Applied Energy 217 (2018) 314–327

Contents lists available at ScienceDirect

Applied Energy

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

Multi-objective genetic optimization of the thermoelectric system for thermal management of proton exchange membrane fuel cells

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HIGHLIGHTS

- The dynamics of the TEG in a PEMFC cooling system is analyzed.
- The model couples together the TEG and PEMFC dynamics.
- The NSGA-II algorithm is used to optimize the TEG design.
- A tradeoff exists between maximum power or system efficiency and mass.
- Active cooling primarily improves the TEG specific power.

ARTICLE INFO

Keywords:
Thermoelectric generator
PEMFC
NSGA-II genetic algorithm
Optimization
1-D thermodynamics

ABSTRACT

As a clean power system with a narrow temperature range of typically 60–95 °C, the low temperature (LT) proton exchange membrane fuel cell (PEMFC) requires an effective thermal management system to enhance its efficiency and durability. This paper focuses on a genetic algorithm based optimization of the thermoelectric generator (TEG) as applied to the PEMFC system. The genetic algorithm approach is advantageous over similar previous research in that it enables multi-objective optimization where the various TEG module parameters can be configured towards critical objectives such as maximum output power, minimal mass and maintaining the PEMFC within its operating temperature range. A second case study is also studied where the combined efficiency of the PEMFC and TEG is selected as an objective in replacement of the maximum TEG output power. Optimization results suggest that, in both cases, there is a trade-off situation between maximum output TEG power or maximum system efficiency with respect to system mass. It is also shown that the most important benefit of increasing the cooling convection coefficient is that it increases the system's specific power where the heat sink areas can be smaller to achieve the same cooling rate.

1. Introduction

The emission of pollutants such as CO_x, NO_x and SO_2 by fossil fuels and their non-renewable nature have raised many concerns and motivated researchers and the industry to develop cleaner and more sustainable technologies. In particular, fuel cells are a promising solution to solve these global issues where they can efficiently generate power while only emitting the harmless byproduct of water.

While there are many different types of fuel cells available, the low temperature (LT) proton exchange membrane fuel cell (PEMFC) is attractive for the automotive application where the key features include low operating temperature and low maintenance requirements [1]. The PEMFC internal design is currently still a research topic. For instance, Cheng et al. [2] proposed the metamodeling optimal approach to determine the PEMFC's power density performance in terms of various environmental parameters and then used a genetic algorithm to optimize towards this objective. More recently, Ribeirinha et al. [3] developed a 3-dimensional model of the high temperature (HT) PEMFC which was integrated with a methanol steam reformer. However, PEMFCs have a narrow operating temperature range (typically 60–90 °C for a low temperature (LT) variant and 150–180 °C for a high temperature (HT) variant [4]) and operation outside the prescribed range can lead to a significant reduction in the cell's efficiency. Furthermore, even under the optimal temperature conditions, the PEMFC is not a perfect system where it has typical electrochemical conversion efficiencies in the order of 40–55% and the remaining power is released as

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https://doi.org/10.1016/j.apenergy.2018.02.097
Received 26 November 2017; Received in revised form 12 February 2018; Accepted 13 February 2018

Nomenclature

V	fuel cell operating voltage (V)
R	fuel cell internal electrical resistance (Ω)
V_{OC}	fuel cell ideal open circuit voltage (V)
V_{act}	fuel cell activation voltage loss (V)
V_{Ω}	fuel cell ohmic voltage loss (V)
η_T	total fuel cell efficiency
η_C	fuel cell electrochemical efficiency
η_E	fuel cell electrical efficiency loss
P_{FC}	fuel cell useful output electrical power (W)
I_o	exchange current (A)
I_{Ideal}	ideal exchange current (A)
α	seebeck co-efficient (V/K)
σ	electrical conductivity (S/m)
λ	thermal conductivity (W/(mK))
ε	surface emissivity
κ	convection co-efficient (W/(m^2 K))
T	surface temperature (K)
i	TEG Operating Current (A)
$V_{oc(TEG)}$	open circuit voltage of the TEG (V)
$I_{sc(TEG)}$	short circuit current of the TEG (A)
I^{*}_{TEG}	the quantity of current flowing through the TEG which obtains the maximum TEG power output (A)
r_{TEG}	internal electrical resistance of a single thermocouple of the TEG (Ω)
R_{TEG}	total internal electrical resistance of the TEG (Ω)
n	number of thermocouples in the TEG
l	length of thermocouple
A	surface area (m^2)
L	length of surface
T_L	temperature of the reservoir at the output side of the hybrid PV/TEG system
Q_{Heat}	total generated heat by fuel cell that is to be removed by the TEG cooling system (W)
Q_r	radiated heat at the output portion of the hybrid assembly (W)
Q_{TEG}	TEG electrical power output (W)
A_R	TEG outlet to inlet ratio
P	the population vector for the NSGA-II algorithm
R	the offspring population vector for the NSGA-II Algorithm

Subscripts and superscripts

In	refers to properties at the inlet of the TEG
Out	refers to properties at the outlet of the TEG
p	p-type type thermopile
n	n-type type thermopile

Abbreviations

HT	High Temperature
LT	Low Temperature
NSGA-II	Non-dominated Sorting Genetic Algorithm II
Mat	an identifier integer for identifying the type of material for the thermocouples.
MPP	Maximum Power Point
PEMFC	Proton Exchange Membrane Fuel Cell
TEG	Thermoelectric Generator

Numerical constants

$\gamma = 5.670373 \times 10^{-8}\ \text{Wm}^{-2}\ \text{K}^{-4}$ the Stefan-Boltzmann constant

waste heat. Thus, it is important to provide an effective thermal management system for the PEMFC so that it can retain its optimal output efficiencies and reliability. In this aspect, references such as Jung et al. and Meidanshahi et al. [5,6] have focused on modelling the internal temperature dynamics of the PEMFC and, in doing so, provided recommendations on how the internal structure should be designed to achieve an optimal temperature distribution.

Indeed, in addition to the optimization of the fuel cell design for improved temperature gradients, the heat generated by an operating PEMFC is usually significant enough that an active cooling system is required. For instance, López-Sabirón et al. [7] conducted a study into the designing an oxygen fan system where the air supplied to the fuel cell stack is also used simultaneously to cool the fuel cell stack itself. Unfortunately, such a design couples together the dynamics of the fuel cell oxygen supply and the cooling effect and thus, according to Zhang et al. [8], it is often difficult to design an optimal cooling system via this technology. In the meantime, other more flexible techniques are mentioned in the literature review Zhang et al. [8] and these include using head spreaders and subsequently applying external air cooling or liquid cooling with one example reference being Clement et al. [9]. In addition, the potential of adopting nanofluids in the liquid cooling system for the PEMFC application has been reviewed in Islam et al. [10]. It is noted that similar cooling technologies have also been applied in HT-PEMFCs (Chandan et al. [11]) where the design requirements are more stringent. This is simply because the HT-PEMFC operates at higher temperatures than that of the LT-PEMFC. While the HT-PEMFC offers a higher average efficiency than that of LT-PEMFCs, it finds less practical applications because the required higher operating temperature is often less compatible with other system components.

Because fuel cells tend to generate a significant amount of waste heat, they also serve as excellent candidates for a cogenerate heat and power (CHP) system which essentially supplies both heat and electrical power to the end users. For example, Barelli et al. [12] and Chang et al. [13] investigated the PEMFC when used in a cogenerate heat and power (CHP) generation system with the common conclusion that the PEMFC is a very efficient system for this application. A COMSOL based thermodynamic model and a ANN neural network based electrical model of the fuel cell was also coupled together in Asensio et al. [14] to simulate a PEMFC based CHP system.

In the meantime, the thermoelectric generator (TEG) is a potential alternative technology who can be adopted in cooling systems for fuel cells. It is currently recognized in literature as being an effective robust, clean and noiseless electric power generator [15–21] where practical applications include the recovery of waste heat from automotive exhaust systems [22,23], the solar thermoelectric hybrid system [24–26], hypersonic engines [27] and so on. In addition to power generation, the output characteristics of the thermoelectric device have even been exploited for measurement purposes such as that of solar intensity measurements in Rahbar et al. [28]. Recently, the application of the TEG into the fuel cell application has also been considered, with a relatively early example being that of Chen et al. [29]. Some references such as [4,30] also consider using the TEG to extract waste heat from the exhaust products of the fuel cell. The optimization of the TEG design for extracting heat from the exhaust of a HT-PEMFC was also studied in Gao et al. [31]. Unfortunately, heat extraction from exhaust products is not really considered as a fuel cell cooling system since the TEG is not acting directly on the fuel cell stack itself. Moreover, as raised in [8,10], in most cases, only a minority of the generated heat by a fuel cell is carried through the exhaust products and that active cooling of the fuel cell stack is still necessary for sustainable operation. In this aspect which involves TEGs, Hasani et al. [32] considers using the TEG as part of a liquid cooling system where it is used in a heat exchanger to