Applied Thermal Engineering 130 (2018) 637–659

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Freeze start drive cycle simulation of a fuel cell powertrain with a two-phase stack model and exergy analysis for thermal management improvement

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HIGHLIGHTS

- A freeze start drive cycle of a FCV powertrain is done with a two phase stack model.
- Exergy sankey is used to show exergy loss distribution during entire drive cycle.
- Inefficient energy consumption is mainly in the city stage after the freeze start.
- Optimization directions like split cooling and power demand threshold are suggested.
- Reaching optimal temperature for water drainage by lowering humidification proposed.

ARTICLE INFO

Article history:
Received 12 August 2017
Revised 2 October 2017
Accepted 19 October 2017
Available online 16 November 2017

Keywords:
PEM fuel cell powertrain
Cold start
Drive cycle
Exergy analysis

ABSTRACT

This paper integrates a two-phase fuel cell stack model, previously published and validated in Tang et al. (2017) for the specific purpose of investigating freeze start behavior, into a full-hybrid fuel cell powertrain model to simulate cold start. The aim of the simulation is to provide an overview of exergy loss distribution during a cold start drive cycle scenario. Another intention is to propose a methodology for suggesting the directions in thermal management development. The powertrain model simulates an Artemis-like transient drive cycle starting from −20 °C. The heater-core bypass and fuel cell stack power threshold are selected as representative thermal/energy management options. To evaluate the impact of the selected options on the warm up, the accumulated energy consumption and exergy flow rates are analyzed. The statistics from our simulation show that the inefficient energy consumption occurs mainly in the city stage shortly after the successful freeze start. The tank-to-wheel efficiency merely achieves 10.3% in the city stage, while the fuel cell stack can reach nearly 73% exergy efficiency throughout the entire drive cycle and tank-to-wheel efficiency reaches 29.3% at the end of the whole drive cycle. The improvement is suggested to be focused in the low power demand stages by cutting down to the actual power ratio needed and simultaneously minimize the relevant thermal-hydraulic inertia. Several optimization directions such as cascaded fuel cell stack alignment, split cooling and power demand threshold for active rapid warm up are drawn. The established fuel cell powertrain model combined with exergy analysis is a suitable methodology for further detailed thermal and energy management investigations.

1. Introduction

The cold start challenge is one of the most critical criteria to be fulfilled for a PEM fuel cell powertrain. The advantage of fairly high theoretical thermodynamic efficiency and mainly water as waste product can easily become a hinderness for PEM fuel cell stacks to achieve quick freeze starts under subzero conditions. For automotive and other transportation applications, PEM fuel cell stacks and its relevant thermal systems must be designed to meet cold climate environment for successful introduction to the market. Thermal management strategies not only should achieve fast and robust freeze starts, but should also keep energy consumption during cold start as low as possible.

Thorough review on the challenges and experiments of fuel cell cold start in the automotive environment can be found in Refs. [3–5]. Ref. 3] gives a list of publications on single PEM fuel cell

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https://doi.org/10.1016/j.applthermaleng.2017.10.100
1359-4311/

Nomenclature

α	active reaction area per volume
α_{Back}	charge coefficient (negative)
α_{Batt}	temperature coefficient of resistance
α_{Forw}	charge coefficient (positive)
β	mass transport coefficient
β_G	gas-holdup value
ΔH	change of enthalpy
δ_{nom}	nominal dimensionless channel length [43]
$\dot{m}$	mass flow rate
$\dot{m}_i$	mass flow rate of gas component i
$\dot{Q}$	heat flow rate
$\dot{W}_{irr}$	irreversible loss of technical work
$\dot{W}_t$	technical work
$\dot{X}$	exergy flow rate
Γ_m	uptake coefficient [2]
$\gamma_{phaseCh}$	phase change rate
γ_{sub}	volum. sublimation rate
Γ_s	Accommodation coefficient [2]
λ_{An}	anode stoichiometry
λ_{Ca}	cathode stoichiometry
λ_w	water content
Ψ_{GDL}	shape factor in GDL transport phenomena [43]
$a_{contact}$	rib-to-channel aspect ratio [43]
amb	ambient condition
An	anode side
C_{dl}	double-layer capacity
c_i	concentration of component i
c_p	spec. heat capacity
Ca	cathode side
d_{BPP}	BPP thickness of one side
D_i	diffusion coefficient
E	energy
FC	fuel cell
g	gas phase
h	spec. enthalpy of gas mixture
Hu	calorific value of hydrogen
i_0	reference current density
ice	frozen state
K	permeability
k_{SOC}	ohmic resistance SOC dependency
l	liquid phase
m	molar
P_{el}	electric power
R_s	battery internal ohmic resistance
s_i	spec. entropy of gas component i
sg	superficial gas
sl	superficial liquid
T_{ref}	reference temperature
V	volume
X	exergy
ACL	anode catalyst layer
AGC	anode gas channel
Batt	battery
BPP	bipolar plate
CAC	charge air cooler
CCL	cathode catalyst layer
FCV	fuel cell vehicle
GDL	gas diffusion layer
CGC	cathode gas channel
HVAC	Heating, Ventilating and Air-Conditioning
OCV	Open Circuit Voltage
PID	Proportional-Integral-Differential control
PTC	PTC heater
R.H.	Relative Humidity
SOC	state of charge
TPD	traction power distributor

startup from −30 °C and small stack up to 2 kW start from −5 °C. In Ref. [4], the impact from water freezing on the material lifetime of PEM, on the MEA and flow channel is described. Ref. [5] summarizes systems and methods for fuel cell shutdown into two categories of purge solutions and materials to avoid freezing, and also gives a survey of cold startup strategies based on an exhaustive survey of journal papers and patents. Regarding system and solutions for fuel cell startup, the heating solutions are classified into internal and external heating methods.

Based on the reviews, the majority of the experimental work on PEM fuel cell cold start were on single cell, while only a handful of researchers conducted subfreezing stack startup tests such as in Ref. [6] or Ref. [7]. In Ref. [8], Li et al. have experimented with heat storage and electric heating to improve the cold start of a stack. Henao et al. used both external electric heater and generated waste heat from the electrochemical reaction within the stack as a cold startup strategy for a 23-cell stack in Ref. [9]. From the experimental conclusions of Ref. [9], it could be inferred that internal heating solutions are more effective and efficient in terms of energy consumption. This is verified by the freeze start experiments from Schießwohl et al. in Ref. [10], wherein a potentiostatic method was successfully applied on a 60 cell stack to freeze start within 30 s from −6 °C above 0 °C. The review in Ref. [5] concludes that since the last few years the research trend in fuel cell powertrain has been focusing on internal heating more than external heating. Especially in the automotive industry, controlled accelerating of the internal heating by potentiostatic method or similar has become preferred for robust cold start. Many patents more than journal articles have been published on fuel cell freeze start. However, those filed patents usually only cover a certain subsystem aspect. For example Ref. [11] published a method for simultaneous monitoring valve control, supercapacitor charge and discharge control as well as heating process for a freeze start capability from −20 °C within 11 s. In Ref. [12], a technique of water separation after shutdown is described to achieve improved preconditioning for the next freeze start. Refs. [13,14] each patented a method to use the compressor for load reduction to assist in cold starting.

To understand the interaction of subsystems and their roles during cold start, so as to develop optimized materials or startup methods, either measurements or a model of the complete powertrain is needed. Nowadays it is common practice to use system simulation for this development procedure: due to the complexity a fuel cell powertrain setup, to find the proper cold start strategy must often be done by simulation before going to hardware design. On the other hand, testing equipment installed for large fuel cell system test benches have higher inaccuracy than sensors used on single fuel cell test benches. It is technically too difficult to obtain detailed information on freeze start onset, flooding or other internal behavior inside a fuel cell stack with the same precision as on a single fuel cell test bench. There are hardly publications with in situ measurement of a complete fuel cell powertrain. One reason is that, compared to the trend of battery electric cars, there are still few fuel cell vehicle prototypes running on the street performing online in-depth measurements. Another important aspect not to be neglect in a fuel cell powertrain is the inclusion of an auxiliary battery. The hybrid ratio (power sizing between fuel cell stack and the battery) has been studied in numerous researches such as Refs.