INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 6637–6645

Available online at www.sciencedirect.com
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journal homepage: www.elsevier.com/locate/he

Optimization of a thermoelectric generator subsystem for high temperature PEM fuel cell exhaust heat recovery

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ARTICLE INFO

Article history:
Received 17 September 2013
Received in revised form
26 January 2014
Accepted 27 January 2014
Available online 20 February 2014

Keywords:
TEG subsystem
Fuel cell
Heat recovery
Heat exchanger
Electrical connection
Optimization

ABSTRACT

In previous work, a thermoelectric (TE) exhaust heat recovery subsystem for a high temperature polymer electrolyte membrane (HT-PEM) fuel cell stack was developed and modeled. Numerical simulations were conducted and have identified an optimized subsystem configuration and 4 types of compact heat exchangers with superior performance for further analysis.

In this work, the on-design performances of the 4 heat exchangers are more thoroughly assessed on their corresponding optimized subsystem configurations. Afterward, their off-design performances are compared on the whole working range of the fuel cell stack. All through this study, different electrical connection styles of all the thermoelectric generator (TEG) modules in the subsystem and their influences are also discussed. In the end, the subsystem configuration is further optimized and a higher subsystem power output is achieved. All TEG modules are now connected into branches. The procedures of designing and optimizing this TE exhaust heat recovery subsystem are drawn out. The contribution of TE exhaust heat recovery to the HT-PEM fuel cell power system is preliminarily concluded. Its feasibility is also discussed.

1. Introduction

Fuel cells are considered as a cornerstone of the approaching hydrogen economy [1,2]. Among other fuel cell technologies, high temperature polymer electrolyte membrane (HT-PEM) fuel cells, operating around 160 °C, offers promising market potential [3–5]. Thanks to the increased operating temperature, they have better fuel impurity tolerance and easier cooling (greater temperature differences versus ambient air), in turn much simpler system configuration and possibility of high system efficiencies [6,7]. Yet another benefit of the relatively high operating temperature, the HT-PEM fuel cell exhaust heat is of higher quality and easier to utilize as process heat or recycle. To recover the exhaust heat for electricity and further boost the system efficiency, a thermoelectric (TE) exhaust heat recovery subsystem has already been introduced to the cathode exhaust of the fuel cell stack in a previous work [8].

In the previous work [8], the subsystem architecture was decided, model was made, and configuration was

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http://dx.doi.org/10.1016/j.ijhydene.2014.01.193

Table 1 – -Main equations [8,10].

Description	Equations
TEG properties	$\sum^{n_{x,TE}}\sum^{n_{y,TE}}\alpha_i = \alpha_{TE},\ \sum^{n_{x,TE}}\sum^{n_{y,TE}}R_{e,i} = R_{TE,e},\ \sum^{n_{x,TE}}\sum^{n_{y,TE}}R_{t,i} = R_{TE,t}$
TEG power output	$I_i = 0.5(\alpha_i) - (\overline{T}_{h,TE}(i)\overline{T}_{c,TE}(i))/R_{e,i}$ $w(i) = \alpha_i I_i(\overline{T}_{h,TE}(i) - \overline{T}_{c,TE}(i)) - I_i^2 R_{e,i},\ P_{TEA} = \sum^{nx} n_x \sum^{ny} n_y w(i)$
Heat transfer	$\dot{q}_{h,TE}(i) = \dot{q}_{gas}(i) = \dot{m}_{gas}(h_{gas,i} - h_{gas,i+1})$ $\dot{q}_{gas}(i) = \varepsilon_{ctf}(i)\dot{m}_{gas}(h_{gas,i} - h^{cw}_{gas,i})$ $\dot{q}_{h,TE}(i) = UA_{hx}(i)(\overline{T}_{gas}(i) - \overline{T}_{h,TE}(i)),\ \overline{T}_{gas}(i) = (T_{gas}(i) + T_{gas}(i+1))/2$
Pressure drop	$\Delta p_{hx} = (u^2_{gas}/(2\rho_{gas,in}))[4f_{hx}L_{hx}\rho_{gas,in}/(D_h\overline{\rho}_{gas}) + (1+\sigma^2)((\rho_{gas,in}/\rho_{gas,out}) - 1)]$

preliminarily optimized. As illustrated in Fig. 1, the subsystem is constructed in a way similar to a compact plate-fin gas–liquid heat exchanger. Part No. 3 is the compact heat exchanger housing for the fuel cell stack exhaust gas, which works as the heat source. Part No. 1&4 are two aluminum blocks with a liquid coolant circulating inside, as the heat sink. The coolant is actually a methanol–water mixture, which is stored in a tank primarily as fuel and will be gradually reformed into hydrogen for the fuel cell stack [9]. Thermoelectric generator (TEG) modules, namely part No. 2, are interposed between the aforementioned two parts. As a whole, these parts form the sandwich structure subsystem. The subsystem was then modeled using a finite-element approach with higher precision and better versatility for both design-type and simulation-type problems. Main equations are presented in Table 1. On the model, a sensitivity analysis was carried out and has identified the subsystem main variables. In the end, the subsystem configuration was optimized. There were 6 TEG modules crossing the exhaust gas flow by 7 modules along the flow. They together scale the subsystem size. All the modules were electrically in series. On this optimized configuration, 4 types of heat exchangers with superior performance were also identified.

In this work, instead of keeping the subsystem size invariant in all cases, it is adjusted correspondingly to each of the 4 chosen heat exchangers to more properly assess their performances. Besides the above on-design performance optimization under the same fixed fuel cell stack operating point as in the previous work, research is also carried out on the whole working range of the stack. It is the off-design performance optimization. Another factor that evidently affects the subsystem performance, the electrical connection styles of TEG modules, is also more thoroughly investigated in this work. Finally, the further optimized subsystem is depicted; a more efficient and practical electrical connection scenario of all the TEG modules is proposed; the procedures of designing and optimizing the TEG subsystem are generalized. At the end of this work, the contribution and perspectives of the TE exhaust heat recovery to the HT-PEM fuel cell power system are also discussed.

2. On-design performance optimization

In this paper, all simulation settings not explicitly given are corresponding with the previous work [8] and 'the subsystem power output' refers in particular to its maximum value. The 4 types of heat exchangers studied here were identified by their outstandingly low pressure drop still with high heat transfer performance. Table 2 lists their brief information. More details can be found in Ref. [11].

In this section, the on-design performances of 4 different subsystems denoted by their equipped heat exchangers are analyzed. The word "on-design" refers to the nominal working point of the HT-PEM fuel cell stack. The stack current density is fixed to ≈0.67 A/cm^2; the stack cathode stoichiometry is assumed to be around 19 [12,13]. To this nominal working condition, 4 subsystems are optimized respectively for determining the final optimal subsystem configuration. Results are as follows.

2.1. *Heat transfer process optimization*

To enhance the heat transfer process, the size of the subsystem needs to be optimized, which is scaled by the number of TEG modules crossing the exhaust gas flow and the number of modules along the flow, n_{cro} and n_{run}. Two steps are needed here: 1) finding out the candidate n_{cro}, and 2) choosing the optimum n_{cro} and n_{run}.

Before finding out the candidate n_{cro}, an adequate n_{run} for all the 4 heat exchangers needs to be identified. It requires, under any n_{cro} and any heat exchanger type, all possible exhaust heat will be always recovered by the subsystem. The minimum applicable n_{cro} of 2 is used to pinpoint the adequate n_{run}. For each heat exchanger, there is a smallest n_{run} when the subsystem power output varies less than 0.5% between n_{run} and $n_{run}-1$. Then the largest n_{run} among the four is the adequate n_{run}, which equals 26 in this study. Afterward, this n_{run} is kept invariant to identify the candidate n_{cro} for each of the 4 heat exchangers. Results are presented in the following figures.

Table 2 – The 4 types of heat exchangers [8].

Index	Name	Page no. in Ref. [11]
1	'Plain plate-fin, surface 15.08'	229
2	'Pin-fin plate-fin, surface PF-10(F)'	262
3	'Strip-fin plate-fin, surface 1/6-12.18(D)'	250
4	'Pin-fin plate-fin, surface PF-4(F)'	260