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Performance evaluation of a solar water heater integrated with a PCM nanocomposite TES at various inclinations

Hussain H. Al-Kayiem [a,*], Saw C. Lin [b]

[a] Mech. Eng. Dept., Universiti Teknologi PETRONAS, 31750 Tronoh, Perak, Malaysia
[b] Department of Mechanical Engineering, Politeknik Ungku Omar, 31400 Ipoh, Perak, Malaysia

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Abstract

The present work presents and analyzes the results acquired from outdoor experimental measurements of a flat plate solar collector integrated with built-in thermal energy storage. Paraffin wax as a PCM and a nanocomposite of paraffin wax with 1.0 wt% of 20-nm nano-Cu particles were tested as the energy storage medium for TES. Three cases have been investigated, namely without PCM, with PCM, and with the Cu-PCM nanocomposite, at 10°, 20°, and 30° inclination angles of each case. The system performance was evaluated for water heating. The process involved a total change of the 60-l water tank at 7:00 PM and 7:00 AM. The use of water circulation of 0.5 kg/min and setting the collector at a 10° inclination angle was found to be the best operational condition. The measurement result of the tank water temperature at 7:00 AM, after 24 h of operation, was 35.1 °C when the system operated without TES, while the operation with the PCM and with the Cu-PCM nanocomposite resulted in 40.1 °C and 40.7 °C tank water temperatures, respectively. The best performances analyzed were at 10°, with efficiencies of 47.6%, 51.1% and 52.0% for the cases without PCM, with PCM and with Cu-PCM nanocomposite, respectively. This indicates that the enhancement of the system using TES with paraffin wax is considerable, while further enhancement is not significant in the case of nanocomposite. Further measurements with various flow rates are recommended to investigate the performance of the developed solar-TES integrated system.

Keywords: PCM; Solar collector; Nanocomposite; TES

1. Introduction

The use of domestic water heating utilizing solar energy for residential and industrial consumption is increasing in demand due to awareness of renewable energy technologies and their beneficial impact on the environment. However, the drawback of using solar energy systems is the non-continuous operation due to the lack of solar irradiation during the night. As a solution, thermal energy storage (TES) techniques have been proposed and evaluated from the points of view of the storage materials, the storage design, and the integration methods with the solar collector.

1.1. Integrated solar-TES

The advantage of using TES as an energy storage method is the absorption of the extra heat at peak radiation hours that is released when the solar radiation is absent. The purpose of TES is to reduce the temperature fluctuations during the peak solar radiation hours. The

* Corresponding author.
E-mail addresses: hussain_kayiem@petronas.com.my (H.H. Al-Kayiem), clsaw78@gmail.com (S.C. Lin).

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Nomenclature

A_c	area of solar collector (m^2)
C_p	specific heat (J/kg °C)
Cp_{LH}	specific latent heat (J/kg)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
η_c	collector efficiency (%)
ΔT	temperature different (°C)
I_T	total solar radiation (W/m^2)
Q_u	useful heat gain (W)
T	temperature (°C)
B_η, P_η	random and systematic uncertainty
W_η	total uncertainty or error (%)

Subscripts

c	collector
PCM	PCM
Nanocomp.	Cu-PCM nanocomposite
W	water
l,PCM	PCM during liquid phase
l,Nanocomp	Cu-PCM nanocomposite during liquid phase
s,PCM	PCM during solid phase
s,Nanocomp	Cu-PCM nanocomposite during solid phase

second reason to use TES is to minimize the heat loss from the solar collector by absorbing the excess heat from the absorber plate. As such, Kürklü et al. (2002) integrated 50 kg of paraffin into a 1.8 m × 1.8 m solar collector area to investigate the system performance experimentally on a 24-h basis. The experimental results indicated that 60% collector efficiency was obtained. The collector also exhibited high heat loss of 12.5 W/m^2 °C and 9.0 °C of temperature drop. To improve the performance, Khalifa et al. (2013) replaced the flat absorber plate with 6 circular pipe absorber plates and integrated it with 43 kg of paraffin wax. The experimental investigation was performed from January 2012 until March 2012. The results indicated that the collector efficiencies ranged from 45.0% to 54.0% with a 1.6 m × 0.8 m collector size. The solar collector top loss coefficients were 6.22 W/m^2 °C, 6.39 W/m^2 °C and 6.23 W/m^2 °C for the month of January, February and March, respectively. The high top loss coefficient in February was due to the high intensity of solar radiation, which increased the absorber plate temperature compared to the other months. Al-Hinti et al. (2010) stored paraffin wax inside the water storage tank instead of inside the solar collector. A total of 49 kg of paraffin wax was used and connected with 4 units of 1.5 m^2 area for the solar collector. By including the drawn off effect, the experimental investigation indicated that 55 °C of hot water temperature can be produced in the daytime, while 30 °C of hot water was obtained for the next morning. However, no collector efficiency was reported. Recently, Bouadila et al. (2014) published experimental results of a solar water heater integrated with latent heat TES in a configuration of two rectangular cavities. They concluded that their TES approach extended the operation of the system after sunset by approximately 5.0 h. The system efficiency varied from 25.0% to 35.0%.

1.2. PCM in TES

Thermal energy can be stored in the form of latent heat by using suitable phase change materials (PCMs), such as inorganic PCM, organic PCM and organic–inorganic PCM, which can offer high storage capacity per unit volume and per unit mass. The melting of a phase change material (PCM) enables the absorption of larger amounts of heat, which can be excessively available during the daytime. This stored heat can then be released to the surrounding medium during the evening and night hours as the PCM changes its phase again from liquid to solid. Another way to improve the heat storage medium is by using nano-additives. Various nano-fluids and nanocomposites have been reported, primarily for enhancement of the thermal conductivity. The thermal conductivity of paraffin wax was enhanced by 35% and 40% when mixed with multi-walled carbon nanotubes (MWCNTs) of 1% and 2%, respectively (Wang et al., 2009). The researcher doped 1% carbon nanotubes (CNTs) into an acid-based phase change material and found that the thermal conductivity was enhanced by 30.0% (Wang et al., 2010). Song and Youn (2005) reported an enhancement of 100% when epoxy was mixed with 1.5% carbon nanotube (CNT) mass fraction.

The specific heat capacity, C_p, of base materials exhibited enhancement by mixing with nanoparticles. Zhou and Zhao (2011) and Vajjha et al. (2010) reported decreased values of C_p of aqueous nanofluids. In contrast, Nelson et al. (2009) reported that the C_p of poly-alpha-olefin (PAO) was enhanced by 50.0% when mixed with 0.6% of graphite nanoparticles.

To date, nanofluid experimental investigations related to solar collectors have been reported, but no attempt has been made on the use of a nanocomposite as a PCM in an integrated TES with solar collector experimental work. Most of the reported works mainly focus on the laboratory characterization of the nanocomposite material properties.

Yousefi et al. (2012a,b) used MWCNT and Al_2O_3 nanofluid of 0.2% and 0.4% weight fractions to improve the fluid heat absorption. The experimental measurements revealed that the use of 0.2% MWCNTs as a surfactant improved the collector efficiency, but a decrease was found when 0.4 wt% was used.