Dynamic modeling of high temperature PEM fuel cell start-up process

Y. Wang [a,b,*], D.U. Sauer [a,b,c], S. Koehne [d], A. Ersoez [e]

[a] Electrochemical Energy Conversion and Storage Systems Group, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Germany
[b] Juelich Aachen Research Alliance, JARA-Energy, Germany
[c] Institute for Power Generation and Storage Systems (PGS), E.ON ERC, RWTH Aachen University, Germany
[d] TS TestingService GmbH, Germany
[e] Scientific and Technological Research Council of Turkey (TUBITAK), Jaegerstrasse 17/19, D-52066 Aachen, Germany

ARTICLE INFO

ABSTRACT

High temperature proton exchange membrane fuel cells (HT-PEMFCs) are considered to be the next generation fuel cells. Compared with standard low temperature proton exchange membrane fuel cells (LT-PEMFCs) the electrochemical kinetics for electrode reactions are enhanced by using a polybenzimidazole based membrane at an operation temperature between 160 °C and 180 °C. However, starting HT-PEMFCs from room temperature to a proper operation temperature is a challenge in application where a fast start of the fuel cell is required such as in uninterruptible power supply systems. There are different methods to start-up HT-PEMFCs. Based on a 3D physical model of a single HT-PEMFC, the start-up process is analyzed by comparing the start-up duration of the different start-up concepts. Furthermore, the temperature distribution in the HT-PEMFC is also analyzed. Finally, an optimal start-up method is proposed for the given cell configuration.

Introduction

High temperature proton exchange membrane fuel cells (HT-PEMFCs) have attracted more and more attention in the last decade. They are considered to be a promising energy conversion system for many applications, such as stand-alone power [1], backup power, uninterrupted power supply (UPS), automotive application [2–6], auxiliary power unit (APU), and Combined-Heat-and-Power (CHP) applications [7–11].

Compared with low temperature proton exchange membrane fuel cells (LT-PEMFCs) which typically operate between 70 °C and 80 °C, the electrochemical kinetics for electrode reactions of HT-PEMFCs are enhanced in an operation temperature range of 160 °C–180 °C by using polybenzimidazole (PBI) based membranes [12–17]. Another advantage of introducing the PBI based membrane is that reaction gases do not need to be humidified. Moreover, water produced by the chemical reaction is gaseous at the operation temperature. Therefore, the water management of LT-PEMFC systems is not necessary for

* Corresponding author. Electrochemical Energy Conversion and Storage Systems Group, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Germany. Tel.: +49 (0)241 80 49315; fax: +49 (0)241 80 92203.
E-mail addresses: batteries@isea.rwth-aachen.de, ywa@isea.rwth-aachen.de (Y. Wang).

Nomenclature

A	specific surface area, m^{-1}
A_c	Tafel slope, V
C_p	heat capacity, J kg^{-1} °C^{-1}
D	multicomponent Fick diffusivities, m^2 s^{-1}
D^T	thermal diffusion coefficient, kg m^{-1} s^{-1}
E_{eq}	equilibrium potential, V
F	Faraday constant, A s mol^{-1}
$\mathbf{F}$	body force vector, N m^{-3}
i	current density, A m^{-2}
i_0	exchange current density, A m^{-2}
i_{loc}	local charge transfer current density, A m^{-2}, which is i_a/i_c at the anode/cathode
I	identity matrix
k	thermal conductivity, W m^{-1} °C^{-1}
k_{br}	permeability, m^2
M	molecular mass, kg mol^{-1}
p	pressure, Pa
Q	source term, A m^{-3}
Q_{br}	mass source or sink term, kg m^{-3} s^{-1}
Q_h	heat source or sink, W m^{-3}
R	gas constant, J mol^{-1} °C^{-1}
R_i	production or consumption of species i, kg m^{-3} s^{-1}
t	time, s
T	temperature, °C
$\mathbf{u}$	velocity, m s^{-1}
x	mole fraction

Greek alphabet

α	charge transfer coefficient
β	Forchheimer coefficient, m^{-1}
ε	porosity
η	overpotential, V
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
σ	conductivity, S m^{-1}
ϕ	potential, V
ω	mass fraction

Superscripts and subscripts

a	anode
c	cathode
i, k	different species in mixture
j	joule heating source
l	electrolyte
m	electrode reaction on anode or cathode
s	electrode

HT-PEMFC systems. Additionally, higher carbon monoxide tolerance [18—20] makes it possible to simplify the fuel processing system by integrating the fuel cell with a fuel processing unit, e.g. a reformer [21—24]. In this kind of system, the exhaust heat of the fuel cell can be used for the steam reforming in order to reduce the fuel consumption in the reformer for maintaining the catalyst temperature. This improves the system efficiency significantly [23,24].

Temperature is a critical parameter in HT-PEMFCs. The variation of temperature strongly affects the performance of HT-PEMFCs [25—27]. Zhang [28] investigated the dependency of the cell performance on temperature. In the range of 120 °C—180 °C, increasing the temperature decreases the membrane resistance, and therefore the cell power density is increased accordingly. Parrondo [29] got similar results and concluded that 180 °C is the optimal operation temperature for HT-PEMFCs. In the work of Ong [30], the optimal operation temperature for the cell performance is found to be 170 °C. However, for a long-term operation, Oono [31] had a different conclusion. After the fuel cell durability test at different temperatures 150 °C, 170 °C and 190 °C, it was clarified that a higher cell temperature results in a higher cell voltage, but a shorter cell life time.

Due to the high operation temperature, starting HT-PEMFCs from room temperature to a proper operation temperature is a challenge. Before discussing the start-up process for HT-PEMFCs, it is worth mentioning the start-up strategies for LT-PEMFCs developed in the last few years. The main emphasis of the work is the cold start of LT-PEMFCs [32—41]. Most of the cold start strategies are to start the electrochemical reaction to warm-up the fuel cell from room temperature or even lower temperature such as below freezing point [42]. Different models have been reported such as modeling the cold start at a subfreezing temperature under both constant current and constant cell voltage conditions [43], 3D model for the cold start by moderating the current density with the anode catalytic reaction [44], and the cold start by applying maximum power in vehicular application [45,46]. Many experiments have also been reported for the cold start of LT-PEMFCs [47—54]. Rasheed [55] developed a model to investigate the warm-up process of HT-PEMFCs from room temperature by extracting constant current from the fuel cell and applying an external heating source with a constant heat input rate simultaneously. Although the model is useful to understand the dynamics of a warm-up process, especially the boiling phase change phenomenon in HT-PEMFCs around the water boiling point, the effect of this start-up process on HT-PEMFCs is unknown. Since the normal working temperature of PBI membrane (e.g. high temperature Celtec-P series MEAs developed by BASF) is between 120 °C and 180 °C. Working at a temperature under the water boiling point can damage the PBI membrane.

Therefore, many start-up strategies have been studied for HT-PEMFCs. In the work of Andreasen [56], the fuel cell stack is heated by blowing hot air into the stack or by electrical heaters such as heating cartridges assembled in the end plate or heating mats assembled at the edge of the stack. It is shown that the hot air heating is faster than the electrical heating. Singdeo [57] summarized different heat strategies for HT-PEMFCs including the direct electrical heating, reactant heating, coolant heating and reaction heating for the given configurations with co-flow and counter-flow. It is shown in Singdeo's simulation that the reactant heating with the co-flow configuration is more suitable than the counter-flow. Additionally, the combination of the co-flow reactant heating with the reaction heating can reduce the start-up time. Several temperature measurements were also made for understanding the temperature distribution for the given