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Investigation of separate or integrated provision of solar cooling and heating for use in typical low-rise residential building in subtropical Hong Kong

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ABSTRACT

In this study, the technical effectiveness of solar cooling and heating was investigated for typical low-rise residential building in the subtropical Hong Kong. Since water heating was required for domestic hot water supply rather than space heating, a separate or an integrated provision of solar cooling and heating could be considered. In the separate provision, cooling was handled by an independent solar absorption air-conditioning system, while water heating was offered by a packaged solar thermal collector already equipped with a storage tank. In the integrated provision, all the solar collectors and a centralized hot water storage tank were collectively applied for both driving the absorption chiller and generating domestic hot water. Through year-round dynamic simulation, it was found that the integrated provision could have annual primary energy saving of 13.5% against the separate provision. The effectiveness of the integrated provision was further verified through two energy-saving scenarios, with energy reduction by 17.7% and 18.0% correspondingly as compared to the separate provision. Under the synergistic effect of centralized thermal harness and storage, the integrated solar cooling and heating is more appropriate for typical low-rise residential application in Hong Kong.

1. Introduction

Solar energy, as one of the popular renewable energy sources, has been involved in various applications around the globe. The studies of solar heating for building applications have been started for decades. Methodology of economic evaluation of solar heating system was developed [1], and life-cycle economic viability of solar heating was carried out against the conventional provisions for residential applications, assuring the benefit in places with various climatic conditions [2–5]. With the global concern extended to the environmental impact of renewable energy systems, life cycle assessment was conducted for solar heating system against the conventional heaters. The environmental payback with respect to the embodied energy required for equipment production and installation of the solar heating system was a few years only [6–8]. Over the years of implementing solar heating projects, review was also made to the real operating performance of the installed systems against the theoretical information [9,10]. Solar heating has been established to be a proven technology, with affordable economic and environmental payback periods. On the other hand, solar cooling has been widely promoted in recent decade, with feasible options to apply absorption chiller, adsorption chiller or desiccant cooling cycle [11]. In particular, solar absorption cooling is popular and the associated studies have been carried out in different climatic conditions, no matter in small or medium applications [12–15]. Application of solar cooling has been extended to industrial refrigeration, and technical and economic advantages were identified [16]. Life cycle assessment of solar cooling system was conducted, and it was found that carbon reduction and other environmental merits were certain [17,18]. The performance of solar cooling system was also evaluated after years of operation, and appropriate measures of improvement have been implemented from the experience gained [19,20]. Energy and carbon merits of solar cooling are generally assured in the places with different climatic and building features.

In order to fully utilize this renewable energy source, solar heating and cooling has been considered together in various building applications, which provide space heating in cold time and

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air-conditioning in hot season. Life cycle assessment was conducted for solar heating and cooling system for year-round operation [21,22]. In order to enhance the overall performance of solar heating and cooling, different measures, like collector design and heat storage medium were proposed [23,24]. These studies were mainly related to the applications in the temperate, Mediterranean or arid climates, with emphasis on heating rather than cooling due to the climatic feature [25–28]. There was also little mention to involve water heating for domestic purpose in the context of solar heating and cooling. As a result, the objective of this study is to investigate whether solar cooling and heating was effective to handle both the demands of air-conditioning and water heating for a typical residential building in the subtropical Hong Kong (22.32°N, 114.17°E). The application is mainly on cooling, accompanied with water heating for domestic use. Space heating is not necessary due to mild winter of subtropical climate. As such, the appropriate approach to design solar cooling and heating should be explored. From the latest energy end-use data report in Hong Kong [29], residential buildings account for 26% and 40% for the total electricity consumption and the total gas consumption in 2011 respectively. It is therefore worthy investigating the application potential of solar cooling and heating for such building type in order to reduce the consumption of fossil fuel.

In this study, design of solar cooling and heating was based on the use of solar thermal gain as the essential energy source. Indeed, solar electric gain can be acquired from the photovoltaic (PV) panels, while solar electric and thermal gains can be received from the photovoltaic/thermal (PVT) panels. With the adoption of PV or PVT panels, the design of corresponding cooling and heating equipment would be quite different due to the availability of electrical power. Conventional compression type air-conditioners can be involved and more design alternatives would be generated. However, both the PV and PVT panels themselves have demerits in life cycle environmental and economic analysis, therefore it is more appropriate to adopt solar thermal collectors in order to effectively advocate solar cooling and heating.

The paper is structured in the following ways. Section 2 describes the possible approaches to design solar cooling and heating, as well as the conventional provision, for a typical low-rise house. The design parameters of the building zone and different provisions are also addressed. Section 3 states the methodology of study and the performance indicators of evaluation. Section 4 discusses the performance results of the various scenarios of solar cooling and heating provisions. Section 5 is conclusion and recommendation.

2. System design and building zone

2.1. Design of solar cooling and heating

In Hong Kong, the typical low-rise residential buildings are the small houses called “village houses”, which are commonly found in the outskirt of urban area. As Hong Kong has subtropical climate and no snowing in winter, the roof of the residential building is flat and available for equipment installation. With the solar collectors installed on the roof, hot water could be supplied to a thermally-driven absorption chiller, and chilled water was delivered to the fan coil units (FCUs) installed in the respective rooms for air-conditioning purpose. In the mild and cold seasons, the hot water requirement for cooling was low, but it could be used for domestic water heating.

The provision of solar cooling and heating can be designed in two ways – a separate approach or an integrated approach. In small-scale application, it is common to have the packaged solar thermal collector completed with a storage tank. Thus, a separate provision of solar cooling and heating could be generated: The packaged solar collectors were adopted for water heating, while the solar absorption cooling with its own storage tank was designed for air-conditioning separately. Fig. 1 illustrates the separate provision of solar cooling and heating. These two parts would be independently operated according to the respective load demands without any system influence in between.

On the other hand, Fig. 2 depicts an integrated provision of solar cooling and heating, in which the full array of solar collectors were used together to harness thermal energy in a centralized storage tank. To apply the integrated approach, the hot water drawn and the make-up water refilled would reduce the temperature of hot water stored in the centralized storage tank. This might in turn affect the cooling capacity offered and cause more frequent involvement of auxiliary heating. As such, the year-round system performances of the separate and integrated provisions would be evaluated. Indeed, the energy consumption of the conventional provision, which was to make use of air-conditioners for cooling and gas water heaters for heating in the residential building, would also be compared in this residential application.

In either the separate or integrated provision, the $LiBr/H_2O$ absorption chiller and evacuated tubes would be adopted in solar absorption air-conditioning, which would offer the highest energy-saving potential among the various types of thermally-driven cooling systems in Hong Kong according to a previous study [30]. A regenerative water pump (RWP) was used to furnish hot water for energizing the absorption refrigeration cycle, then a chilled water pump (EWP) supplied chilled water to the supply air coil of each FCU, which provided the conditioned air to the respective room through a supply air fan (SAF). A cooling tower was used to provide cooling water to the absorption chiller through a cooling water pump (CWP) for heat rejection purpose. In the centralized chilled water circuit, a supply air coil valve (SAV) was used to modulate the chilled water flow at the bypass line during part-load operation. By running a hot water pump (HWP), thermal energy from the solar collectors could be harnessed into the storage tank. To ensure fulfillment of the cooling load and water heating demand even when the solar irradiation was insufficient, individual auxiliary heaters were provided as backup heat sources. The setpoint of the auxiliary heater for the chiller was modulated by a part-load controller to minimize the auxiliary heating demand.

2.2. Information of building zone

In this study, a village house was used as the typical low-rise residential building in Hong Kong. It had three stories, with the gross floor area of 65 m^2/floor and the floor-to-floor height of 2.74 m. This architectural information followed the standard requirements stipulated by the local regulation [31]. Fig. 3 shows the typical floor layout of village house adopted in this study, all dimensions were in mm. Each floor included one living/dining room (LDR), three bedrooms (BR1, BR2 and BR3), one toilet and one kitchen. A glass door of 2500 mm (W) × 2000 mm (H) was erected on an external wall of the LDR, with a balcony built outside. From the orientation of the floor plan indicated in Fig. 3, the LDR and its glass door was facing south. Besides the glass door, a number of windows of size 600 mm (W) × 1200 mm (H) were installed on the external walls as mentioned in the corresponding rooms in Fig. 3. The U-values of external wall, window/glass door and roof were 2.73 W m^{-2} K^{-1}, 5.68 W m^{-2} K^{-1} and 0.39 W m^{-2} K^{-1} respectively, which were based on the local design practice for residential building.

For the typical village house, the design information of the various loadings and the associated operating schedules was developed according to the representative design for residential buildings [32] and the local design practice. The estimated design cooling load for each zone was based on the design indoor