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Energy analyses of an integrated solar powered heating and cooling systems in UAE

Fadi A. Ghaith*, Rasha Abusitta

School of Engineering and Physical Sciences, Heriot-Watt University, Dubai 294345, United Arab Emirates

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ABSTRACT

This paper addresses the viability of using the integrated Solar Heating Cooling (SHC) systems in residential buildings in UAE, by studying the thermal performance and potential energy savings, in addition to the economical and environmental aspects such as payback period and reduction in CO_2 emissions. This work involves integration of the absorption chiller with solar thermal collectors to provide a continuous cooling. In the absence of sun, the bio-mass heater is used as an auxiliary heating source.

A comprehensive mathematical thermal model was developed to represent the fully integrated system, which was implemented to determine the useful energy for two selected building configurations based in UAE; fully solar cooling powered one-floor office building and hybrid four-floor residential building at different percentages of solar penetration. The obtained results for the fully solar powered system, showed that about 159 kWh and 126 ton/year savings were achieved in the Annual Energy Consumption (AEC) and CO_2 emissions, respectively. Based on the performed numerical studies on the integrated SHC system of the residential building, the maximum solar penetration of 20% was found to be optimum as it reduced AEC by 176 kWh and cut off CO_2 emissions by 140 ton/year with a payback period of 4 years.

1. Introduction

Electricity consumption in UAE is recorded to be 11,044 kWh per capita in 2010 [1], making it one of the greatest energy consumption globally with carbon emissions per capita two times higher than the developed countries and the world annual average emission [2]. This is due to urbanization, high economic and population growth. There is an annual increase of about 10% in electricity demand and is expected to reach a capacity of 60 GWe by 2015 [3]. The household sector is the leading sector in energy usage globally. In UAE, residential sector is the major electricity consumer with 33% of total electricity consumption. Surprisingly, energy consumption in UAE for HVAC and Domestic Hot Water (DHW) is around 55% of the total energy consumption, residentially. Also global warming can increase the energy demand for cooling in residential buildings existed in UAE by 23.5%, which in return will contribute to higher level of CO_2 and Greenhouse Gases (GHG) emissions by 5.4% in the next decades [4]. The reasons behind high electricity demand in domestic sectors in UAE are due to the inevitable use of air-conditioning. Precisely, the power demand in summer a way larger than in winter, because it is linked with the increasing demand for cooling as a result of the climatic conditions that are considered crucial in summer days for about six continuous months in UAE. The importance of integrated SHC systems became significant because of the increased demand for energy conservation and the increased cost of fossil fuels coupled with the increase in environmental awareness related to GHG emissions and global warming. Therefore, any saving in cooling load demand in residential buildings is considered a very important measure in reducing energy consumption [5]. Mittal et al. [6] showed that LiBr–H_2O is considered to be more appropriate among the other working solutions. They showed that the main key parameter in the designing for solar powered Absorption Cooling System (ACS) is to determine accurately the generator inlet temperature of the chiller. Also it was found that double effect absorption chiller can obtain higher COP but it requires high operating temperatures more than 120 °C, which can still be applicable in UAE. Hang et al. [7] investigated an efficient and effective multi-objective optimization method for integrated Solar Absorption Cooling and Heating (SACH) systems, which use solar energy to provide water heating, space cooling and heating. The system configurations were identified in order to enhance the economic, energy, and environmental aspects. The proposed method which was applied to medium sized office buildings in the United States involves Central Composite Design (CCD), regression analysis, and multi-objective optimization. Central composite design is used to select the significant experimental data generated by energy system simulation and life cycle analysis.

* Corresponding author. Tel.: +971 4 4358713; fax: +971 4 4477344.
E-mail addresses: f.ghaith@hw.ac.uk (F.A. Ghaith), mecheng.rasha@yahoo.com (R. Abusitta).

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The obtained results suggested that the proposed approach could provide a systematic mechanism to optimally design SACH systems. The overall performance of an integrated solar absorption cooling system located in a sub-tropical region was investigated by Darkwa et al. [8]. The performed analysis showed an operational efficiency of 61% for the Evacuated Tube Collectors (ETC) at a mean differential temperature of 51 °C. The absorption chiller achieved a satisfactory value of coefficient of performance (COP) reaching 0.69 as compared with the manufacturer's rating of 0.7. The obtained findings concluded that the system has proved its potential as a viable cooling technology for application in buildings. Supplementary heat source such as gas or bio-mass heating system is recommended to be incorporated into solar absorption cooling systems to maintain appropriate hot water supply during low radiation. Chemisana et al. [9] used high efficient solar concentrator systems with temperatures around 150 °C integrated with two stage absorption chillers. They compared two types of cooling systems for a three-floor building type: (i) conventional system which consists of ETC feeding a single-effect absorption chiller. (ii) Fresnel reflective solar concentrating system installed and integrated with a double-effect absorption chiller. The obtained results showed a dominant saving in the solar collectors' area in the concentrating system compared with the standard solar thermal installation. On the other hand, it was shown that the solar concentrating system needs a large aperture area with lower rejected heat in the double-effect chiller, indicating that the investment and operation costs of the solar concentrating cooling system can be reduced significantly. A mini type solar absorption cooling system was designed and installed by Yin et al. [10] at Shanghai University. Their main findings were represented by achieving a cooling capacity of 4.6 kW and COP of 0.31 during 9 h of continuous operation. Under similar weather conditions, the cooling output by means of radiant cooling panels increased by 23.5% adjoined with 43.5% energy savings when compared with the conventional operation mode of fan coils.

The performance of solar cooling systems with building-integrated solar collectors was simulated by Fong et al. [11]. The proposed system was compared using two types of solar collectors based on weather data in Hong-Kong: Flat Plate Collectors (FPC) integrated with absorption system and the PV panels for DC-driven vapor compression refrigeration with conventional system installed on the roof. According to this study, the use of BI solar cooling systems should be restricted only to situations where the roof availability was limited or insufficient when implemented in sub tropical regions like Hong Kong. Al-Alili et al. [12] used TRANSYS to study the impact of varying some design parameters on the performance of a solar powered ACS in Abu Dhabi such as the mass flow rate, collector area, the volume of storage tanks and tilt angle. His results showed that the proposed solar ACS fitted with ETC reduced the electricity consumption by 47% compared to conventional systems, which is a significant amount of saving under the same cooling load. Same researchers expanded their work to optimize solar powered absorption cycle in UAE, in order to find more cost effective and best alternative to conventional systems. Total cost analysis were generated using single objective optimization algorithms together with simulation by using Pareto curve [13]. Alternatively, solving mathematical models representing integrated SHC systems can be useful approach governed by generic equations based on the principles of heat transfer, energy and thermodynamics. The most significant variable in the optimization of SHC are the collector area and the optimal size of the storage tank; since it is proportionally related to the operating and initial costs. It was shown that the substitution of conventional A/C chiller by solar powered system which consists basically of parabolic thermal collectors and high COP double stage LiBr–H_2O absorption chiller, in addition to replace conventional gas heaters by biomass-fired heaters achieved more than 80% of primary energy saving with lower payback period [14]. Boopathi et al. [15] proposed wide variety of ideas to minimize the capital and operation costs as well as reduce heat loss from generator and thus increase COP of assisted absorption cooling system. It was shown that life-cycle cost which includes all cost factors (first cost, operating cost, maintenance, replacement and estimated energy use) can be used to evaluate the total cost of the system over the complete life of the system. It was found that FPC and ETC are more reliable and economical for solar cooling system. The main parameters affecting the economical solar cooling systems are the cost of solar collectors and the storage technologies. Enhancing the performance of the solar integrated system by placing hot water storage tank above the solar collector and avoiding heat loss due from storage tank to generator by placing the generator inside the insulated storage tank is considered a new reliable approach.

The primary objective of this paper is to investigate the thermal performance of integrated SHC in UAE by proposing reliable mathematical model and carrying wide range of numerical and comparative studies in order to predict the savings in energy and reduction in CO_2 emissions. In order to verify the systems' overall performance, the proposed model is implemented for two selected building configurations; fully solar powered one-floor office building and hybrid four-floor residential building at various solar penetrations. It is noted that most of previous conducted research within this area are still at experimental stage and relatively small scale and did not reach the commercial stage due to the lack of prototyping which resulted high initial costs. The proposed model is expected to contribute to the existing models posted in the literature as it is designed to provide a continuous cooling which covers 24 operating hours by incorporating the bio-mass auxiliary heater. On the other hand, most of the conducted research reported in the literature was limited to a maximum daily operating period of 9 h (i.e. Yen et al. [10]). Moreover, the developed model in this study presents a comprehensive analysis of the integrated SHC system that suits UAE climate with substantial economic assessment based on the commercialized system components which are commonly existed in the UAE but rarely utilized adequately and properly for such an application.

2. General description of the solar-powered air conditioning system

The solar-powered absorption system consists basically of thermal collectors, a hot water storage tank, LiBr/water absorption chiller, bio-mass auxiliary heater and a cooling tower which is shown schematically in Fig. 1. The proposed system was implemented for two case studies; one-floor office building and four-floors residential building. The office building is located in Abu Dhabi and consists of four offices of 100 m^2 area each with a total roof area is 400 m^2, in which 60% only of this area is available for installing solar collectors. The analysis chosen for this building represents fully solar-powered integrated cooling system which was compared with electrical conventional air-cooled chiller. Using Hourly Analysis Program (HAP) [16], the total required cooling load for this building was estimated to be of 70 kW. Solar collectors are used to generate hot water to drive the absorption chiller in order to provide space cooling. Two different types of solar collectors were used: FPC and ETC. U_L value of FPC is approximately 8 W/m^2 K. The absorption chiller used is LiBr/H_2O of capacity 70 kW and COP is equal to 0.7. Hot water is driven to the generator side at approximated temperature of 88 °C. As a back-up source, a bio-mass auxiliary heater of 50 kW was used to supply hot water. The properties of the building materials are shown in Table 1. The residential building is located in Dubai and consists of four floors, with total roof area of 400 m^2. The proposed cooling system for this building is hybrid (i.e. 20% solar penetration and 80% electrical