Journal of Power Sources 257 (2014) 21–26

Contents lists available at ScienceDirect

Journal of Power Sources

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

Solid oxide fuel cell application in district cooling

Ayman Al-Qattan [a,*], Abdelrahman ElSherbini [b], Kholoud Al-Ajmi [a]

[a] Kuwait Institute for Scientific Research, Energy and Building Research Center, Innovative Renewable Program, P.O. Box 24885, Safat 13109, Kuwait
[b] United Technologies Research Center, 411 Silver Lane, East Hartford, CT 06108, USA

HIGHLIGHTS

- A cogeneration system based on solid oxide fuel cells is proposed for cooling and power.
- Combining district cooling with SOFC improves the cooling-to-fuel efficiency significantly.
- Thermal storage reduces capital cost by reducing the SOFC system size.
- The proposed system improves efficiency by up to 346%, and reduces CO_2 by 54%.
- The total cost to produce one unit of cooling is 53% less than current practice.

ARTICLE INFO

Article history:
Received 15 September 2013
Received in revised form
28 December 2013
Accepted 3 January 2014
Available online 31 January 2014

Keywords:
Cogeneration
Solid oxide fuel cell
District cooling
Thermal storage
Air-conditioning
Coefficient of performance

ABSTRACT

This paper presents analysis of the performance of a combined cooling and power (CCP) system for district cooling. The cogeneration system is designed to provide cooling for a low-rise residential district of 27,300 RT (96 MWc). A solid oxide fuel cell (SOFC) generates electric power to operate chillers, and the exhaust fuel and heat from the SOFC run gas turbines and absorption chillers. Thermal energy storage is utilized to reduce system capacity. Part-load operation strategies target maximizing energy efficiency. The operation of the system is compared through an hourly simulation to that of packaged air-conditioning units typically used to cool homes. The CCP system with the district cooling arrangement improves the cooling-to-fuel efficiency by 346%. The peak power requirement is reduced by 57% (24 MW) and the total fuel energy is reduced by 54% (750 TJ y^{-1}). The system cuts annual carbon dioxide emissions to less than half and reduces other harmful emissions. A cost analysis of the system components and operation resulted in a 53% reduction in the cost per ton-hour of cooling over traditional systems.

1. Introduction

In hot climates, a considerable share of end-use energy is consumed to provide comfort cooling. For example, air-conditioning (A/C) in Kuwait accounts for nearly 70% of the electricity demand during peak hours and 45% of the annual consumption. For the residential sector, the shares of A/C reach 85% of peak power and 55% of annual consumption. In addition to the high costs of power generation and distribution, high rates of greenhouse gases and harmful emissions are released. This article analyzes a high-efficiency low-emission system for combined cooling and power (CCP) for a district cooling application.

Several studies on cogeneration had focused on the performance of systems with microturbines. Ho et al. [1] experimentally evaluated the performance of a cogeneration system designed to provide electrical power and space cooling to a laboratory. The system's technical configuration included a Capstone microturbine, a 10-RT (35 kW) Yazaki absorption chiller, two heat exchangers, a propane fuel supply system, and a cooling tower. The results from the performance tests showed that the microturbine electrical efficiency was 21% at near full load of 24 kW whilst the chiller operated with coefficient of performance (COP) ranging from 0.5 to 0.58, depending on the electrical output. The overall system efficiency ranged from 40% to 49%.

Another interesting investigation, Kong et al. [2], experimentally studied a combined cooling, heating and power (CCHP) microsystem consisting of a small-scale generator set driven by a gas engine and a new small-scale silica–water adsorption chiller. The system can supply 12 kW electrical power, 28 kW heating power, or 9 kW refrigeration power simultaneously with overall electrical and thermal efficiency over 70%.

* Corresponding author. Tel.: +965 24989258; fax: +965 24989139.
E-mail addresses: aqattan@kisr.edu.kw, aqattan@gmail.com (A. Al-Qattan).

0378-7753/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jpowsour.2014.01.099

Moya et al. [3] presented a detailed experimental analysis of an advanced trigeneration system designed to operate with a natural gas microturbine, air-cooled absorption chiller that uses ammonia or water, and a heat recovery boiler. In their work, the micro gas turbine provided up to 28 kW of electrical power and 60 kW of heat to derive the absorption chiller with 17 kW nominal cooling capacity. Detailed analysis results revealed that the COP and capacity of the chiller were influenced by the indirect effect of the ambient temperature on the micro gas turbine, and its direct effect on the condenser and the absorber of the chiller. At high ambient temperatures over 40 °C, the chiller capacity is reduced by 0.5 kW $^{\circ}C^{-1}$.

Power generation using fuel cells is a promising alternative to traditional turbines. The main advantages of fuel cells include high efficiency, low emissions, quietness and modularity. Such features are well suited for distributed generation applications, where the efficiency can be further enhanced by utilizing the released heat. In hot regions, that extra energy is needed for cooling.

Silveira et al. [4] and Leal and Silveira [5] analyzed the use of fuel-cell cogeneration systems for cooling utilizing molten carbonate fuel cells (MCFC). The results manifested the potential of such technology for cooling. Burer et al. [6] investigated the optimization of a multicomponent system for district heating, cooling, and power generation. The complex system integrated a combined fuel-cell gas-turbine cycle with compression and absorption chillers and a heat pump. The system was optimized for cost and carbon dioxide (CO_2) emissions.

In an assessment study, Dorer et al. [7] evaluated the performance of micro-cogeneration systems for residential buildings. The study assessed two types of natural gas driven fuel cell systems (SOFC and polymer electrolyte membrane fuel cell (PEMFC)). The results showed that the fuel-cells-based systems achieved reductions of 6–48% in the primary energy demand of buildings.

Zink et al. [8] analyzed an SOFC system with absorption cooling and heating for buildings. They reported a total system efficiency of up to 95%. Darwish [9] presented a case study for using phosphoric acid fuel cell (PAFC) systems to produce cooling. The analysis suggested that FC-based A/C systems would result in significant savings if target system costs are reached.

In an earlier work [10], the authors introduced an integrated cogeneration system based on SOFC, which was designed to provide cooling and power. In another study, Clausse et al. [11] explored the theoretical performance of a natural gas fuel cell system with adsorption-based air conditioning. The researchers analyzed the performance for three different adsorption pairs: activated carbon and methanol, silica gel and water, and zeolite and water. They found that the zeolite and water pair showed the best cooling performance.

Calise et al. [12] presented a dynamic model combining solar heating and cooling technologies with PEMFCs. The system included evacuated solar collectors, single-stage lithium bromide (LiBr) absorption chiller and PEMFC. Their model showed that the maximum operating temperature of the PEMFC (80 °C) was too low to derive the absorption chiller at high COP. They suggested using high temperature fuel cells (SOFC), combined with parabolic trough collectors and double stage absorption chillers.

In a recent study, Guizzi et al. [13] analyzed the annual energy consumption, operating cost and CO_2 emissions of a distributed generation plant based on a PEMFC with a vapor compression chiller. The results showed that the annual energy cost was reduced by 47% when the thermal energy from the system was usefully recovered. An absorption chiller was not used because most of the heat was recovered at low temperatures. In that study, the authors did not consider high temperature fuel cells, which could solve this problem and provide even more energy savings. Takezawa et al. [14] studied a high temperature SOFC-gas-turbine system and analyzed the use of absorption chillers to recover the exhaust heat. They found that a double effect absorption chiller would produce less than 10% additional capacity than a single effect chiller.

The goal of the present work is to evaluate the performance of a fuel cell air conditioning (FCAC) system for a large district cooling application at various loading scenarios. The system combines high temperature fuel cells with gas turbines and various cooling technologies to maximize energy efficiency. The paper also assesses the cost effectiveness of the system for such an application.

2. System description

The integrated FCAC system targets improvements in energy efficiency at the generation, distribution and utilization stages. It consists of an SOFC, a gas turbine, absorption and compression chillers and a thermal storage tank, as shown in Fig. 1. The SOFC converts fuel energy into electricity. The exhaust heat is used to generate more electricity and to drive absorption chillers. The generated electricity runs vapor compression chillers. The integrated system primarily supplies chilled water to a district cooling network, which delivers cooling to individual homes and buildings. A thermal energy storage tank is utilized to reduce the required cooling capacity of the system. This FCAC system is designed to provide sufficient cooling for the district it serves during peak summer. For periods of lower cooling demand, the system will feed extra electricity to the grid.

The FCAC system can be divided into a power generation subsystem that includes the SOFC and the gas turbine, and a cooling subsystem that includes the absorption and compression chillers, their auxiliaries and the thermal storage tank. The key parameters for the power generation subsystem and the cooling subsystem are summarized in Tables 1 and 2, respectively. For this analysis, the SOFC was selected to have a tubular design, which allows for pressurized operation (3 bar). The cell operating temperature is 1000 °C. For the cooling subsystem, the temperature differential between the leaving and returning chilled water was slightly higher than typical. This is a common practice in district cooling applications to reduce the power needed to pump chilled water. Also, the cooling tower water temperature was high, due to the hot climate of the region.

3. Analysis

3.1. System model

A model for the power generation subsystem was developed. The model calculates the fuel cell voltage and current density, power produced, the composition and temperature of the mixture at

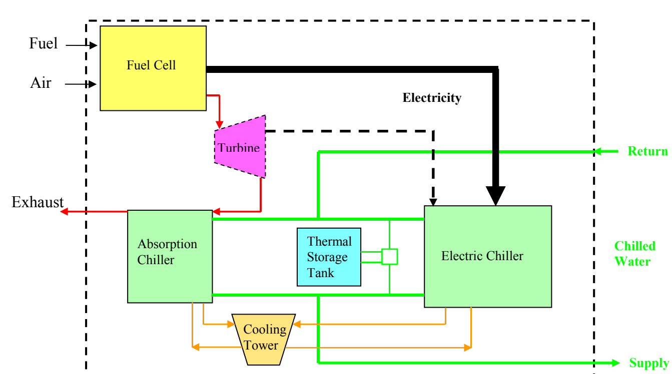

Fig. 1. The proposed integrated fuel cell air conditioning (FCAC) system.