

0378-7753/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2005.05.076

is then used to inform a cost minimisation model that calculates the minimum equivalent annual cost of meeting given energy demands, and chooses the optimum stack capacity[1] to install for that energy demand.

Firstly, relevant performance characteristics of the fuel cell stack under consideration – an anode-supported intermediate-temperature direct internal reforming SOFC – are presented. The technical and design requirements for a power converter that produces alternating current from the direct current fuel cell are then considered. The optimisation model, which brings these technical depictions together and reflects them into model inputs and constraints, is then presented. The model is applied to analyse the influence of an upper and lower bound on the change in current density on the minimum cost and optimum micro-CHP system capacities in a residential situation corresponding to a large UK household. This particular analysis is justified in that a greater rate of change in current density in a SOFC stack implies a greater induced temperature gradient across the stack, and therefore a greater induced thermal stress. Given that increased stress is likely to adversely impact on stack lifetime, there is a rationale behind limiting the rate of change of current density such that it is below a certain specified value, and consequently prolonging the lifetime of the stack. As no quantitative basis exists to relate a specific limit on change in current density to a particular cell lifetime a sensitivity analysis across a range of values is performed to inform our conclusions.

2. Solid oxide fuel cell performance

Solid oxide fuel cells [2,3] consist of air and fuel channels, a three-layer ceramic region composed of the anode and cathode separated by a dense electrolyte (PEN structure) and an interconnect structure used to combine cells together. SOFCs operate at high temperatures and atmospheric or elevated pressures, and can use H_2, CO or hydrocarbons as fuel and air as oxidant. In a SOFC, the O^{2-} ions formed at the cathode migrate through the ion-conducting electrolyte to the anode/electrolyte interface where they react with the H_2 and CO contained in (and/or produced by) the fuel, producing H_2O and CO_2 while releasing electrons that flow via an external circuit to the cathode/electrolyte interface. SOFCs can be classified according to their geometry, operating temperature, relative thickness of PEN components or method of processing the fuel. This paper focuses on the performance of planar anode-supported intermediate-temperature (IT) direct internal reforming (DIR) SOFCs. The operating temperature range of IT-SOFCs is from 823 to 1073 K, as compared to the 1073–1273 K range of high-temperature SOFCs. The temperature reduction allows IT-SOFCs to use a wider range of materials and have a more cost-effective fabrication method. Anode-supported SOFCs (where the anode is the thickest PEN component and the electrolyte must have high ionic conductivity and small thickness) have been developed to minimise the high ohmic losses attributed to IT operation. DIR is a possible approach to convert a primary fuel into the H_2-rich gas required by SOFCs. In this approach, the CH_4 is fed directly to the cell and reforming takes place on the anode, eliminating the need for a separate fuel reformer. It is known that DIR in high-temperature SOFCs may lead to steep local cooling effects caused by the endothermic DIR reaction, and can generate large, potentially damaging, temperature gradients. However, the lower operating temperature of IT-SOFCs has been shown to be beneficial as it naturally reduces the DIR reaction rate.

For operation, a SOFC stack must be embedded within a SOFC system incorporating a balance of plant (BoP) to supply air and clean fuel at the appropriate operating conditions, convert the direct current (dc) to alternate current (ac), and remove or process the depleted reactants, products and heat [4–6]. 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. For a SOFC system, the starting point is the fuel processing: natural gas is first partially or totally externally steam reformed in a pre-reformer before being fed to the SOFC stack, producing hydrogen and carbon monoxide, both of which can be used by the stack as fuel; any natural gas remaining can be reformed internally in the stack, providing useful cooling. The electrochemical power generation takes place when dc electricity is produced within the fuel cells, normally combined in a varying number of cells or stacks that can match a particular power requirement. The power-conditioning unit converts the electric power from direct current into regulated direct current or alternate network current and is described in more detail in Section 3. The heat recovery unit refers to the recovery of residual heat in the exhaust gas that can be used, for example, to heat water for local space heating, thus giving a higher overall system efficiency. The control sub-system guarantees that both the BoP and the SOFC stack respond rapidly and safely to any variations, such as a change in electrical or thermal load.

2.1. SOFC stack model

References [7] and [8] reported on the development of a dynamic one-dimensional planar co-flow anode-supported IT DIR-SOFC model, which is used here to predict the stack performance. To produce a useful voltage, a SOFC consists of several repeating electrochemical cells in a module, connected both in series and/or in parallel and assembled to compose a stack. However, SOFC models are usually developed

---

[1] “Stack capacity” is defined as the maximum electrical power output capacity of the SOFC stack and dc–ac converter combined. It therefore includes losses in the dc–ac converter, but does not consider parasitic loads of micro-CHP system. Parasitic loads are accounted for in the optimisation model through inclusion in demand curves, and a percentage power loss (e.g. 5%) on stack/converter output.