Energy Conversion and Management 165 (2018) 137–151

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental investigation and comparative performance analysis of a compact finned-tube heat exchanger uniformly filled with a phase change material for thermal energy storage

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ARTICLE INFO

Keywords:
Thermal energy storage (TES)
Phase change material (PCM)
Solar domestic hot water (SDHW)
Effectiveness-number of transfer units (ε-NTU)
Fin efficiency

ABSTRACT

In the present paper, a latent heat storage system using a heat-transfer enhancement technique has been built and tested. The potential of using a natural phase change material of Moroccan provenance for energy storage was studied by experimental analysis. The enhanced heat transfer surface of the compact finned-tube heat exchanger presents geometric complications. Therefore, a new method based on equivalent circular fin efficiency for the calculation of the effective heat transfer surface area was developed and applied to the system under study. In order to carry out the performance analysis for this innovative system, charging and discharging experiments were conducted for different heat transfer fluid flow rates. It was found that increasing the flow rate from 0.2 to 1 l/min divides melting time by 2.5 and solidification time by four. The average effectiveness was calculated for each flow rate and was proven to decrease during charging from 0.95 for a flow rate of 0.2 l/min to 0.63 for 1 l/min. Likewise, increasing flow rate from 0.2 to 1 l/min for discharging process decreases heat exchanger effectiveness from 0.99 to 0.7. The combination of the effectiveness-number of transfer units method with the procedure that was developed to compute the effective heat transfer area lead to derive an empirical correlation. This equation was used to compare the finned-tube compact storage system with other heat and cold storage units. The comparison showed that the present system displayed satisfactory results. The second use of the correlation was to design, through a case study, a heat storage system suitable for solar domestic hot water production in a residential building.

1. Introduction

With the depletion of fossil energy resources and the alarming increase in greenhouse gas emissions leading to global warming, the need for renewable energies is becoming increasingly imperative. Solar energy is one of the most important since the solar radiation is the largest energy input of the Earth system with a flux of 1368 W/m^2 above the atmosphere [1]. The intermittent nature of this source of energy calls for considerable innovation in energy storage technologies. Indeed, a mastery of the latter bridges the gap between supply and demand for energy. Thermal storage is divided into sensible, latent and thermochemical [2]. Latent heat storage (LHS) is particularly interesting because it offers a high storage density and allows charging/discharging of energy at a constant temperature corresponding to the phase change.

Phase change materials (PCMs) have been a major research focus for latent energy storage over the last 30 years [3]. The advantageous thermal behavior of PCMs has been exploited in various fields of energy conservation [4].

Solar thermal power generation systems have been an important domain of application of LHS. Su et al. [5] performed comparative analyses on dynamic performances of a hybrid photovoltaic–thermal solar collector integrated with PCM. The effect of several parameters has been simulated and the position of PCM layer in the collector was found to play a significant role in the performance of the collector. Seitz et al. [6] studied the economic impact of integrating a LHS system to a direct steam generation power plant with parabolic troughs. A wide parametric study provided data for the levelized electricity costs that were used to recommend specific target values for new systems. Integrating PCM to buildings has also been experimentally and theoretically studied to obtain optimal thermal comfort. Sharifi et al. [7] evaluated, through simulation, the efficiency of integrating PCM in gypsum boards on the energy performance of buildings. They showed that choosing a suitable PCM improves thermal comfort by reducing peak temperature and extending the time during which temperature

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https://doi.org/10.1016/j.enconman.2018.03.041
Received 21 December 2017; Received in revised form 17 February 2018; Accepted 15 March 2018
0196-8904/

Nomenclature

Abbreviations

HTF	heat transfer fluid
LHS	latent heat storage
NTU	number of transfer units
PCM	phase change material
SDHW	solar domestic hot water

Symbols

A	heat transfer surface area (m^2)
C	constant specific for a tank design (kg/s/m^2)
Cp	specific heat capacity (kJ/kg·K)
d	inner diameter of the tube (m)
h	heat transfer coefficient (W/m^2·K)
L	latent heat (kJ/kg)
k	thermal conductivity (W/m·K)
m	fin parameter (m^{-1})
$\dot{m}$	mass flow rate (kg/s)
Q	thermal energy (kJ)
$\dot{Q}$	heat transfer rate (kW)
r	radius (m)
Re	Reynolds number
T	temperature (°C)
t	time (s)
U	overall heat transfer coefficient (W/m^2 °C)
v	velocity of the water inside the tube (m/s)
$\dot{V}$	volume flow rate (l/min)

Greek letters

δ	uncertainty (–)
ε	effectiveness (–)
η	efficiency
μ	dynamic viscosity of the water (Pa·s)
ρ	density of the water (kg/m^3)
τ	fin thickness (m)

Subscripts

e	equivalent
ext	external
f	fusion
i	inner
in	inlet
o	outer
out	outlet

stays within the comfort zone. Energy consumption of HVAC systems decreases as well. Prieto et al. [8] compared the performance of three space heating systems: two based on PCMs (palmitic acid and RT60 paraffin) in a plate heat exchanger and one using a hot water tank. The system using palmitic acid was found to have better performance during discharging, greater storage capability and lower cost. Erlbeck et al. [9] tested different PCM package shapes included in concrete blocks in order to adjust the thermal behavior of walls. The experiments showed that thin and positioned microencapsulated PCM layers generate fast phase change compared to massive blocks.

The integration of PCMs with cooling systems can effectively improve their performance [10–16]. Sokhansefat et al. [17] conducted a transient simulation of a 5-ton solar absorption cooling system that they validated with the data of the existing installation. The model was used to quantify the effect of various parameters of the performance of the system. The optimization lead to a performance enhancement of 28%. Ezan et al. [18] numerically studied the effect of integrating a PCM slab inside a beverage cooler on the energy consumption, the thermal stability and flow characteristics of air inside the cooler. PCM integration was proven to increase compressor off duration while preserving air temperature in the desired range. Other industrial applications of PCM have been explored as well. Itani et al. [19] tested a PCM on personal cooling vest used in hot environment. A fabric-PCM-desiccant combination was proposed for the aim of regulating body temperature and maintaining dry air around the skin. The air temperature and humidity increased respectively by 0.6 °C and 1.5 g/kg dry air in PCM-Desiccant case compared to PCM-only case. Nejman et al. [20] used microencapsulated n-hexadecane and n-octadecane to modify the thermoregulating properties of fabrics. Melting and crystallization temperatures change with heating/cooling rate, whereas phase change enthalpy is not affected. Latent heat storage finds an interesting application in industrial heat recovery. Indeed, the time and space gap between heat release and heat demand can be solved by PCMs. Johar et al. [21] integrated Erythritol used as PCM to Micro cogeneration system. A shell and tube heat exchanger was used to store exhaust heat of a single cylinder diesel engine. A percentage of energy up to 15.2% was saved. Ji et al. [22] built a LHS system intended to recover waste heat from a low temperature gas flow. They performed a 3D simulation taking into account natural convection and validated it with experimental results. After 4 h of heat recovery, the LHS unit stored 2239 kJ.

Production of solar domestic hot water (SDHW) has been a major application of latent heat storage. Indeed, since the 1980 s, the use of SDHW systems has increased at a rate of about 30% each year [3]. The main problem encountered while harvesting solar energy with these systems is that peak radiation is available at noon time, whereas maximum domestic hot water demand occurs in the evening or early in the morning. This leads to the necessity of implementing heat storage systems to lessen the mismatch between availability and demand. Conventional SDHW systems habitually store hot water. They are still the most widely adopted systems due to their economic advantage over newer alternatives. But this solution presents some disadvantages: water storage is cumbersome and weighty, sensible heat storage needs high temperatures meaning heat losses are considerable. Moreover, heat retrieval does not occur at constant temperature making a big part of the energy stored useless. The use of PCMs in SDHW production resolves some of these problems making it an interesting alternative. Indeed, their high heat storage density reduces the space taken by the storage unit. On the other hand, choosing the PCM with a melting temperature between 50 and 70 °C will help make most of the energy stored useful during retrieval.

Many researches have been conducted to investigate experimentally and/or numerically the effect of integrating PCMs to water heating systems. Nkwetta et al. [23] studied the potential of using PCMs in SDHW production in buildings to shift peak power demand based on a model including an experimentally validated hot water tank containing PCMs. Chaabane et al. [24] developed two 3D numerical models of an integrated collector storage solar water heater: one for sensible heat storage used to validate the model and one with PCMs integrated in the parabolic collector. Frazzica et al. [25] tested a hybrid sensible/latent heat storage system consisting of a water tank containing macro-encapsulated PCMs (RT65 paraffin and a salt hydrate eutectic mixture). The hybrid system showed a 10% increase in heat storage capacity after adding 1.3 dm^3 of PCM in a 48 dm^3 water storage tank. They also used the experimental results to validate a numerical model that proved to be accurate. Hosseini et al. [26] experimentally and numerically studied heat transfer performance of paraffin RT50 in a shell and tube heat