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Heat transfer and exergy analysis of a novel solar-powered integrated heating, cooling, and hot water system with latent heat thermal energy storage

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ABSTRACT

A thermal network model is developed to study the performance of a solar thermal-powered heating, cooling and hot water system comprised of evacuated tube collectors, a latent heat thermal energy storage unit and related heat exchangers, and an absorption chiller/heat pump. The system performance is studied for a residential building in a hot climate zone (Phoenix, Arizona) on two typical solar days representative of a relatively cold day and a relatively hot day. A systematic sizing methodology is presented to minimize the phase change material mass and the output temperature fluctuations. An exergy analysis is also performed to quantify the second law efficiency of the system. Analysis of the energy performance of the system shows that more than 80% annual energy saving can be achieved by using a solar collector area of 10 m^2 coupled with a 29 kWh latent heat thermal energy storage system. The effect of the heat transfer design of the thermal energy storage system, in particular the number of condenser pipes of the input heat pipe and evaporator sections of the output heat pipes embedded within the phase change material, on the thermal and exergetic performance of the system is also investigated. It is shown that increasing the number of pipes decreases the temperature fluctuations and increases the exergy efficiency due to minimized temperature drops. Quantitatively, increasing the number of pipes from 60 to 112, decreases the maximum temperature drops across the latent heat thermal energy storage system from about 30 °C to 15 °C, and increases the exergy efficiency from about 75% to 90%. This study demonstrates the capability of a solar thermal-powered heating, cooling and hot water system integrated with latent heat thermal energy storage to significantly reduce the auxiliary energy input needed to meet the demands of a residential building located in a hot climate zone.

1. Introduction

For the past several decades, fossil fuels have been heavily relied on for supplying the world's energy demands. In 2015, approximately 81% of the world's energy came from these non-renewable energy sources [1]. Burning of these fuels is the largest source of emissions of carbon dioxide, which contributes greatly to global warming. It is forecasted that the energy-related carbon-dioxide emission will more than double by 2050 [2]. A renewable energy revolution is in urgent need. Renewable energies, such as solar, wind, and geothermal heat, are generally clean, safe, and sustainable. According to REN21'S 2014 report [3], renewable energy contributed to 19% of the world energy consumption in 2012 and 22% of electricity generation in 2013. Among various sources of renewable energy, solar energy is arguably the most attractive option due to abundance, virtually zero emission and unlimited supply. However, further efforts are needed to take full advantage of its potential to aid in addressing the challenges of climate change and sustainable development.

Residential heating, ventilation and air-conditioning (HVAC) and hot water production accounts for about 60% of the energy consumed in the U.S. homes [4]. Effective utilization of the solar energy to meet the domestic HVAC and hot water demands can greatly contribute to decreasing fossil fuel consumption and related environmental concerns. One major challenge, however, is the mismatch between the times of solar energy availability and heating, cooling and hot water demand, since homes are frequently not occupied during the peak solar harvesting times. As such, any effort to utilize solar energy for domestic applications must address an effective energy storage solution. Photovoltaic (PV) systems have emerged as a prominent technology to convert solar energy to electricity. However, storing electricity requires

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Nomenclature

A	surface area (m^2)
c	specific heat (J/kg K)
E	thermal element
Ex	exergy (kJ)
H	height of PCM compartment (m)
h_{sl}	heat of fusion (kJ/kg)
k	thermal conductivity (W/m K)
k_{PCM}	thermal conductivity of PCM (W/m K)
k_s	thermal conductivity of metal in the metal foam (W/m K)
L	input (output) HP spacing (m)
M	related to number of PCM thermal elements in the solid region
m	mass (kg)
N	number of PCM thermal elements in the liquid region
q	heat transfer rate (W)
r	radius (m)
S	entropy (kJ/kg K)
s	melting front location (m)
T	temperature (°C)
T_b	temperature at the interface of PCM regions around input and output HPs (°C)
$T_{i,n}$	temperature at the interface of PCM thermal elements E_n and E_{n-1} (°C)
T_m	PCM melting temperature (°C)
T_n	temperature of the elements E_n calculated in the middle of the element (°C)
T_w	metal wall temperature (°C)
t	time (s)
V_f	melt volume fraction
V_l	melted PCM volume (m^3)

Greek

δ	thermal element half-thickness (m)
ρ	density (kg/m^3)
ϕ	generic variable
ϵ	porosity
$\eta_{collector}$	collector efficiency
η_{II}	exergy efficiency

Acronyms

COP	coefficient of performance
DNI	direct normal irradiance
HP	heat pipe
HVAC	heating, ventilation, and air conditioning
LHTES	latent heat thermal energy storage
ODE	ordinary differential equation
PCM	phase change material
PV	photovoltaic
TMY	typical meteorological year

batteries that are characterized by relatively high cost and fast deterioration, hindering large-scale deployment of photovoltaic air conditioning systems. Moreover, when thermal energy is needed, photovoltaics efficiency is far below that of the solar thermal collectors. Quantitatively, considering typical PV efficiencies of 15% and assuming perfect electrical-to-thermal conversion efficiency, the overall solar-to-thermal efficiency of PV-based systems is about 15%. On the other hand, non-concentrating solar thermal collectors have efficiencies in the range of 50–80% in typical operating conditions [5].

Several investigators have studied solar thermal-driven HVAC systems including thermo-mechanical, absorption, adsorption and desiccant solutions. Kim and Infante Ferreira [6] studied various solar-thermal technologies and concluded that a single-effect lithium bromide (LiBr)-water absorption system benefits from the lowest cost. El-safty and Al-Daini [7] presented an economic analysis to compare single- and double-effect absorption and vapor compression air conditioning systems for application in Middle East. They concluded that when compared with vapor compression systems, double-effect solar vapor absorption system had the lowest present worth and equivalent annual cost. Hildago et al. [8] studied experimentally a single effect LiBr-water absorption cycle driven by a 50 m^2 flat plate solar collector field and coupled to a hot water storage tank. They found that the absorption cooling power reached 6–10 kW, with a generator driving power input of 10–15 kW, achieving a mean cooling period of 6.5 h of complete solar autonomy on a seasonal average day. Assilzadeh at al. [9] conducted simulations of a solar-powered absorption cycle integrated with a hot water storage tank. The results demonstrated the critical role of the thermal storage tank for reliable and continuous operation of the system.

Compared to the sensible heat thermal energy storage systems, latent heat thermal energy storage (LHTES) systems provide operational advantages of smaller temperature swings, higher collector efficiency (due to lower temperature), smaller size and lower weight per unit of storage capacity [10]. Palomba et al. [11] performed an experimental study to measure the performance of LHTES systems for solar thermal applications using a lab-scale LHTES specifically designed for solar cooling applications. The test rig consisted of a paraffin blend with a melting temperature of 82 °C and a compact fin-tube heat exchanger. The results confirmed that the LHTES energy storage density increased by about 50% compared with hot water storage systems. Nallusamy et al. [12] conducted experiments to investigate the thermal behavior of a combined sensible and latent heat thermal energy storage unit to provide hot water for domestic applications. Paraffin was used as the latent heat storage medium and water served as both heat transfer fluid and sensible heat storage material. It was found that the combined storage system performed better than the conventional sensible heat thermal energy storage system in which the heat transfer fluid was directly mixed with hot water in the storage tank.

In other related work, Esen [13] studied, experimentally and theoretically, a solar-powered heat pump system with a cylindrical phase change storage tank filled with calcium chloride hexahydrate ($CaCl_2{\cdot}6H_2O$) as the phase change material (PCM). Kaygusuz et al. [14] conducted experiments to investigate the performance of a solar-assisted heat pump system with latent heat thermal storage. The apparatus consisted of 30 m^2 of flat plate solar collectors and a LHTES tank filled with 1500 kg of encapsulated PCM to provide heating to a lab space with 75 m^2 floor area. The experimental results for the collector efficiency, heat pump coefficient of performance (COP), system COP and storage efficiency were 70%, 4.2, 4.0, and 60%, respectively. Zhou et al. [15] investigated experimentally a hybrid solar cooling system consisting of solar collector arrays, a single/double hybrid effect absorption chiller, and a latent heat thermal energy storage tank containing HITEC® molten salt. The absorption chiller achieved COP of 0.73 and 1.09 for single effect and double effects, respectively. Moreover, it was shown that an optimized system can achieve an average seasonal cooling capacity of 102 kW, a seasonal COP of 0.88, and a seasonal solar fraction of 27.2% in typical meteorological summer conditions of Shanghai. Fan et al. [16] numerically studied the performance of a double-effect LiBr-water absorption system combined with solar collectors and a tube-shell thermal energy storage system filled with PCM. They found that a 12.6 m^3 LHTES system was capable of satisfying the 10 kW peak cooling demand of a 2400 m^2 office