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Performance evaluation of solar-assisted air-conditioning system with chilled water storage (CIESOL building)

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ABSTRACT

This study presents the performance of solar-assisted air-conditioning system with two chilled water storage tanks installed in the Solar Energy Research Center building. The system consists mainly of solar collectors' array, a hot-water driven absorption chiller, a cooling tower, two hot storage tanks, an auxiliary heater as well as two chilled storage tanks. The chilled water storage tank circuit was further investigated in order to find the optimum solar system's operation sequence while providing the best energy performance. Firstly, we carried out a study about the dynamics of building's cooling load and the necessity of the integration of chilled water storage tanks to solar system. Subsequently, the new system's operation mode was proposed to reduce the energy consumption. The results demonstrate that we can save about 20% of the total energy consumption and about 30% of water consumption applying the new operation sequence, which takes into account the chilled water tanks action. Moreover, it was demonstrated that the integration of chilled water storage tanks allows to reduce the sudden absorption chiller on/off cycles, thereby improving the efficiency of the solar-assisted system.

1. Introduction

Generally, the solar supply is the main focus during selection of the solar-assisted air-conditioning system's design, operation and control strategies and only a proportion of that focus is directed towards chilled water distribution system. The selection of the latter is normally based on the internal load profile and weather conditions. Nevertheless, the solar system is usually designed to cover the total cooling load without optimum operation point tracking algorithms and any consideration about the dynamics in the building's load. That results in frequent energy waste and inefficiencies [1]. Very few strategies can be selected in an overcrowded building with non-storage system, because no surplus energy can be accumulated. Moreover, the non-storage system has to follow the building cooling load, working always with the same maximum start-up parameters even in part-load conditions, often triggering sudden Yazaki absorption chiller on/off cycles. Therefore more efficient chilled water storage system has to be applied to increase the total solar-assisted air-conditioning system's efficiency, especially when it is working in the part-load operation mode.

The fundamental principle of chilled water storage system is a reduction of building's peak cooling loads by shifting a portion of peak cooling production to times when the building's cooling load is lower. The chilled water storage technique has been encouraged by electricity pricing schedules where the off-peak rate is considerably lower than the peak rate. Normally cooling, in the form of chilled water, is generated during off-peak hours and stored for future use during peak periods [2]. Nevertheless, in this study, we would like to present an innovative application of the chilled water storage tanks that allows reducing the energy and water consumption in the solar-assisted air-conditioning system.

The concept of chilled water storage tanks had been extensively discussed in literature [3–8]. However, few relative studies that considered the application of variable-speed chilled water pump to chilled water system have been carried out [9]. Arguments supporting chilled water system design based on variable flow have been proposed by influential figures in the industry. However, published literature provides little persuasive proof of performance benefits or detailed application guidance based on the performance of real applications. Such information is necessary to help designers and owners decide whether, and when, this new design approach should be adopted [5]. Thus the main goal of this study is to propose the application of a new strategy for operation of solar-assisted air-conditioning system installed in the Solar Energy Research Center (CIESOL) building. The above mentioned system has been operating since October 2006. Those solar-assisted system modifications allow to find out whether any energy and water savings are attainable. In this work we also attempt to outline a

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Nomenclature

C_p	specific heat capacity of water (4.18 kJ kg^{-1} K^{-1})
T_{amb}	ambient air temperature (°C)
S11	entering generator's temperature (T_{eg}) (°C)
S12	leaving generator's temperature (T_{lg}) (°C)
S18	entering evaporator's temperature (T_{ee}) (°C)
S19	leaving evaporator's temperature (T_{le}) (°C)
S34	temperature in the upper part of the second chilled water storage tank (°C)
S35	temperature in the bottom part of the second chilled water storage tank (°C)
S38	entering first chilled water storage tank's temperature (°C)
S39	entering fan-coils' temperature (°C)
S40	temperature in the middle part of the first chilled water storage tank (°C)
S41	building's return temperature (°C)
$\dot{m}_e$	evaporator's mass flow rate (m^3 h^{-1})
$\dot{m}_g$	generator's mass flow rate (m^3 h^{-1})
$\dot{Q}_{ev}$	the evaporator load (kW)
$\dot{Q}_{gen}$	the heat delivered to generator (kW)

feasible path for the real application of the chilled water system based on the variable flow.

In this study, we aim to analyze the behaviour of this system applying two chilled water storage tanks to satisfy the cooling demand of the CIESOL building. We attempt to demonstrate the reduction of energy and water resource consumption with the application of chilled water storage. To guarantee those savings we need to highlight the pivotal relation between chilled water storage use and building demand variation.

The first part of this work is focused on the study investigating the cooling demand variation influences on the total system operation. The internal building's load was analyzed according to a weekly occupancy profile and its variations during summer months. Secondly we carried out the study examining the integration of chilled water storage tanks to solar system. Finally, we proposed the new system operation mode aiming to reduce the energy consumption.

2. Description of solar-assisted air-conditioning system

In this study, we use data registered in the solar-assisted air-conditioning system installed in the CIESOL building situated at the Campus of the University of Almería. The system employs a flat-plate solar collectors' array with a total surface of 160 m^2. The collector Solaris CP1 which is used as the heat source is a high-performance, single-glazed, selective absorption coated flat-plate collector, having an aperture area of 2.02 m^2. The solar collector medium is water without any additives, due to the favourable conditions of Almería. The collectors' array is divided into ten rows, each row having eight collector units, facing due south and tilted at an angle of 30° to the horizontal line. The solar-assisted air-conditioning system uses the hot water driven single effect LiBr–H_2O absorption chiller manufactured by Yazaki Company with a rated capacity of 70 kW. It also utilises the cooling tower, two hot storage tanks, an auxiliary heater, two chilled water storage tanks, three water pumps and ten three-way valves. The air-conditioning covering the building's cooling and heating load is in operation during office hours from 9 a.m. to 8 p.m., from Monday to Friday. Analysis of the above system and its various operation modes has been recently presented by [10,11]. Fig. 1 presents the view of the CIESOL building with the flat-plate solar collectors installed on the roof and the main system components.

The above system has been operating without interruption since October 2006, partly satisfying the demand of the CIESOL building for cooling in the summer and heating in the winter. Due to the particular meteorological conditions of Almería, the solar-assisted air-conditioning system can operate in different modes. The first division between the summer and winter modes depends only on period of the year; meanwhile, the second division depends on temperatures found in the system. Thus, the system accounts for the heating and cooling demands using the hot water provided from the solar field or hot storage tanks assisted by the auxiliary heater. In this study, we analyze the behaviour of this system working only in the cooling mode. Fig. 2 illustrates the general scheme of the solar-assisted air-conditioning system working in that mode and Table 1 presents description of the solar-assisted air-conditioning system's peripheral components.

The absorption chiller consists of the generator, condenser, absorber, evaporator, heat exchanger and expansion valve. It has a generator's inlet temperature range of 70–95 °C, and a cooling water inlet temperature range of 24–31 °C, and attains its rated capacity of 70 kW under the following conditions:

- Generator's inlet temperature – 88 °C (heat source flow rate: 4.8 ls^{-1}).
- Cooling water inlet temperature – 31 °C (cooling water flow rate: 10.2 ls^{-1}).
- Chilled water outlet temperature – 7 °C (chilled water flow rate: 3.06 ls^{-1}).

The absorption chiller uses a solution of lithium bromide and water as the working fluid. Water is the refrigerant, and lithium bromide, a nontoxic salt, is the absorbent. In the absorber the lithium bromide absorbs the refrigerant coming from the evaporator. As the quantity of lithium bromide that dissolves in the water increases, the temperature of the solution diminishes. Around the absorber refrigeration water is circulated to take away the freed energy from the lithium bromide in the solution and to keep up the absorber's temperature as low as possible. In the generator, the heat transferred from a source of relatively high temperature makes the vapour escapes from the solution, leaving a weak solution in the generator. The liberated vapour goes onto the condenser and the weak remaining solution flows into the absorber. To return the refrigerant into its initial state, at a low pressure, it expands through an expansion valve [12].

The Coefficient of Performance (COP) is defined as the quotient between the heat absorbed in the evaporator $\dot{Q}_{eV}$, and the heat taken in the generator $\dot{Q}_{gen}$, and it is obtained from the following equation [13]:

$$COP = \frac{\dot{Q}_{eV}}{\dot{Q}_{gen}} = \frac{\dot{m}_e \times C_p \times (T_{ee} - T_{le})}{\dot{m}_g \times C_p \times (T_{eg} - T_{\mathrm{lg}})} \quad (1)$$

where COP is the coefficient of performance, $\dot{Q}_{ev}$ is the evaporator's load ($\dot{Q}_{cool}$), $\dot{Q}_{gen}$ is the heat delivered to generator, $\dot{m}_e$ is the evaporator's mass flow rate (m^3 h^{-1}), C_p is the specific heat capacity of water (4.18 kJ kg^{-1} K^{-1}), T_{ee} is the entering evaporator's temperature, T_{le}, is the leaving evaporator's temperature, $\dot{m}_g$ is the generator's mass flow (m^3 h^{-1}), T_{eg} is the entering generator's temperature, T_{lg} is the leaving generator's temperature.

A cooling tower of model SULZER EWK 100 with the cooling capacity of 170 kW was used for rejecting the heat of absorption