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Development and performance of a dual tank solar-assisted heat pump system

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HIGHLIGHTS

- Developed TRNSYS model and controller for dual tank solar-assisted heat pump (SAHP).
- System modes were validated experimentally using a test apparatus.
- Energy savings are increased in comparison to solar domestic hot water system.
- Applying the SAHP system to a larger load would improve economic justifiability.

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ABSTRACT

A novel dual tank solar-assisted heat pump (SAHP) system configuration for domestic hot water heating was developed. Due to the multiple modes of operation arising from the configuration, it was necessary to develop a custom control strategy to minimize electricity consumption. The controller evaluates which modes of operation are possible given the current conditions and selects the best mode from those available.

The system modes of operation were validated experimentally using a test apparatus built at the University of Waterloo. Annual simulations of system performance for a single-family residential home indicate that the dual tank SAHP system developed provides significant energy savings in comparison to a traditional solar domestic hot water system. Using a benchmark comparison of a standard electric domestic hot water system and a solar domestic hot water system, the dual tank SAHP increased energy savings from 60% to 69% for 7.5 m^2 solar collector area. Applying the system to a larger load offers the potential for significant energy and cost savings, which would improve economic justifiability.

1. Introduction

Solar-assisted heat pump (SAHP) systems combine solar thermal collectors (STCs) and heat pumps (HPs) in a synergistic fashion for the purpose of meeting domestic hot water (DHW) and/or space heating loads. A heat pump assists a solar collector in extracting additional energy from the solar loop, which improves solar fraction and reduces source energy consumption. A solar thermal collector improves heat pump coefficient of performance (COP) by increasing the evaporator inlet temperature.

There are many different ways to design a SAHP due to the combination of components for such a system. Two major classifications are: direct systems, where the solar panel becomes the evaporator in the refrigeration cycle; and indirect systems, where the STCs are connected to the HP via its integral heat exchanger.

Investigations of SAHP systems date back to the 1980s, where Chandrashekar et al. [1] used simplified models to analyze the performance of six system configurations for two building types in seven Canadian cities. The study concluded that systems were not effective for single-family dwellings at the time, but justification was better for multiplex dwellings.

Research of SAHP systems has been renewed recently due to improvements in compressor, heat exchanger (HX), and solar thermal performance. Numerical models have been developed, but there is a general lack of model validation, which prevents confidence from being established in the results [2–5]. In other work, experimental analysis of systems has been performed, but models were not developed [6–10]. Some recent work has undertaken model validation, but the results are often limited in context and applicability [11–14].

The general conclusion of studies investigating SAHP systems is that energy savings exist in comparison to traditional solar domestic hot water (SDHW) systems. Many studies have been conducted

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Nomenclature

COP	coefficient of performance
DHW	domestic hot water
HP	heat pump
HX	heat exchanger
SAHP	solar-assisted heat pump
SDHW	solar domestic hot water
STC	solar thermal collector

which use numerical models to investigate the feasibility of SAHP systems. However, unvalidated models limit confidence in the results. Sterling et al. [2] conducted a feasibility study for an indirect SAHP system for DHW using an unvalidated model, which predicted a solar fraction increase to 0.67 in comparison to 0.58 for a SDHW system.

Carbonell et al. [3] analyzed the potential energy savings of a SAHP with ground source for space heating and DHW in comparison to air and ground source heat pump systems. From the numerical model, it was concluded that locations with cold temperatures and high irradiation benefit the most from the SAHP system.

Rad et al. [4] explored the feasibility of a SAHP system with ground source in a cold climate using an unvalidated model with historical building loads. Although ground heat exchanger length could be reduced, the study concluded that adding solar thermal collectors to a ground source heat pump system provided small economic benefit.

Researchers have also investigated the experimental performance of SAHP systems, but the results reported are often limited to very specific test scenarios. Huang et al. [6] built and evaluated a direct SAHP consisting of a small reciprocating compressor and an unglazed solar collector. The measured COP of the system was between 2.5 and 3.7.

Li et al. [7] experimentally analyzed the performance of a direct SAHP, finding a COP of 6.6 during high intensity incident solar radiation and 3.1 during an overcast day. The high COP achieved during an overcast day resulted from unglazed collectors acting as heat exchangers with ambient air. Chaturvedi et al. [8] investigated the effects of a variable speed drive compressor on the performance of a direct SAHP system, showing that COP can be improved by reducing the compressor speed during warm months.

Loose et al. [9] identified that many field tests exist for the separate technologies of solar thermal collectors and heat pumps, but not for systems combining the two technologies. Their in-situ monitoring of a brine to water heat pump using shallow geothermal and solar thermal energy showed a seasonal COP of about 3.5. Loose et al. also share the view that experimental validation of SAHP models is lacking.

Some studies have compared experimental and model results, but the findings are limited to the particular system configuration considered. Chyng et al. [11] modeled a direct SAHP system and simulated annual performance, finding that the COP of the system ranged from 1.7 to 2.5 throughout the year and experimental results agreed well with the model.

Kaygusuz [12] investigated the performance of a dual-source indirect SAHP using computer simulations and a test apparatus in Trabzon, Turkey, showing that a dual-source SAHP had higher energy savings than other configurations. Panaras et al. [13] compared experimental performance of a SAHP for DHW to a numerical model and found good agreement for high radiation conditions, but poor agreement for low radiation conditions. Overall, it was found that the SAHP could save about 70% of auxiliary energy usage in comparison to an electric hot water tank.

Chu et al. [15] conducted a review of many SAHP studies performed for a wide variety of systems. The key conclusion of the review paper was that studies investigating the performance of SAHP systems are very difficult to compare. The main reasons for the difficulty are that a wide variety of configurations exist and that performance criteria used to evaluate systems are not consistent.

Numerical models vary widely due to the large number of system configurations possible. Therefore, each model must be validated to establish confidence. The literature has a gap in model validation to support results and control strategy description which this work aims to address. With a suitable control scheme and a validated, further investigations of system performance with varied inputs can be completed. This work developed a novel configuration with a custom control strategy and uses tuned component models to simulate annual performance in comparison to alternatives.

2. Dual tank solar-assisted heat pump system

An indirect dual tank SAHP system was designed, with a key aspect of the being a second thermal storage tank. A simplified schematic of the system is shown in Fig. 1. Flow direction at branches is controlled with three-way valves. The second tank makes it possible to collect additional solar energy in comparison to a SDHW system. This is achieved by allowing the second tank to 'float' in temperature, hence its name, Float Tank. STC efficiency is increased when the float tank is at a lower temperature than the DHW tank due to decreased thermal losses.

Additional system capabilities make system control more complicated than a simple 'on' or 'off' decision. The addition of the heat pump and second storage tank required more care for controller design because it is possible to collect energy when a SDHW system cannot. The existence of a second storage tank requires further control decisions, as priorities must be established which enable the DHW tank to meet demands, but also maximize energy collection by delivering heat to the float tank when possible.

The extra control decisions required the development of a custom controller. The controller must determine which system operation mode is most appropriate given the circumstances encountered. Controller design relied on the use of a TRNSYS model to test functionality and evaluate performance. Prior to using the model for simulation investigations, a test apparatus was used to tune components and validate modes of operation.

3. Test apparatus

A test apparatus was designed, built, and commissioned [16] and is shown in Fig. 2. The solar collector is replaced with a circulation heater to facilitate controlled laboratory testing. It is capable of validating system modes of operation, tuning component models, and identifying operational issues.

The operating modes used to tune component models are: (1) thermal storage tank heating via internal electric resistance element; (2) thermal storage tank standby losses; (3) solar source charging thermal storage tank via heat exchanger; and (4) solar source directly charging thermal storage tank. In addition, detailed performance characterization of the HP was completed to develop a custom TRNSYS model. The results of model tuning and validation are presented in previous publications [16,17].