Solar Energy 153 (2017) 301–316

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Performance analysis and economic assessment of solar thermal and heat pump combisystems for subtropical and tropical region

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ARTICLE INFO

Article history:
Received 10 April 2017
Received in revised form 15 May 2017
Accepted 22 May 2017

Keywords:
Solar collector
Air-source heat pump
TRNSYS
Combisystem
Domestic hot water
Payback period

ABSTRACT

In the present research, combinations of solar collectors and air-source heat pumps for domestic hot water (DHW) are addressed in terms of hydraulic layout and climate conditions. TRaNsient SYstems Simulation (TRNSYS) software was implemented to simulate and examine the heating capacities of various DHW systems. For validating the numerical results, a demonstration site featuring a solar collector and heat pump combisystem with real-time monitoring sensors was established in Tainan, Taiwan. The corresponding parameters of TRNSYS modules were also tested and validated using experimental data. For comparison with the electrical heating water system, three common DHW systems—a conventional solar DHW system, a single-tank solar combisystem, and a dual-tank solar combisystem—were selected, and their technical and economical aspects were assessed. To determine the effect of climate conditions, two metropolitan cities in Taiwan were simulated: Taipei represented subtropical cities and Kaohsiung represented tropical cities. Results for both Taipei and Kaohsiung showed that the dual-tank solar combisystems had the lowest electrical consumption levels and operating costs. The incremental capital costs of the solar combisystems were considered, and realistic payback periods were calculated to determine economic feasibility.

1. Introduction

Extensive consumption of fossil fuels leads to irreversible natural resource depletion and increases in carbon dioxide emission. Approximately 81.4% of energy supplied from fossil fuels is consumed for power generation and heating (Chaturvedi et al., 2014). In order to mitigate environmental deterioration, prioritizing the contribution of renewable energy is a timely and urgent issue. Strictly speaking, Taiwan is endowed with almost no energy resources and relies on imports for nearly 98% of its energy consumption (Bureau of Energy, Ministry of Economic Affairs, 2015). Of the imports, 8.3% is nuclear fuel and more than 90% consists of fossil fuels (i.e., petroleum, natural gas, coal). The commercial sector, industrial sector, residential sector, and transportation sector are the four major energy end-use sectors. To confront these challenges, considerable efforts have been undertaken in Taiwan to develop and disseminate renewable energy technologies such as wind energy, solar thermal energy, photovoltaic energy, geothermal energy, biomass energy, and ocean energy (Wu and Huang, 2006; Chen et al., 2008; Chang et al., 2008) The development of solar thermal energy for residential and industrial hot water systems has been particularly widespread. Because of subsidy programs offered by the Bureau of Energy and Ministry of Economic Affairs, the payback period of a solar domestic hot water (SDHW) system is appealing compared with that of an electrical water heating system (Lin et al., 2015).

Recently, combisystems that combine solar collectors and heat pumps for domestic hot water (DHW) systems (Moreno-Rodríguez et al., 2012) and space heating (SH) systems (Xi et al., 2011) have gained increasing consideration for meeting various hot water demands. For SDHW and SH systems, the combination of solar collectors and heat pumps is promising and prevalent in high-altitude regions. The configurations of solar combisystem have been extensively discussed (Liu, 2016; Wang et al., 2010; Buker and Riffat, 2016; Emmi et al., 2015; Liu et al., 2016; Chow et al., 2010). Li et al. (2007) investigated the system performance of a direct-expansion solar-assisted heat pump water heater. Kumar et al. (2016) used artificial neural network (ANN) integrated with genetic algorithm (GA) to predict the performance of direct expansion solar assisted heat pump. Mohanraj et al. (2012) review the applications of artificial neural network (ANN) on different cooling and heating systems. It is noted that the ANN can be successfully applied in heat pump systems. The ANN is a way to applied for

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http://dx.doi.org/10.1016/j.solener.2017.05.067
0038-092X/

modeling. Qu et al. (2015) examined the effect of hydraulic layout on the system performance of a solar-assisted heat pump water heating system. The results showed that the system with a latent heat storage tank obtained energy performance superior to that of a system with sensible-heat storage. Comparisons of conventional solar thermal systems with solar collectors and heat pump combisystems have indicated that combisystems not only offer superior performance (Buker Mahmut and Riffat, 2016; Carbonell et al., 2014), but also produce much lower CO_2 emissions (Chaturvedi et al., 2014). Lerch et al. (2015) introduced six different configurations of solar combisystems and compared the corresponding performance levels with that of a conventional heat pump system. The solar combisystem appeared to exhibit favorable performance. Although a solar-assisted heat pump can achieve high efficiency, various uncertainties and system factors can influence its overall efficiency and performance, such as compressor speed, solar irradiation, collector area, storage tank volume, and solar collector tilt angle (Hawlader et al., 2001).

Solar collectors can be installed either in parallel or series with a heat pump to manage intermittent solar radiation on a seasonal or daily basis. Consequently, the layouts of solar combisystems can be categorized as series mode layouts and parallel mode layouts (Chu and Cruickshank, 2014). In a parallel system, a solar collector and heat pump provide heat for loads either directly or through a storage system. In a series system, collected heat from a solar collector is used indirectly as a heat source for the heat pump evaporator. In terms of hydraulic connections and system control, parallel systems have the advantage of being less complex than series systems. Therefore, parallel systems may be more robust and reliable (Carbonell et al., 2014). Lund (2005) studied the sizing and applicability of solar combisystems with short-term heat storage, and concluded that large collectors are not suitable for low-energy buildings in regions with high solar irradiation. Li et al. (2014) used TRNSYS software to examine the performance effects of collector areas, storage factors, and dead-band temperatures for air-source heat pump combisystems. Dott et al. (2012) evaluated several configurations of solar collectors and heat pumps regarding the direct or indirect uses of solar irradiation. Poppi et al. (2016) numerically investigated the effects of climate, load, and main components size on electricity use. Panaras et al. (2013) compared the experimental performance of a combined solar thermal heat pump system for DHW with a numerical model and observed favorable agreement for high radiation conditions, but poor agreement for low radiation conditions; they found that the combined solar thermal heat pump system could save approximately 70% of auxiliary energy usage compared with an electric hot water tank. Buker Mahmut and Riffat (2016) curated a number of past and current studies on system design, modeling, and the optimization of the performance characteristics of solar-assisted heat pump systems for low-temperature water heating applications. Haller et al. (2014) used TRNSYS software to estimate the effect of hydraulic integration and the control of a heat pump connected to a solar combi-storage system. The results revealed that unfavorable hydraulic integration causes the system to require additional electrical energy. Kong et al. (2017) developed a mathematical model to analyze the direct-expansion solar-assisted heat pump water heater. Banister and Collins (2015) developed a TRNSYS model and a controller for a dual-tank solar-assisted heat pump. Their system is feasible for application to large loads and produces energy and cost savings. In addition, the effect of climate condition on performance of solar combisystem has been experimentally and numerically discussed in different regions, such as Canada (Asaee et al., 2017; Rad et al., 2013), Denmark (Jradi et al., 2017), Tunisia (Awani et al., 2017), Athens (Tzivanidis et al., 2016), China (Zhu et al., 2015), and Hong Kong (Chow et al., 2010). The climate conditions of these studies pertain cold weather condition or Mediterranean climate, but rarely subtropical and tropical climate. Based on aforementioned literature, many factors would influence the heating performance of solar combisystem. Consequently, the effect of hydraulic layout and climatic condition on the performance of solar combisystem in tropical and subtropical regions will be numerically discussed in this study. Eventually, the incremental capital costs of the solar combisystems were considered, and realistic payback periods were calculated to determine economic feasibility.

2. Validation of DHW system

In this study, commercial TRNSYS 17 software (TRNSYS, 2012) was engaged to analyze the effects of hydraulic layouts on DHW systems and the feasibility of various solar combisystems in Taipei and Kaohsiung. These simulated results were validated with experimental results from a physical solar combisystem. Parameter settings of the solar collector model, such as latitude, longitude, the solar incident angle, and solar radiation, were adjusted to improve the simulation accuracy. For instance, the tilt angle of solar collector can influence the solar thermal quantity. The optimal tilt angle of a solar collector is similar to the latitude in which the system is located (Le Roux, 2016). The validated simulation model was used to assess the performance of various solar systems in Taipei and Kaohsiung, the components and the detailed parameters of solar combisystem were shown in Table 4. Three individual hydraulic layouts were considered in this study, namely a solar combisystem with single tank, a SDHW system, and a heat pump hot water system.

2.1. Experimental setups and simulation model

A lab-scale solar combisystem with real-time monitoring sensors was constructed and tested in Tainan city, the configuration of the experimental apparatus is shown in Fig. 1. The demonstration system consisted of four solar collector panels which are flat-plate type (each of which had an area of 1.92 m^2), two water tanks (each of which held 460 L), two 1-ton storage tanks, and one 1.7 kW heat pump. The working fluid of the heat pump system is R410A. R410A is an environment-friendly refrigerant, and does not contain the chlorine which can cause the damage on the ozone layer. In addition, R410A can achieve much higher performance than traditional refrigerant. Despite of high global warming potential (GWP), R410A is widely used in the world due to its advantages. All water tanks and pipes were thermally insulated to reduce heat loss or gain, allowing the water to be delivered at the intended temperature. K-type thermocouples were used to monitor water temperatures in tanks and pipes. Electromagnetic valves were used to control the water delivery. Flowmeters were used to gauge the water flow rates. Regarding to the environment detection system, a heliograph was used to detect the solar radiation, an anemometer was used to monitor the wind direction and wind speed, and a psychrometer was used to measure the air relative humidity. All data from all sensors were digitally transmitted to and recorded in a computer. Fig. 2 schematizes this solar combisystem and its monitoring sensors. This demonstration system had three configurations corresponding to three types of DHW system. The first configuration acted as a traditional SDHW system, comprising solar collectors and a thermal storage tank. The second configuration acted as a heat pump domestic hot water (HPDHW) system, comprising a heat pump and a thermal storage tank. The third configuration acted as a solar collector and heat pump domestic hot water system (SC-HP DHW), consisting of solar collectors, a heat pump, and a thermal storage tank. These three types of DHW system were simulated in TRNSYS 17; the simulated