WASTE HEAT RECOVERY FROM FUEL CELLS APPLIED IN ADSORPTION SYSTEMS

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Abstract. *This manuscript reports a thermodynamic analysis to assess the feasibility of using the heat rejected by a proton exchange membrane fuel cell (PEMFC) to drive commercial adsorption chillers, in a cogeneration scheme to produce electricity and cooling power. The PEMFC was assumed to have efficiency in the range of 40 % to 60 %. Commercial adsorption chillers have COP in the range of 0.46 to 0.67. For a PEMFC efficiency of 40 %, our analysis showed a cogeneration system efficiency within 61 to 71 %, according to the chiller COP. For a PEMFC efficiency of 60 %, the cogeneration system efficiency reached up to 75 %. Such cogeneration scheme improved the hydrogen energy utilization in between 46 and 123 % when compared to the hydrogen energy utilization by single fuel cell. The results are considered promising, and show a technical feasibility of the proposed cogeneration scheme for industrial and even automotive applications.*

Keywords: *waste heat, fuel cell, adsorption system*

1. INTRODUCTION

Fuel cell has been widely studied in various applications and it has emerged as a promising alternative in the automotive industry (Ismail et al., 2009), distributed generation and other industrial applications (Barbir, 2005). This device works from an electrochemical process, converting the chemical energy of a fuel into electrical energy. Among the available fuel cells there is the proton exchange membrane fuel cell (PEMFC), which works from hydrogen as fuel and oxygen as oxidant, delivering H_2O and heat as byproducts. PEM fuel cell works at low temperature (< 90 °C), and has efficiency range of 40-60 % (Rand and Dell, 2008). Basically, the energy is not converted into electricity is converted into heat. This feature points to recovery opportunities of the fuel cell waste heat in an integrated system, thereby increasing the fuel energy utilization.

The fuel cell thermal control is necessary to avoid membrane damage and to ensure its best performance. Forced convection of air or water commonly have been used to control the fuel cell temperature (An et al., 2009; Kothmann and Cyphers, 1981; Tajima et al., 1996). Different techniques have been proposed using capillary pumping systems to achieve higher compactness and homogeneity of the fuel cell temperature, and to improve its performance, which are heat pipes integrated in the fuel cells (Faghri, 2005; Koji et al., 1986; Oro and Bazzo, 2015; Silva et al., 2012; Vasiliev and Vasiliev Jr., 2008).

Some works have been presented where waste heat recovery from PEMFC was used to heat residential water, as Hamada et al. (2004) and Hwang et al. (2010). However, in the present work, the fuel cell waste heat was used to recovery part of the waste heat into a cogeneration scheme to produce electricity and cooling power. Among the cooling power devices which are powered by waste heat, adsorption refrigeration system are the most suitable due to the PEMFC working temperature (Wang et al., 2013). This type of system comprises a reactor with the adsorbent bed, the adsorbate (refrigerant), a condenser, and an evaporator. Cooling power is produced in a cycle in which the reactor undergoes heating, desorption of refrigerant to the condenser, cooling, and adsorption of refrigerant from the evaporator.

In Tab. 1 is presented some of the characteristics of the adsorption systems available in the market, with their operation conditions. Basically, the systems are divided in those using zeolite and water as working pair and those using the pair silica gel and water. The cooling power covers a wide range, from 8 to 168 kW, with production of chilled water between 7 and 15 °C. The temperature levels of the heat supply are from 65 to 90 °C, and for the heat sink, it is between 27 and 31 °C. The coefficient of performance (COP) reported by the manufacturers are between 0.46 and 0.67.

Regarding the combination of PEMFC and adsorption refrigeration systems, Oh et al. (2013) compared the theoretical performance of two adsorption chillers drive from waste heat of a PEMFC. One of the chillers used silica gel and water as working pair, whereas the other one used activated carbon fiber and ethanol. The results showed an efficiency improvement of 22 % with the use of first chiller and of 15 % with the use of the second one.

In both fuel cell and refrigeration systems there are auxiliary devices as pump, fun, and control module, which consume electric power. Commonly this consumption is related with the power generated by the systems, and result in a power fraction consumed, i. e., how much is consumed in regard to generated. The number and capacity of each device will depend on the system capacity.

For example, in fuel cell of medium capacity, its cooling is realized by forced air convection. In this case the auxiliary devices assembly comprises basically by air compressor, which provides oxygen to fuel cells, and a blower responsible of cooling the system. In bigger systems, forced liquid convection is required, hence it is added a pump to flow the refrigerant into the fuel cell. Concerning to fuel cells, Hussain et al. (2005) showed power fraction consumed in regard to generated electric power were in the range of 30-16 % to a current density of 0.2-2 A/cm², respectively. The results included the sum of the powers from air compressor, cooling fluid pump, and radiator blower.

Table 1. Available adsorption chillers in the market.

		Inversor		Mayecawa[c]	Mitsubishi Plastics[d]	GBU[e]		HIJC[f]	Nishiyodo Air Conditioner[g]	Power Partners[h]	SorTech AG[i]	
Model		LTC 10-plus[a]	LTC 10- e-plus[b]	AdRef-Noa Z3515	AQSOA-10kW	NAK 020/70		ADCM1-060	NADAC-050	AD3-C-10	ACS 08	ACS 15
Pair		zeolite/water				silica gel/water						
Chilled water	Capacity [kW]	10	10	92	10	37.1	49.7	115.0	168.78	35	8	15
	T_{in} [°C]	18	18	15.6	16	-		9.6	14	12.8	18	
	T_{out} [°C]	15	15	9	11	-		7	9	7.2	15	
	flow [m³/h]	2.9	2.9	12	1.72	-		37.8	29.4	5.4	2	4
Heated water	Capacity [kW]	16.7	15.4	200	20	80.7	95.6	184.9	251.91	67.9*	12.7*	25.5*
	T_{in} [°C]	72	72	75	70	65	70	70	88	90.6	72	
	T_{out} [°C]	66	67	66.9	65	59.4	64.4	66.6	83.3	83.9	65	
	flow [m³/h]	2.5	2.5	21.3	3.44	-		46.2	46.2	9	1.6	3.2
Cooling water	Capacity [kW]	26.7	25.4	301	-	-		299.9				
	T_{in} [°C]	27	27	29	-	-		29.4	31	29.4	27	
	T_{out} [°C]	31.5	31	34.2	-	-		34.0	35,3	35	32	
	flow [m³/h]	5.1	5.1	49.5	-	-		84	84	16.56	3.7	7
COP		0.60	0.65	0.46	0.50	0.46	0.52	0.62	0.67	0.52	0.60	0.60

a) Inversor (2016a); b) Inversor (2016b); c) Mayecawa (2016); d) Mitsubishi (2016); e) GBU (2016); f) HIJC (2016); g) Nishiyodo (2016); h) Power-Partners (2016); i) SorTech (2016).

* Estimated by $q = flow \cdot \rho \cdot Cp \cdot (T_{in}-T_{out})$

Differently, in the study of Sasmito et al. (2011) some cooling strategies were analyzed. Considering air convection power fraction consumed reached 5 %, whereas in the liquid convection case the system consumed 13 %.

Hosseini et al. (2012) comment air compressor is the auxiliary device most consume electric power in a fuel cell system, and show its consumption can reach 20 % of the generated electric power. In the refrigeration chillers, an estimative can be conducted considering the pressure drop experienced by the fluid flow.

Therefore, the present work aims to assess the feasibility of using the heat rejected by a PEMFC to drive commercial adsorption chillers, in a cogeneration scheme to produce electricity and cooling power. The analysis was based on fuel cell efficiency and the COP of the refrigeration system, and took into account the power fraction consumed by the auxiliary systems, as presented in the next section.

2. THERMODYNAMIC EVALUATION

The cogeneration system efficiency is a function of the fuel cell efficiency and of the COP of the adsorption refrigeration system.

Fuel cell efficiency was calculated with a model based on Kordesch and Simader (1996), Larminie and Dicks (2003), and Barbir (2005), whereas the COP was assumed to be in the range of the values presented in Tab. 1.

Differently from heat engines, in fuel cells the external work involves electron flow through an external circuit, where the energy available to perform the work is delivery by the change in Gibbs energy of the products and reactants (Larminie and Dicks, 2003).

In a chemical reaction, the change in Gibbs energy is equal to the maximum work possible, $W_{max} = -\Delta G$, which is related with enthalpy (H), temperature (T), and entropy (S) as shown in Eq. (1).

$$\Delta G = \Delta H - T\Delta S \tag{1}$$

From the First Law of Thermodynamics, taking account heat absorbed (Q), work done (W), and work of expansion at constant pressure ($P\Delta V$), the enthalpy change can be written as:

$$\Delta H = Q - W + P\Delta V \tag{2}$$

There are two types of work in the fuel cell, i.e. electrical work (W_{el}) and expansion work ($P\Delta V$). Electrical work is defined as a function of number of electrons (n_e) per mol of fuel (two for hydrogen), Faraday constant (F = 96485 C/mol), and electrical potential generated between cathode and anode (E), so $W_{el} = n_e F E$, and the total work is shown in Eq. (3),

$$W = W_{el} + P\Delta V = n_e FE + P\Delta V \tag{3}$$

For a reversible process, $Q = T\Delta S$, and from the combination of Eqs. (1) to (3), we obtain Eq. (4).

$$\Delta G = -n_e FE \tag{4}$$

Commonly, Eq. (4) is used at the reference condition, where products and reactants are in their standard states (1 atm and 25 °C). Thus, it is defined the standard electromotive force E_0 = 1.23 V (also named standard reversible potential of the cell), and Eq. (4) is rewritten as:

$$\Delta G_0 = -n_e FE_0 \tag{5}$$

The theoretical or ideal fuel cell efficiency is defined $\eta_{th} = \Delta G_0 / \Delta H_0$, which is equal to 83 %. Another way to evaluate fuel cell performance is by the electrochemical efficiency, which relates electrical work produced with available energy of the fuel.

$$\eta_{el} = \frac{W_{el}}{\Delta G_0} \tag{6}$$

Therefore, the fuel cell efficiency takes account both theoretical and electrochemical efficiencies, as shows Eq. (7), where E_{LHV} is the electrical potential based on fuel low heat value, $E_{LHV} = \Delta H_0 (n_e F)^{-1}$.

$$\eta_{cell} = \eta_{th}\, \eta_{el} = \left(\frac{\Delta G_0}{\Delta H_0}\right)\left(\frac{W_{el}}{\Delta G_0}\right) = \frac{n_e FE}{\Delta H_0} = \frac{E}{E_{LHV}} \tag{7}$$

The hydrogen consumed (N_{H2}) by the fuel cell reaction is proportional to the generated electric current (I), so the fuel energy (W_{H2}) is calculated as:

$$W_{H2} = N_{H2}\Delta G_0 = \left(\frac{I}{n_e F}\right)\left(n_e FE_0\right) = IE_0 \tag{8}$$

The electric power generated by fuel cells is basically product of current and electrical potential, as shows Eq. (9). Application of current produces some losses, such as activation and ohmic, which reduce fuel cell performance and generate heat. Therefore, the thermal load produced in fuel cells can be estimated by Eq. (10), which represents the fuel cell waste heat.

$$q_{el} = IE \tag{9}$$

$$q_{ther} = I\left(E_0 - E\right) \tag{10}$$

The waste heat was assumed to drive an adsorption refrigeration system to produce cooling power (CP). The performance of a refrigeration device can be verified by its COP, which is obtained by Eq. (11).

$$COP = \frac{CP}{q_{ther}} \tag{11}$$

Auxiliary systems consume part of the gross power produced by each device. These consumptions are represented here by power fraction (*PF*) used to drive each auxiliary system. In fuel cell, it was named PF_{cell} and in refrigeration system PF_{ref}.

Therefore, from electric power and cooling capacity delivered by the combined system, and taking account fuel cell efficiency, COP, and power fractions consumed, the system efficiency (η_{sys}) was evaluated with Eq. (12).

$$\eta_{sys} = \frac{\eta_{cell}}{\eta_{th}}\left(1-PF_{cell}\right)+COP\left(1-\frac{\eta_{cell}}{\eta_{th}}\right)\left(1-PF_{ref}\right) \tag{12}$$

The improvement in the hydrogen utilization reached by cogeneration scheme can be obtained with Eq. (13), which is the ration between the efficiency improvement obtained with the cogeneration system and the net fuel cell efficiency.

$$\Delta\eta_{rel} = \frac{\eta_{sys}}{\eta_{cell,net}}-1=\frac{\eta_{sys}}{\eta_{cell}\left(1-PF_{cell}\right)}-1 \tag{13}$$

3. RESULTS AND DISCUSSION

To evaluate the integrated system it was assumed fuel cell auxiliary devices consumed power fraction of 0.2, taking into account the literature (Hosseini et al., 2012; Hussain et al., 2005; Sasmito et al., 2011). The power fraction for the adsorption refrigeration system was estimated by considering the fluid flow pressure drop. From data provided in Tab. 1, and considering pump efficiency of 80 %, the average consumption was 5.2 % or a PF_{ref} of 0.052. Thereby the integrated system efficiency was analyzed as a function of the COP of the adsorption refrigeration and the fuel cell efficiency.

Figure 1 shows the estimated system efficiency considering expected fuel cell efficiency from 40 to 60 % and commercial devices representing the expected COP from 0.46 to 0.67. The region highlighted and named “integrated system” represents the values of system efficiency considering prior COP and fuel cell efficiency ranges. The rectangular region named “commercial devices” represents the range of COP reached by the adsorption chillers available in the market, which are 0.46-0.67 as presented in Tab. 1. It is clear that the higher the COP the higher system efficiency to the point that the best case should be an integrated system consisting of a good adsorption chiller even driven by a fuel cell with low efficiency. Of course this should imply in a lower electric power but higher cooling power. Anyhow for adsorption chillers available in the market the best case will be for fuel cell efficiency of 60 %, in this case representing system efficiencies from 70 to 75 %. Note that the two lines converge to the system efficiency in theory equal to 100 % with chiller COP equal to 1 if auxiliary power neglected, and taking account the auxiliary power the lines converge to system efficiency of 80 % with COP 0.844, as can be seen algebraically solving Eq. (12).

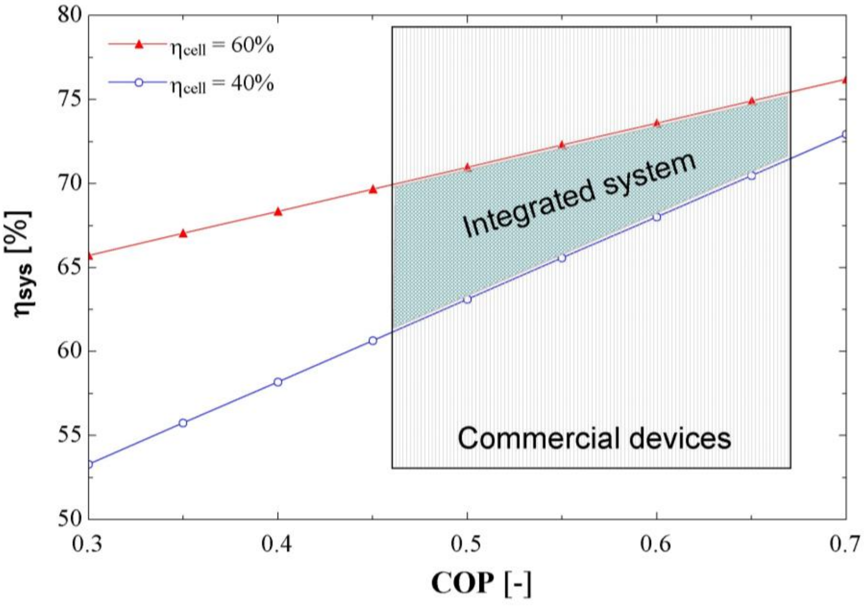

Figure 1. Integrated system efficiency as COP function.

The results show that the proposed integration provides a significant improvement in using the hydrogen energy. Figure 2 presents the relative efficiency increment with the COP. It is observed that with cell efficiency of 60 %, the efficiency increment was between 46 and 57 %, whereas with cell efficiency of 40 %, the efficiency increment was from 91 to 123 %. This feature shows if it is needed higher cooling power, the best choice would be a system with lower fuel cell efficiency. This behavior occurs because when the fuel cell operates with low efficiency, there is a larger amount of waste heat to drive the adsorption chiller and hence, produce higher amount of cooling power.

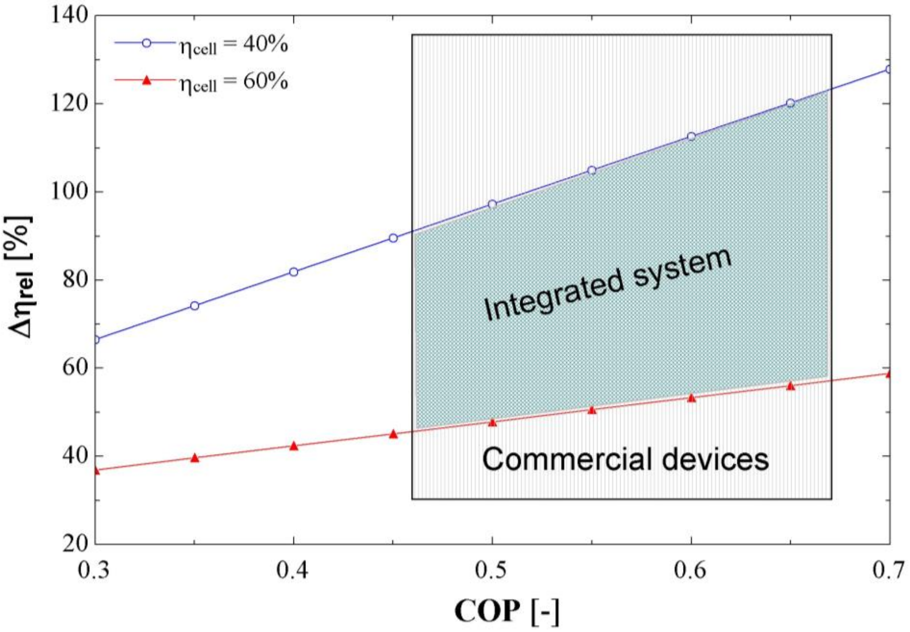

Figure 2. Efficiency relative increase as COP function.

The behavior of the system efficiency was also verified as a function of the fuel cell efficiency, taking into account the range of COP available in the market. Figure 3 shows the system efficiency increase with the improvement of fuel cell efficiency, and also with the improvement of COP. In this figure, one may observe that the system efficiency is more sensitive to the cell efficiency when the adsorption chillers has low COP.

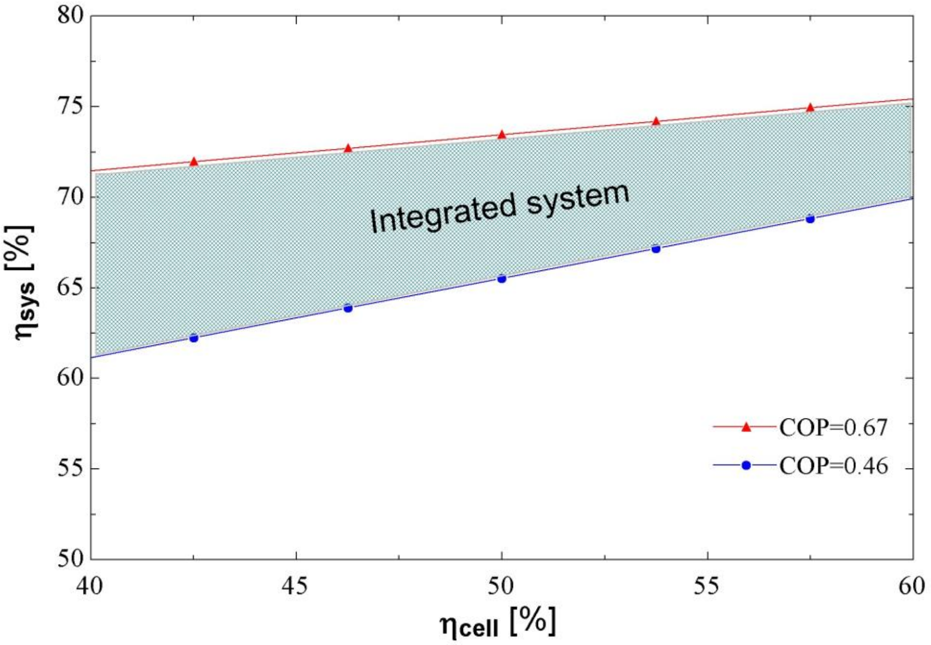

Figure 3. Integrated system efficiency as function of the fuel cell efficiency.

Figure 4 shows the efficiency relative increase as function of fuel cell efficiency, considering the range of COP values also presented. $\Delta\eta_{rel}$ reduces as fuel cell efficiency increases, i. e., higher cell efficiencies has lower influence on the system efficiency increment. In the case of cell efficiency of 40 %, the increment was higher than 100 %, whereas with cell efficiency of 60 %, the efficiency increment was about 50 %.

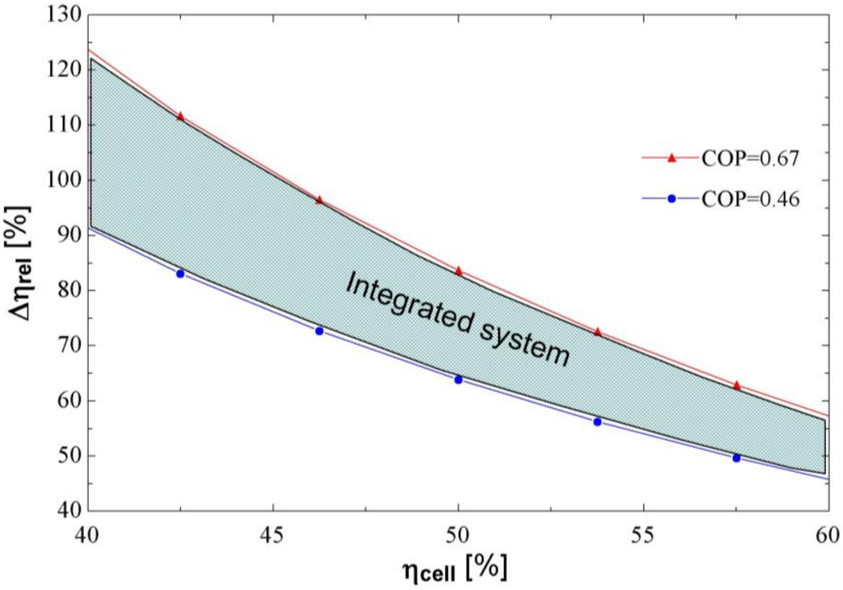

Figure 4. Efficiency relative increase as function of fuel cell efficiency.

4. CONCLUSIONS

Considering the range of PEMFC efficiency and the COP of the adsorption chillers available in the market, the cogeneration system achieved overall efficiencies in the range of 61 to 75 %. Regarding the relative increment of the hydrogen utilization efficiency, it reached up to 123 %. A low efficient fuel cell is more adequate when the main interest is in cooling power, because there is more waste heat available to drive the adsorption chiller. The results are preliminary and they are considered promising. Further studies are necessary to evaluate the operation of the integrated system, taking into account particularities of each device.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

An, S., Kweon, H., Kim, H., Kim, J., Eun, Y., Cho, S., Lee, D., 2009. Cooling apparatus for fuel cell and fuel cell system having the same. US 7485384.

Barbir, F., 2005. PEM fuel cells: theory and practice. Elsevier Academic, Amsterdam, Londres.

Faghri, A., 2005. Micro heat pipe embedded bipolar plate for fuel cell stacks. N° de apliicação US 2005/0026015.

GBU, 2016. NAK 020/70 [WWW Document]. URL http://www.gbunet.de/outgoing/nak-prospect.pdf (acessed 1.20.16).

Hamada, Y., Nakamura, M., Kubota, H., Ochifuji, K., Murase, M., Goto, R., 2004. Field performance of a polymer electrolyte fuel cell for a residential energy system. Renew. Sustain. Energy Rev. 9, 345–362.

HIJC, 2016. ADCM1-060 [WWW Document]. URL http://greenchiller.biz/images/__ADCM1-Vs._HT_SameChilled_Water_Flow.xls (acessed 1.20.16).

Hosseini, M., Shamekhi, A.H., Yazdani, A., 2012. Modeling and Simulation of a PEM Fuel Cell (PEMFC) Used in Vehicles. SAE Tech. Pap. 2012-01-1233.

Hussain, M.M., Baschuk, J.J., Li, X., Dincer, I., 2005. Thermodynamic analysis of a PEM fuel cell power system. Int. J. Therm. Sci. 44, 903–911.

Hwang, J.J., Zou, M.L., Chang, W.R., Su, A., Weng, F.B., Wu, W., 2010. Implementation of a heat recovery unit in a proton exchange membrane fuel cell system. Int. J. Hydrogen Energy 35, 8644–8653.

Inversor, 2016a. LTC10 plus [WWW Document]. URL http://www.invensor.com/en/pdf/InvenSor_Datasheet_LTC10_EN_Web.pdf (acessed 1.20.16).

Inversor, 2016b. LTC10 e plus [WWW Document]. URL http://invensor.info/en/wp-content/uploads/sites/3/2015/05/InvenSor_LTC10_e_plus_Datasheet.pdf (acessed 1.20.16).

Ismail, A.F., Naim, R., Zubir, N.A., 2009. Fuel Cell Technology Review, in: Zaidi, S.M.J., Matsuura, T. (Orgs.), Polymer Membranes for Fuel Cells. Springer US, p. 27–49.

Koji, S., Narihisa, S., Haruichiro, S., Kazuhito, K., Yoshiki, N., 1986. Fuel cell. JP61-161669.

Kordesch, K., Simader, G.R., 1996. Fuel Cells and Their Applications. John Wiley & Sons.

Kothmann, R.E., Cyphers, J.A., 1981. Fuel cell system configurations. US 4276355.

Larminie, J., Dicks, A., 2003. Fuel Cell Systems Explained, 2nd ed. John Wiley & Sons.

Mayecawa, 2016. Adref-Noa Z3515 [WWW Document]. URL http://www.mayekawa.com.au/wordpress/wp-content/uploads/2011/02/AdRef-Noa-Adsorption-Chiller1.pdf (acessed 1.20.16).

Nishiyodo, A.C., 2016. NADAC-050 [WWW Document]. URL http://www.etstudio.it/allegati/adsorbitori.pdf (acessed 1.20.16).

Oh, S.T., Saha, B.B., Kariya, K., Hamamoto, Y., Mori, H., 2013. Fuel cell waste heat powered adsorption cooling systems. Int. J. Air-Conditioning Refrig. 21, 1350010.

Oro, M.V., Bazzo, E., 2015. Flat heat pipes for potential application in fuel cell cooling. Appl. Therm. Eng. 90, 848–857.

Partners, P., 2016. AD3-C-10 [WWW Document]. URL http://www.ppiway.com/sites/default/files/downloads/submittal_ad3-c_metric.pdf (acessed 1.20.16).

Plastics, M., 2016. AQSOA-10kW [WWW Document]. URL http://www.aaamachine.com/products/saveenergy/pdf/Brochure_Adsorption_chiller_AQSOA_10KW_Utype.pdf (acessed 1.20.16).

Rand, D.A.J., Dell, R.M., 2008. Hydrogen Energy: Challenges and Prospects, RSC Energy Series. Royal Society of Chemistry, Cambridge.

Sasmito, A.P., Birgersson, E., Mujumdar, A.S., 2011. Numerical evaluation of various thermal management strategies for polymer electrolyte fuel cell stacks. Int. J. Hydrogen Energy 36, 12991–13007.

Silva, A.P., Galante, R.M., Pelizza, P.R., Bazzo, E., 2012. A combined capillary cooling system for fuel cells. Appl. Therm. Eng. 41, 104–110.

SorTech, A., 2016. ACS 08 [WWW Document]. URL http://www.solarcombiplus.eu/docs/D44_Sortech_v02_English.pdf (acessed 1.20.16).

Tajima, O., Hamada, A., Tanaka, J., Yoshimoto, Y., Miyai, K., Nishizawa, N., Tsutsumi, M., Ikenaga, T., Nakato, K., Hori, K., 1996. Fuel cell using a separate gas cooling method. US 5541015.

Vasiliev, L., Vasiliev Jr., L., 2008. Heat Pipes in Fuel Cell Technology, in: Kakaç, S., Pramuanjaroenkij, A., Vasiliev, L. (Orgs.), Mini-Micro Fuel Cells, NATO Science for Peace and Security Series C: Environmental Security. Springer Netherlands, p. 117–124.

Wang, R.Z., Yu, X., Ge, T.S., Li, T.X., 2013. The present and future of residential refrigeration, power generation and energy storage. Appl. Therm. Eng. 53, 256–270.

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