Renewable Energy 62 (2014) 571–581

Contents lists available at ScienceDirect

Renewable Energy

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

Experimental study of the phase change and energy characteristics inside a cylindrical latent heat energy storage system: Part 1 consecutive charging and discharging

Robynne E. Murray, Dominic Groulx*

Mechanical Engineering, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4R2

ARTICLE INFO

Article history:
Received 21 February 2013
Accepted 12 August 2013
Available online 11 September 2013

Keywords:
Latent heat energy storage
Dodecanoic acid
Phase change heat transfer
Natural convection
Solar domestic hot water

ABSTRACT

Solar domestic hot water (SDHW) systems are a cost effective and efficient way to pre-heat domestic water for hot water use in buildings. Currently used sensible energy storage systems (commonly using water as the storage medium) are simple and inexpensive, but require large amounts of storage material, and therefore are heavy and take up considerable space. Latent heat energy storage systems (LHESS) store the energy absorbed/released when a material goes through a phase transition: these materials are called phase change materials (PCMs). Because of the large quantities of energy that are stored during a phase change, latent heat energy storage is more dense than sensible energy storage, and can therefore reduce the weight and space requirements of the energy storage system. The main objective of this research is to study the heat transfer processes and phase change behavior of a PCM during consecutive charging and discharging of a LHESS. This leads to better understanding of the melting and solidification processes in order to optimize future LHESS design.

In part 1 of this paper the design of a LHESS that can operate under both consecutive and simultaneous charging and discharging modes is introduced. Dodecanoic acid is used as the PCM, as it has been shown to be safe, relatively inexpensive, and has a melting temperature in a range suitable for use with SDHW. Experimental results of consecutively charging and discharging the system are presented and the effect of the heat transfer fluid flow rate is explored. It was found that during charging a faster flow rate leads to shorter melting times; however, during discharging, the flow rate does not affect the rate of solidification.

1. Introduction

Solar domestic hot water (SDHW) systems are used to collect solar radiation to pre-heat domestic water for use in buildings. Solar energy is collected by a heat transfer fluid (HTF) (typically a glycol–water mix in colder Canadian climates) and transferred to the domestic water via a heat exchanger. These systems are charged when solar energy is available, and are discharged at irregular intervals throughout the day when there is a demand for domestic hot water in the building. Although SDHW systems make efficient use of the sun's energy, the space and weight requirements of commonly used water storage systems may not be suitable for some buildings. Using phase change materials (PCMs) in latent heat energy storage systems (LHESS) can reduce the weight and space requirements of energy storage for SDHW systems [1]. PCMs store energy during melting and release energy during solidification. When the PCM melting temperature falls within the operating temperature range of the application, in this case SDHW, they have high energy densities compared to sensible heat storage systems, and can store up to 14 times more energy than water in the same volume [1]. From an energy efficiency point of view, PCM storage systems have the advantage that their operation is nearly isothermal [2].

There has been significant research published on LHESS, including studies of various PCM thermal properties, LHESS geometry, heat transfer mechanisms, and heat transfer enhancement designs. A wide range of PCMs have been studied for their heat transfer and thermal properties, and organic PCMs have been shown to be less corrosive [3], to have less sub-cooling, and to have less deviation of thermal properties during melting and freezing cycles than inorganic PCMs [4]. Many storage system geometries have been considered as well, and vertical cylindrical containers [5]

---

* Corresponding author. Tel.: +1 902 494 8835.
E-mail address: dominic.groulx@dal.ca (D. Groulx).

0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.08.007

Nomenclature

Dimensional variables

C_p	heat capacity (J kg^{-1} K^{-1})
m	mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
Q	energy (kJ)
$\dot{Q}$	power (W)
R	distance from center-point of LHESS (cm)
t	time (s)
T	temperature (K)

Greek letters

δ	Uncertainty
Δh_m	latent heat of fusion (J kg^{-1})
ΔT	temperature difference (K)

Subscripts

amb	ambient
cold	cold HTF
f	final
i	initial
in	inlet
hot	hot HTF
l	liquid
m	melting
out	outlet
s	solid
ste	associated with the Stefan number
water	water

Abbreviations

LHESS	latent heat energy storage system
HTF	heat transfer fluid
PCM	phase change material
SDHW	solar domestic hot water

Definitions of non-dimensional variables

Ste	Stefan number ($C_p \Delta T_{ste}/\Delta h_m$)

and multi-tube arrays [6] have been shown to be the best geometry for enhancing heat transfer due to the large heat transfer surface areas and the presence of natural convection. Spherical containers and encapsulation have their advantages as well. Encapsulated PCMs have a barrier which protects the PCM from harmful interaction with the environment, and encapsulation provides sufficient surface area for heat transfer while maintaining structural stability [7,8]. Some researchers have even chosen rectangular flat plate containers for PCM storage because the melting/solidification is symmetric about a plane at the center of the plate, and the surface area to volume ratio for heat transfer is largest compared with other geometries studied [9].

Due to the low thermal conductivity of PCMs, heat transfer enhancement mechanisms are essential to the efficient operation of a LHESS [10]. Heat transfer inside a LHESS has been shown to be mainly by conduction during the initial stages of the charging (melting) process, followed by natural convection heat transfer once a sufficient volume of PCM has melted [2]. During discharging (solidification), the primary mechanism of heat transfer has been shown to be conduction [11]. Many different methods to enhance heat transfer through PCMs have been studied, and the use of fins and/or high conductivity matrixes has been shown to be the most promising options [12]. The proper selection of materials, especially with respect to their thermal conductivity, is also very important as they directly affect the time required for the PCM to melt [13]. Longitudinal fins in a horizontally oriented LHESS with erythritol as the PCM have been shown to meet the requirements for a solar absorption cooling system [14]. This system was also used to determine the optimum operating parameters (inlet temperature and flow rate) to enhance the performance of the solar absorption cooling system. In one analytical study radial fins were found to be the most effective fin type [15], however, most experimental results show that longitudinal fins are best because they do not interfere with natural convection during melting and aid in the solidification process [16]. Using the past literature as a guide, a vertical cylindrical container design with longitudinal copper fins has been chosen for the research presented in this paper.

This study has been broken into two stages: part 1) the experimental study of a LHESS during separate charging/discharging, and part 2) the experimental study of a LHESS during simultaneous charging/discharging. This paper presents the first stage of this research in which a vertical cylindrical LHESS is consecutively charged and discharged. Experimental results demonstrating the heat transfer processes present, phase change behavior of the PCM, and the energy storage capacity of the LHESS are presented here. The effect of the HTF flow rate on charging and discharging is also investigated.

2. Experimental setup

2.1. Phase change material

Dodecanoic acid, or lauric acid ($CH_3(CH_2)_{10}COOH$, 98% pure, Alfa Aesar) was chosen as the PCM for this experiment because it is safe, relatively inexpensive and has a melting temperature of 42.5 ± 0.5 °C, which is in the desired temperature range for a SDHW application [4]. It was also found to have stable thermal properties during thermal cycling [17]. Table 1 outlines the thermophysical properties of dodecanoic acid.

2.2. Apparatus

A 60.96 cm (2 ft) long, 20.32 cm (8 in) outer diameter acrylic plastic container with 1.9 cm ($^3/_4$ in) thick fiberglass insulation is used to store the PCM. Two copper pipes (1.27 cm (1/2 in) in diameter) with four longitudinal copper fins extending the full length of the container, are used to charge and discharge the LHESS. The fins are 0.061 cm (0.024 in) thick and vary in width from 2.54 to 4.45 cm (1–1.75 in), depending on their location, so that each extends to within 1.27 cm (1/2 in) from the inside of the container wall. Both pipes are oriented vertically through the acrylic plastic container, as shown in Fig. 1. Hot HTF is circulated through one pipe

Table 1
Dodecanoic acid thermophysical properties [20].

Molecular weight	200.31 kg/kmol
Density of powder at 20 °C/liquid at 45 °C	869/873 kg/m^3
Fusion temperature	42.5 ± 0.5 °C
Latent heat of fusion	182 kJ/kg ± 5%
Heat capacities solid/liquid	2.4/2.0 kJ/kg K ± 3%
Thermal conductivities solid/liquid	0.150/0.148 W/m K
Viscosity	0.008 Pa s