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Thermodynamic analyses of an integrated PEMFC–TEARS-geothermal system for sustainable buildings

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ABSTRACT

In this paper we undertake a comprehensive study to meet the building heating/cooling and power demand through a sustainable operation. We integrated polymer electrolyte membrane fuel cell (PEMFC) system and triple effect absorption refrigeration system (TEARS) for space cooling/heating and water heating applications in buildings. The analysis is carried out to observe the effects of different operating conditions on the efficiency of the fuel cell, output of the fuel cell and TEARS, and the utilization factor of the system. It is found that the efficiency, the utilization factor, and change in temperature of hot water increases from 36% to 48.8%, 49% to 86%, and 14 K to 23 K, respectively when the temperature of the cell is increased for different cooling loads and membrane thicknesses. In addition, the increase in membrane thickness affected the efficiency, the utilization factor, and change in temperature of hot water in a negative way and they were found to be decreasing from 47.3% to 42%, 85% to 49%, and 23 K to 12 K, respectively for different cooling loads. The water supplied to the house is obtained from a geothermal water source which makes the system more sustainable.

1. Introduction

Energy plays a base role in our fast moving life. We require energy for almost everything we do in our life. Energy is required from comfort in house to comfort out on roads. This ever growing demand of energy has become a major concern for not only developing countries but also for developed countries. Buildings in residential, commercial and even in industrial sectors play a critical role due to their high energy demand which comes out as a significant amount (consuming up to 40–45% of the total energy use overall and may reach up to 60–65% particularly in Gulf countries, like UAE). That is why it is very crucial to provide power, heat and cooling by sustainable energy systems in order to really make buildings sustainable.

In order to meet the future energy demand it has become very important to come up with a solution which is reliable, sustainable, efficient, and eco-friendly. By sustainable we mean that it should be able to cater almost all the energy needs of a place where it is being utilized if not all. In addition, worldwide the majority of energy is being consumed for running the refrigeration system which provides cooling, heating or hot water to the supplied space. The refrigeration systems used at present consume high amount of energy due to the compression process. Therefore, in this paper we have studied the integrated PEM fuel cell with absorption system to provide cooling and hot water to a medium size house, and the water used in the system is obtained from a geothermal water source so a house can be made as sustainable as possible.

In recent times PEM fuel cells have received great attention from many researchers and government organizations around the world. It is believed that PEM fuel cell will be able to solve our problem of high energy demand in an effective, efficient, and eco-friendly manner. In the last 10–15 years great attention has been focused on the effort to scale-down the fuel cell system to provide an alternative to replace batteries for portable applications [1]. PEM fuel cells have the capability of catering the overall demand of any country. The introductions of fuel cell systems into the power generation market will not only supply clean decentralized power to users, but it will help to reduce emissions and dependence on primary energy sources, which is of critical importance particularly for the industrialized countries [2]. Fuel cells are an emerging technology with applications in transportation, stationary and portable power generation, with outputs ranging from mW to MW [2]. Another benefit of using PEM fuel cell is that they are highly efficient as compared to present power generating sources which depends on fossil fuels. They potentially may have a high efficiency, theoretically 83% but in practice around 40%, with hydrogen as fuel around 50% [3]. Also, the byproduct of PEM fuel cell is water and steam which is another

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Nomenclature

a	surface area of PEMFC, m^2
COP	coefficient of performance
$\dot{E}$	rate of energy, kW
$\dot{E}x$	rate of exergy, kW
F	Faraday's constant (96,485 C mol^{-1})
h	specific enthalpy, kJ kg^{-1}
i	current density (A cm^{-2})
i_0	exchange current density (A cm^{-2})
i_{max}	limiting current density (A cm^{-2})
$\dot{m}$	mass flow rate, kg s^{-1}
n	number of electrons involved
$\dot{n}$	molar flow rate, mol s^{-1}
$\dot{Q}$	heat transfer rate, kW
P	PEM fuel cell pressure
r	ratio
R	universal gas constant (8.314 J mol^{-1} K^{-1})
T	temperature, K
t_{mem}	membrane thickness (cm)
$\dot{W}$	work rate, kW
x_A	anode dry gas mole fraction
x_C	cathode dry gas mole fraction
x_{H_2}	hydrogen mole fraction
x_{O_2}	oxygen mole fraction

Greek letters

α_A	anode transfer coefficient
α_C	cathode transfer coefficient
β_1, β_2	concentration of overvoltage constants
λ_{mem}	membrane water content
ε	utilization factor
η	efficiency
ξ_A	anode stoichiometry
ξ_C	cathode stoichiometry
ΔT	change in temperature

Subscripts

A	anode
C	cathode
F	fuel
FC	fuel cell
LHX	low temperature heat exchanger
MHX	medium temperature heat exchanger
mem	membrane
O	ambient or reference condition
req	required
sat	saturation
1, . . ., 28	state numbers

benefit over conventional systems which emits green house gasses and harms our environment. When hydrogen is used as fuel, the fuel cells have no emissions other than water [3].

On the other hand adsorption and absorption systems are being looked at as a promising source of replacing conventional vapor-compression refrigeration systems. The major benefit of adsorption and absorption systems is that they omit the use of compressors which are the major energy eating sources in conventional systems. Also, it is very easy to integrate adsorption and absorption systems with the renewable/alternative energy sources because of their lower energy demand. Reasonable amount of work has been done on adsorption systems such as by Gadalla [4]. In recent times absorption systems have attracted many researchers due to its capability of having high COP at low operating cost. The energy need especially for food refrigeration applications is huge and requires potential solutions through renewable/alternative sources such as solar. Absorption refrigeration systems appear to be a key solution to meet the energy requirement [5]. There are many works being carried out in order to study the performance of single effect and double effect systems by researchers [6–8]. There are rarely any studies being carried out in the field of triple effect absorption systems. Triple effect absorption systems are believed to improve the COP of the absorption systems by 30% over double effect absorption systems [9]. Some researchers such as [10,11] studied TEARS integrated with renewable/alternative energy sources. These researchers found that integrated systems studied provide an attractive efficient and eco-friendly solution to the recent energy crisis.

Geothermal energy is the thermal energy which is available for free inside earth's surface. Geothermal energy can be used to generate electricity using binary systems and can be used to provide direct heating and cooling for buildings and industries. The usage of geothermal energy for producing power or for direct use depends on the temperature of the ground water. High-temperature geothermal resources above 150 °C are generally used for power generation. Moderate- (between 90 and 150 °C) and low-temperature (below 90 °C) geothermal resources are best suited for direct uses such as space and process heating, cooling, aquaculture, and fish farming [12]. In this era, when need of energy is growing day by day, and the major energy provider fossil fuels are depleting at a high rate, the use of renewable/alternative energies come into play. The uses of renewable/alternative energies are expected to grow as the concern over environmental problems caused by fossil fuel systems become more transparent. Geothermal energy appears to be a potential solution where it is available to some of the current energy and environmental problems, and a key resource for making society more sustainable [13]. Also, the advantages which give geothermal energy an upper hand is that they are safe, simple, flexible, easily adaptable, and can be integrated with any system with ease. Use of high temperature geothermal source for power production is an economical, environmental friendly and sustainable solution to the fossil fuels as studied by researchers [14–17]. Moreover, geothermal resources having low or moderate temperatures are not suitable for power production, as they are not sufficient enough to produce power with good efficiency. However, these low and moderate temperature geothermal resources provide an excellent alternative to fossil fuels for providing heating and cooling by using them directly in the absorption systems. However, low or moderate temperature geothermal resources are more effective when used directly than when converted to electricity since the direct use of geothermal heat in such processes as heating and cooling can replace the burning of fossil fuels from which electricity can be generated much more efficiently [18].

There are works being carried out to integrate renewable/alternative energy sources with the refrigeration systems in order to make them efficient, eco-friendly and sustainable. The achievement of sustainability in the building sector necessitates a tremendous effort to reduce energy demand, boost energy efficiency and increase the share of renewable energy sources [19]. Most of this work has concentrated on integrating solar energy with absorption system. Solar or waste heat driven absorption cooling plants can provide summer comfort conditions in buildings at low primary energy consumption [20]. However, solar energy on its own cannot be looked at as the sustainable source because of its low efficiency and dependence on the sun. Besides the grid-connected photovoltaic (PV) system, another timely example of the distributed residential energy supply technology is small-scale combined heat and power (micro CHP) generation, with a maximum electrical output capacity of roughly between 1 kW and 10 kW