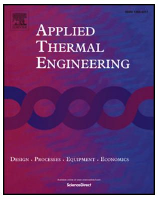
Applied Thermal Engineering 136 (2018) 747–754

Contents lists available at ScienceDirect

Applied Thermal Engineering

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



Research Paper

# An integrated solution for waste heat recovery from fuel cells applied to adsorption systems

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## HIGHLIGHTS

- Analysis of a system composed of a PEM fuel cell and a chemisorption chiller.
- Adsorption chiller energized by heat rejection from fuel cells.
- Thermosyphon as solution to integrate fuel cells and adsorption chillers.
- Thermosyphon for fuel cell controlling and energization of adsorption chillers.
- Fuel cells integrated to adsorption chillers producing electricity and cooling power.

## ARTICLE INFO

*Keywords:*
Fuel cell
Heat recovery
Adsorption refrigeration
Thermosyphon heat reservoir

## ABSTRACT

Fuel cells have been widely studied and proposed as a promising alternative in the automobile industry, distributed generation, and other industrial applications. Therefore, a cogeneration scheme to produce electricity and cooling power is analyzed with the aid of a numeric simulation, considering the possibility of using the heat rejected by a proton exchange membrane fuel cell (PEMFC) to drive a chemisorption chiller. The chiller employed ammonia as refrigerant and NaBr impregnated in expanded graphite as adsorbent. The thermal energy integration between the chemisorption system and the PEMFC was accomplished by a thermosyphon, which acted as a heat reservoir to reduce the temperature drop in the PEMFC stack. Experimental results were used to validate the simulation of the adsorbent behavior, and the PEMFC operation was simulated from a dynamic model available in the literature. The fuel cell stack fueled by hydrogen, the bed length of chiller reactors and the amount of working fluid used in the thermosyphon heat reservoir are considered in the analysis. For fuel cell power outputs in the range of 600–1400 W, cooling powers up to 400 W were found. This increases the useful energy of the hydrogen, with overall efficiencies up to 63%.

## 1. Introduction

Fuel cell (FC) has been widely studied in various applications and it has emerged as a promising alternative in the automotive industry [1], distributed power generation and other industrial applications [2]. This device converts the chemical energy of a given fuel into electrical energy. Proton exchange membrane fuel cell (PEMFC) is one of the types of fuel cells. It uses hydrogen as fuel and oxygen as oxidant, delivering $H_2O$ and heat as byproducts. PEMFC has efficiency around 50% and the energy which is not converted into electricity is converted into low-grade heat, operating between 60 and 80 °C [2]. This feature points to recovery opportunities of the FC waste heat in an integrated system, thereby increasing the fuel energy utilization.

The FC thermal control must be used to avoid membrane damage and to ensure its best performance. Forced convection of air or water commonly has been used to control the FC [3–5]. However, results published elsewhere [6–9] showed this technique can generate high thermal gradients in the FC, which decreases its performance. Alternative techniques for thermal control have been proposed, as the utilization of capillary pumping systems to achieve higher compactness and thermal homogeneity, thus improving its performance [10–15]. A detailed solution was previously reported [15] using flat heat pipes, where a numerical and experimental analysis was presented, as well as a heat transfer model for evaluating the capillary limit, the operating temperature and the required working fluid inventory.

Some works have been presented where waste heat recovery from

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https://doi.org/10.1016/j.applthermaleng.2018.01.081
Received 4 August 2017; Received in revised form 2 December 2017; Accepted 22 January 2018

FCs was used to heat residential water [16,17]. However, in the present work the FC waste heat was used to produce cooling power instead of useful heating power. Regarding the former utilization of waste heat, several studies have been conducted concerning the integration between FCs and sorption chillers. Liu and Leong [18] reported a cogeneration system based on solid oxide fuel cell (SOFC) and zeolite-water adsorption chiller, wherein the chiller was driven from the heat recovered of a post-combustor at 661 °C. Similarly, Yu et al. [19] studied an integrated system based on SOFC, wherein the waste heat at 165 °C was used to drive a double-effect water-LiBr absorption chiller. Chen et al. [20] evaluated the performance of a system composed basically of a PEMFC and a single-effect water-LiBr absorption chiller, wherein the PEMFC operating temperature was set in the range of 85–95 °C and the inlet temperature of the chiller was taken as 5 °C lower than the PEMFC operating temperature. Arsalis [21] proposed an integration of a high-temperature proton exchange membrane fuel cell with a double-effect water-LiBr and a single-effect NH3-water absorption chillers, wherein the waste heat temperature was 160 °C and the chillers were driven at 155 °C. Recently, Chen et al. [22] proposed a system composed of PEMFC, parabolic trough solar collector (PTSC) and double-effect absorption chiller, wherein the cooling water preheated by the PEMFC was further heated in the PTSC to drive the chiller at 165 °C.

Regarding the utilization of solid sorption chillers, Oh et al. [23] compared the theoretical performance of two adsorption chillers driven from waste heat of a PEMFC and also from a SOFC. One of the chillers used silica gel-water as working pair, whereas the other one used activated carbon fiber-ethanol. Regarding the results with the PEMFC, there was an efficiency improvement of 22% using the first chiller and of 15% with the use of the second one, both considering hot water temperature of 65 °C to drive the chillers. As the authors did not address in detail the behavior of the FC system, the analysis was incomplete.

Considering the PEMFC operating temperature, the most suitable type of sorption chillers to recover its waste heat are the solid sorption (adsorption) ones. This is because the adsorption chillers can be driven by heat sources below 70 °C, whereas in the liquid sorption (absorption) chillers the heat source temperature is higher than 70 °C [24]. Differently, from the absorption chillers and FCs, that may operate at steady state, adsorption chillers operate in a transient cycle composed of two distinct periods, where in the first one, the adsorbent is heated in a certain temperature range, while desorbs refrigerant to the condenser. On your turn, in the second period, the adsorbent is cooled in the corresponding temperature range and adsorbs refrigerant from the evaporator. Therefore, to produce cooling power continuously, adsorption chillers should have two reactors containing adsorbent material. While one of the reactors absorbs heat from a source, the other one rejects it to a sink.

From the point of view of heat recovery, the transient characteristic of heat transfer to the adsorbent bed imposes a technological challenge to be solved, once the heat consumed by the adsorption chiller varies with the time. On the other side, the heat coming from steady-state sources remains constant.

In the previously mentioned research with FCs and sorption chillers [18–23], both the FC temperature and heat transfer fluid temperature were assumed to remain constant during the heat recovery. Furthermore, except for the last, the heat transfer fluid temperature used to drive the sorption chillers was considered at least 80 °C.

The present study addresses challenges involving the use of thermal waste heat sources at low temperatures (below 80 °C) to drive an adsorption chiller. It also takes into account the transient characteristic involved in the adsorption chiller operation and its impact in the PEMFC performance, due to the temperature changes along each refrigeration cycle. Another challenge in the combined operation of a PEMFC and an adsorption chiller is the heat transfer fluid leaving the former device needs to have a temperature level sufficiently high to drive the chiller, however without causing any impact on the PEMFC performance. In recent studies [25–27] a composite material of NaBr impregnated in expanded graphite was used in chemisorption chillers driven by temperatures below 80 °C. Therefore, it was analyzed with the aid of a numerical model, a PEMFC cogeneration system employing a chemisorption chiller with NaBr impregnated in expanded graphite as adsorbent and ammonia as refrigerant. The integration between the PEMFC and the chiller was accomplished by a two-phase closed thermosyphon, which not only acted as heat exchanger, but also, as heat reservoir, to minimize the impact of transient behavior of the chemisorption chiller in the FC operation and performance. Therefore, it is addressed the challenge of coupling a steady-state source to a transient-state consumer. The reactors of the adsorption chiller considered in this work were similar to that presented by Kiplagat et al. [26].

## 2. Materials and methods

The proposed system is composed of a PEMFC stack, a chemisorption chiller, and a thermosyphon heat reservoir. The chemisorption chiller consists of two reactors, one condenser, and one evaporator. The chiller is connected to a thermosyphon and a heat sink by closed circuits. The thermosyphon works as a thermal reservoir to manage the heat supplied from the FC stack, alternatively, to the reactors. Water is used as the working fluid. Once the chiller behavior is transient, the inclusion of a thermal reservoir is important to storage all remaining heat supplied by the FC stack. The thermal reservoir is also required in order to minimize the changes in the fluid temperature at the FC inlet. As shown in Fig. 1, on the PEMFC side, water flows in a closed circuit, cooling the PEMFC and transferring heat to the thermosyphon. On the chiller side, also water flows in a closed circuit, removing heat from the thermosyphon to deliver it to the reactors. Gray lines represent circuits concerning the next cycle, where the reactor 1 is cooled while the reactor 2 is heated.

The thermosyphon is shown in Fig. 2. It consists of one cylinder separated into two main parts: the evaporator on the bottom and the condenser on the top. It is designed for working at the vertical position, wherein the working fluid evaporates on the bottom, by receiving heat from the PEMFC cooling circuit, and condenses on the top, where heat is delivered to the adsorption chiller circuit.

A numerical simulation was performed using the software MatLab®, considering the integration of the PEMFC, the thermosyphon, and the chemisorption chiller. The corresponding equations are presented in the following section.

## 3. Mathematical model

The mathematical model is proposed taking into account the whole system, consisting of an FC stack, a chemisorption chiller, and a thermosyphon. The following assumptions are here considered:

(i) Adiabatic walls in the heat exchangers;
(ii) Negligible kinetic and potential energy changes;
(iii) Negligible pressure drop along the closed circuits connecting the FC to the thermosyphon and also from the thermosyphon to the chiller;
(iv) Negligible any pumping work required in the closed circuits;

### 3.1. Chemisorption chiller

The chemisorption chiller is a shell and tube heat exchanger. The adsorbent is placed around the tubes, in the shell, and the working fluid flows inside the tubes to supply or to remove heat from the adsorbent, depending on the period of the adsorption refrigeration cycle. Annular fins were placed along the tubes to enhance the heat transfer. The adsorbent bed is composed of expanded graphite impregnated with NaBr. The refrigerant is ammonia and the metal parts (shell, tubes, and fins) were made of steel. The chemical reaction between the adsorbate ($NH_3$)