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Elucidating the constant power, current and voltage cold start modes of proton exchange membrane fuel cell

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ABSTRACT

Constant power cold start mode of proton exchange membrane (PEM) fuel cell is essential in practical applications, however, unlike the constant current and voltage cold start modes, the constant power mode was largely ignored in previous fundamental modeling and experimental studies. In this study, a PEM fuel cell stack cold start model for analyzing the constant power cold start process is developed, and the fundamental differences among the various start-up modes are elucidated. In the constant power cold start mode, the start-up process may fail before the ice fully covers the cathode catalyst layers (CLs), because the stack may not be able to supply the required power output, which is different from the constant current and voltage start-up modes. The initial water content and start-up temperature could limit the power output significantly. The constant power can be controlled at higher current (CPHC) or lower current (CPLC). In the CPHC mode, the current density decreases and the stack voltage increases during the cold start process, while it is reversed in the CPLC mode. Generally, the CPLC mode produces less heat during cold start process than the other start-up modes, because the current density is often kept at low level.

1. Introduction

Since the first practical application of hydrogen–oxygen fuel cell stack in 1960s [1], the development of modern fuel cell has attracted considerable attention. Proton exchange membrane (PEM) fuel cell is a very promising type among the various types of fuel cell. The high power density, zero/low emission and low operating temperature are its major advantages over other kinds of fuel cell and traditional internal combustion engine [2]. According to Mench [3], a bus powered by a PEM fuel cell stack has almost twice the fuel efficiency as a bus powered by a diesel engine. After decades of development, PEM fuel cell stacks are applied in many fields, such as space shuttles, automobiles and sub-water devices [4].

Environmental adaptability is a vital issue for PEM fuel cell stack to be widely applied in transportation and stationary applications, and start-up in cold environment is one of the problems to be solved. Successful cold start from −20 °C has been achieved in commercialized fuel cell vehicles in recent years [5]. Even more strict targets of cold start ability for commercial PEM fuel cell stack have been set, e.g. successful start-up from −30 °C in 60 s set by Ballard [6]. The target of cold start ability may be achieved through the assist of accessory equipment in fuel cell system, and many patents explained the various assisting methods in details [7–9]. The fundamental research for this problem is also important to understand the transport processes and to reduce the power consumption and system complexity required for the successful cold start targets.

Fundamental experimental studies for PEM fuel cell cold start include the visualization of water freezing processes [10–16], degradation tests of different components [17,18], and analysis of relationship between performance and operational parameters [19–22]. Moreover, mathematical modeling can provide insights into the details and mechanisms of the phenomena during the cold start processes. Mathematical modeling studies for PEM fuel cell cold start usually concentrate on the temperature issues [23,24], water transport and ice formation issues [25–28], effect of design parameters and operating methods [29–34], and system characteristics [35]. Generally, the cold start performance predictions are often based on the evolutions of output voltage, current density and temperature.

Although the analysis of PEM fuel cell cold start has developed in various aspects as mentioned above, the start-up modes adopted in these studies are mainly constant current mode and constant voltage mode, and models were rarely developed for constant

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Nomenclature

a	water activity
A	cell geometric area, m^2
ASR	area specific resistance, Ω cm^2
c	mole concentration, mol m^{-3}
C_p	specific heat, J kg^{-1} K^{-1}
D	mass diffusivity, m^2 s^{-1}
EW	equivalent weight of membrane, 1.1 kg mol^{-1}
F	Faraday's constant, 96487 C mol^{-1}
h	surrounding heat transfer coefficient, W m^{-2} K^{-1}
I	current density, A cm^{-2}
j_*	exchange current density, A cm^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
K	permeability, m^2
M	molecular weight, kg mol^{-1}
MEA	membrane electrode assembly
p	pressure, Pa
$\dot{Q}$	heat transfer rate, W
R	universal gas constant, J mol^{-1} K^{-1},
s	volume fraction
S	source terms
t	time, s
T	temperature, K
T^0	standard temperature, 298 K
V	voltage
CPHC	constant power higher current
CPLC	constant power lower current
CC	constant current
CV	constant voltage

Greek letters

α	transfer coefficient
ε	porosity
ζ	water transfer rate, s^{-1}
κ	electric conductivity, S m^{-1}
λ	water content in ionomer
μ	dynamic viscosity, kg m^{-1} s^{-1}
ξ	stoichiometry ratio
ρ	density, kg m^{-3}
ω	volume fraction of ionomer in catalyst layer
δ	thickness, m

Subscripts and superscripts

a	anode
act	activation
atm	atmosphere
BP	bipolar plate
c	cathode, capillary
Cell	cell characteristic
channel	flow channel
CL	catalyst layer
conc	concentration
eff	effective
env	environment
eq	equilibrium
f	frozen
fl	fluid phase
fmw	frozen membrane water
g	gas
GDL	gas diffusion layer
H_2O	water
i	the *i*th components
ice	ice
lq	liquid water
mem	membrane
N	cell number
nernst	Nernst
nf	non-frozen
nmw	non-frozen membrane water
ohmic	ohmic
out	outlet, output
P	power
sat	saturation
sl	solid phase
Stack	stack characteristic
T	energy (for source term)
vp	water vapor
wall	surrounding wall of the stack

power mode. The constant power start-up mode is a traditional and essential operating mode in practical applications, which can be implemented through DC–DC converters [36–38]. In fact, PEM fuel cell stacks are often used to power vehicles through a hybrid system, in which the fuel cell works at steady power to operate a generator, because fuel cell is often favored to work under a constant load for optimum performance and efficiency [39,40], and simultaneously the demand of peak power output can also be satisfied by a secondary system with peak power sources (e.g. batteries [41] and supercapacitors [42]). Since fuel cell vehicles are supposed to satisfy various road conditions, PEM fuel cell stack is required to work in composite modes, which imply the combination of different elementary modes, basically including the constant power, current and voltage modes. However, most of the previous studies for PEM fuel cell constant power operation can only be found for steady-state operating conditions [41,42]. Few experimental studies related to PEM fuel cell cold start in constant power mode were carried out. Oszcipok et al. [43] analyzed the cold start problem of a portable PEM fuel cell through experiment with the constant power operation involved. Datta et al. [44] studied a PEM fuel cell based power generator used in Antarctica. It is mentioned that the DC–DC converter is required to get constant power output, and the constant power mode is good for charging other devices. On the other hand, investigations on the fundamental transport phenomena during the constant power cold start processes of PEM fuel cell were not found by the authors. Therefore, to understand the fundamental difference in the heat and mass transfer among the various cold start modes, it is necessary to develop a cold start model for PEM fuel cell stack with the ability for the simulations of constant power, current and voltage modes.

In this study, a PEM fuel cell stack cold start model is developed and described in details; the differences among the constant power, current and voltage cold start modes are analyzed and elucidated; and the constant power cold start processes are comprehensively investigated under various operating conditions.

2. Model development

The physical problems considered in the PEM fuel cell stack model are illustrated in Fig. 1, and the parameters of the stack design and operating condition are listed in Table 1. The stacks include certain numbers of single cells and are clamped with two end plates. In each single cell, the components considered include the bipolar plate (BP), gas diffusion layer (GDL), catalyst layer (CL)