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Experimental based energy performance analysis and life cycle assessment for solar absorption cooling system at University of Californian, Merced

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ABSTRACT

Traditional air conditioning and heating systems in buildings are fossil fuel based energy systems, which take the main responsible for the carbon emissions. In contrast, using solar energy for air conditioning becomes one of the promising approaches to reduce energy consumptions and negative environmental impacts from buildings. University of California, Merced built a test facility to investigate the technology: solar cooling. The solar system has 54 m^2 external compound parabolic concentrator (XCPC) solar collectors to drive a 23 kW double-effect absorption chiller. This paper first provides the detailed energy performance analysis of the experiments conducted in August, 2012. The data collected from the experiments shows that the system could provide adequate cooling for a test facility between 11AM to 5PM in both sunny and cloudy days. The daily average collector efficiency is at the range of 36% to 39%. The average coefficient of performance (COP) of the LiBr absorption chiller is between 0.91 and 1.02 with an average of 1.0, and the daily solar COP is approximately at 0.374.

In addition to the experimental investigation, a detailed life cycle economic and environmental assessment was also performed by comparing the solar systems to the conventional systems in two types of office buildings at three locations at California. Two different solar cooling system configurations were considered: (i) configuration 1 sizes the area of solar collectors and absorption chiller to meet the peak cooling demand, and uses natural gas as the only backup energy source; (ii) configuration 2 sizes the area of solar collectors and absorption chiller to meet half of the peak cooling demand, and uses natural gas as the backup energy source for the absorption chiller, while incorporates an electrical vapor compression chiller to meet the rest half of peak cooling demand. The annual performance predicts that the systems can achieve the annual solar fraction around 55–68%. And the configuration 2 achieves better life cycle economic and environmental performance than the configuration 1. Specifically, the configuration 2 can achieve lower present worth cost during the entire life span than the conventional systems. And both configuration 1 and 2 can reduce the life time carbon footprint by 35–70%.

1. Introduction

According to 2010 DOE Building Energy Data Book, buildings are responsible for 41% of the primary energy use, and 38% of the carbon dioxide emissions in the United States [1]. Fossil fuel is far from limitless and is responsible for carbon emissions. This realization becomes the main driving force to investigate renewable energy systems, not only for large-scale energy production, but also for stand-alone systems [2]. The coincidence of the high solar radiation and peak cooling demands of buildings in summer makes solar cooling a promising alternative to conventional electrical driven

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Nomenclature

η	solar collector efficiency
Q_{sc}	solar energy received by the solar collectors (kW)
Q_{solar}	solar energy available (kW)
$\dot{m}$	mass flow rate (kg/s)
C_p	specific heat (kJ/kg-K)
$T_{sc,out}$	outlet temperature of solar collection loop (°C)
$T_{sc,in}$	inlet temperate of solar collection loop (°C)
I_{solar}	solar insolation (W/m^2)
A_{col}	aperture area of solar collectors (m^2)
T_{amb}	ambient air temperature (°C)
a_0	optical efficient used in the solar collector efficiency equation
a_1	loss coefficient used in the solar collector efficiency equation
a_2	loss coefficient used in the solar collector efficiency equation
Q_{oil}	oil power (kW)
Q_c	cooling power (kW)
η_{col}	collector efficiency
$\dot{m}_{oil}$	mass flow rate of the heat transfer oil (kg/s)
$C_{p,oil}$	specific heat of the heat transfer oil (kJ/kg-K)
ΔT_{col}	hot oil temperature difference across the solar collectors (°C)
$\dot{m}_c$	mass flow rate of the chilled water (kg/s)
$C_{p,c}$	specific heat of the chilled water (kJ/kg-K)
ΔT_c	chilled water temperature difference across the chiller (°C)
PWC	present worth cost
IC	initial cost, sum of purchase cost and the installation cost
C_i	the capacity of system component i
MC_{annual}	annual based maintenance cost
OC_{annual}	annual based operational cost
N	life span
d	discount rate
FIR	fuel inflation rate
R_{PWC}	the ratio of the present worth cost of a SACH system to that of a conventional HVAC system
PWC_{SACH}	present worth cost of the SACH system
$PWC_{conv.}$	present worth cost of the conventional heating and cooling system
R_{LCCO_2}	the ratio of the life cycle CO$_2$ emissions of the SACH system to that of a conventional HVAC system
$LCCO_{2,SACH}$	the life cycle CO$_2$ emissions of the SACH system
$LCCO_{2,conv.}$	the life cycle CO$_2$ emissions of the conventional system

cooling systems [3,4]. Furthermore, considering that 18% of the primary energy in the building sector is consumed by the space cooling [1] in the USA, tremendous energy can be saved if solar cooling could replace the conventional fossil-fuel based cooling systems in the buildings.

In a solar cooling system, solar thermal energy could be used in absorption cycles [5,6], adsorption cycles [7,8], desiccant cycles [9–11], and solar-mechanical processes for building cooling [12–19], and the most popular one is based on absorption cycle [15–18]. Solar absorption cooling system uses the solar collectors providing thermal energy for an absorption chiller to produce chilled water. Currently, there are single- and double-effect absorption chillers available on the market. The single-effect absorption cycle typically has a rated Coefficient of Performance (COP) at 0.7 when the heat source temperature for the desorber of the absorption chiller is at the range of 85 to 95 °C. The double-effect absorption cycle has COP at 1.2 when the heat source temperature is around 155–165 °C. Flat-plate and evacuated-tube solar collectors are typically used to drive the single-effect absorption cycle, and concentrated solar collectors like compound parabolic concentrators (CPC) and parabolic trough solar concentrators with tracking devices are able to drive the double-effect absorption cycle.

Solar cooling systems have lots of potentials, but they now are less competitive to conventional cooling systems due to the discontinuity of generation, highly dependence on the climate, and relatively high initial and maintenance costs [17]. The system performance is influenced by both predictable factors like characteristics of collector and unpredictable factors such as weather and building types [20]. Computational simulation of SACH systems is typically used to evaluate system performance [6,21–27]. Simulation studies are able to provide understanding of the operation of the entire system and to assist in optimizing system [29–33]. As one of the renewable energy technologies, a solar cooling system is usually not only evaluated at the energy and economic aspects [15,17,27,34–38], but also environmental aspect [24,26,39–41]. Furthermore, to reveal the economic and environmental benefits in the entire life span, life cycle cost and life cycle assessment (LCA) are useful methodologies to evaluate the performance of solar systems [33,39,42–57], however, very few LCA studies could be found on the solar absorption cooling systems [33,39,55,56]. Besides, most studies conducted are based on European scenarios, which may not be suitable for other places since life cycle inventory data is highly dependent on geographic locations.

Although using simulation to evaluate system performance is faster and cheaper than conducting experiments, the results from simulations will be useful only when the simulations are validated by experimental data [58]. Additionally, some input parameters such as the weather information and building thermal loads, used in simulations [59] cannot be accurately modeled in simulations because the estimation of those parameters is full of uncertainties. To date, most installations of solar cooling systems are at experimental and demonstration level [16]. Among them, most of them are dedicated to office buildings; some of them are installed for labs, education centers, and factories; and the rest are for diversity such as hotels, hospitals, sports centers, etc. [60,61]. Most of the projects utilized single-effect absorption cooling [62–69], and a few double-effect solar absorption cooling systems are installed. Bermejo [70] reported the experiment results for a solar assisted double-effect absorption cooling plant located in Seville, Spain. The system is composed of a 174 kW double-effect absorption chiller, powered by 352 m^2 linear concentrating Fresnel collectors. The daily average Fresnel collector efficiency is between 35% and 40%. The absorption chiller operated with a daily average COP of 1.1–1.25, and the solar cooling ratio is 44%. Qu [71] installed a double-effect solar absorption cooling and heating system in Carnegie Mellon University at United States. This cooling and heating system incorporates 52 m^2 linear parabolic trough solar collectors (PTSC) and a 16 kW double-effect absorption chiller. The experiment results showed that this system can provide 15% cooling and 4% heating for the building space. The cost of the system was about $2800/kW nominal cooling power, including installation and initial cost for equipment. Duff [72] introduced a solar absorption cooling system by using integrated compound parabolic concentrator (CPC) to drive a 70 kW double-effect absorption chiller in Sacramento, California. The collectors can provide the operating temperature in the range of 90–130 °C. The daily collector efficiency is about 40–50%, and the daily chiller COP is about 1.1. Hewett [73] discussed the technical and economic performances of a solar cooling project located in Arizona. This project included 1245 m^2 PTSC and a 560 kW double-effect absorption chiller. This project has been operated for nearly 14 years since 1979. Hewett concluded