Applied Energy 175 (2016) 16–30

Contents lists available at ScienceDirect

Applied Energy

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

A thermal battery mimicking a concentrated volumetric solar receiver

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HIGHLIGHTS

- Early initiation of phase change material takes place inside receiver when no mesh is used.
- Aluminum mesh enhances uniform energy storage in receiver.
- Maximum temperature reduces in phase change material with increasing rotational speed of receiver.
- Temperature parameter $\left(\varphi = \frac{T-T_{in}}{T_{max}-T_{in}}\right)$ increases along x-axis with increasing rotational speed.

ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 17 April 2016
Accepted 27 April 2016

Keywords:
Thermal battery
Phase change
Volumetric solar receiver
Metallic mesh
Rotation

ABSTRACT

A mobile thermal battery is a new concept in renewable energy technologies and provides effective and innovative solutions for solar energy utilization in various applications. A thermal battery mimics a volumetric solar receiver, which uses phase change material and metallic meshes in the energy storing medium. In the present study, performance analysis of a mobile thermal battery is presented. $LiNO_3$ is used as the phase change material and aluminum meshes are incorporated to enhance the heat diffusion inside the receiver. The concentrated solar heating is incorporated resembling the actual field data. In order to achieve uniform heating of the phase change material inside the receiver, the rotation of the receiver is introduced along its symmetry axis. It is found that the aluminum meshes improve the heat diffusion significantly and enhances the melting rate of the phase change material inside the receiver. This, in turn, minimizes the local excessive heating and early initiation of the phase change process inside the thermal battery. The rotation of the receiver reduces the maximum temperature of the working fluid through suppressing local excess heating. In addition, receiver rotation lowers the maximum and minimum temperature difference inside the receiver; however, with increasing rotational speed, a small delay is observed for the time completing the phase change process inside the receiver.

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1. Introduction

The earth daily receives significant amount of radiation energy from the sun, which is more than global energy needs for an entire year. One of the challenges is to harness the sun's energy effectively and make it useable efficiently where and when needed. The direct utilization of solar energy can be grouped into two categories, which include direct electricity generation via photovoltaic panels and thermal utilization through solar receivers. Since the availability of sun's radiation energy is limited to day light time, harvesting of solar energy is only possible during this period. Recent developments in thermal energy utilization from the sun radiation using phase change materials facilitates to increase the efficiency of the harvesting, which enables to extend solar thermal energy utilization in various applications [1]. The new concept of a mobile thermal battery, introduced in this study, is one of the promising energy technologies to be developed for effective solar energy utilization in near future. The proposed mobile thermal battery utilizes solar radiation and storing thermal energy during the irradiation period. Introducing concentrated solar heating and phase change material in the storing media increases the possibility for extended use of thermal batteries in space heating and cooling applications. The thermal batteries can be removed from the storage sites and, later, they can be installed easily to the application sites. The mobility of thermal battery can be extremely attractive for many practical applications and it can be chargeable in solar heating site. Although concept of a thermal battery is noble, parts and materials forming a thermal battery has been well studied. The thermal battery purposed consists of parts

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http://dx.doi.org/10.1016/j.apenergy.2016.04.110
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Nomenclature

A_{mush}	mushy zone constant (–)
c	computational constant (–)
c_p	specific heat (J/kg K)
g	gravitational acceleration (m/s^2)
h	sensible enthalpy (J/kg)
h_{ref}	reference enthalpy (J/kg)
H	total enthalpy (J/kg)
ΔH	latent enthalpy (J/kg)
r	radius (m)
S	source term (m/s)
T	local temperature (K)
T_{in}	initial temperature (K)
$T_{liquidus}$	liquids temperature (K)
$T_{solidus}$	solidus temperature (K)
$T_{\max}$	maximum temperature (K)
$T_{\min}$	minimum temperature (K)
$\Delta T_{\max}$	$(T_{\max} - T_{\min})$ temperature difference (K)
T_{ref}	reference temperature (K)
ΔT	$(T - T_{in})$ temperature difference (K)
T_{∞}	fluid inside temperature (K)
u	velocity along the x-axis (m/s)
v	velocity along the y-axis (m/s)
$\vec{V}$	velocity vector (m/s)

Greek letters

β	coefficient of thermal expansion (1/K)
γ	liquid fraction (–)
ρ	density (kg/m^3)
μ	viscosity (kg/m s)
k	thermal conductivity (w/m k)
ω	angular velocity (rad/s)
φ	$\left(\frac{T-T_{in}}{T_{\max}-T_{in}}\right)$ temperature parameter (–)

including cylindrical tube (shell), phase change material, and conductive meshes. The cylindrical tube encapsulates phase change material, which is used as a storing media, and conductive meshes in phase change material increases thermal conductivity of a storing media. One of the challenges is to achieve a uniform heating of phase change material in the thermal battery. This is because of the low thermal conductivity of the phase change material and external heating of the thermal battery shell via solar radiation. The concept of thermal conduction tree in phase change material improves the heat transfer rates inside the thermal battery. Consequently, this configuration is incorporated in the present study.

Considerable research studies were carried out to examine solar thermal receivers. Performance characteristics of a volumetric solar receiver and presence of an absorber plate with a selective surface were studied by Yilbas and Kaleem [2]. They showed that the gain parameter of the concentrated solar volumetric receiver improved by 15% when the absorber plate was located at the left face of the tube opposing the trough surface. The ceramic foam volumetric solar air receiver was investigated by Wu and Wang [3]. They indicated that the transient behavior of volumetric solar air receiver was crucial to the receiver's controllability, and to some extent, the plant's safety. Analysis of a latent heat thermocline storage system with encapsulated phase change materials incorporating concentrated solar power was carried out by Nithyanandam et al. [4]. They studied the influence of the design configuration and operating parameters on the dynamic storage and delivery performance of the system. They reported the configurations that maximize the utilization of the storage system. Phase change material for high temperature thermal energy storage and heat transfer was studied by Elmozughi et al. [5]. Their findings revealed that the presence of the void had profound effects on the thermal response of the encapsulated phase change material during both energy storage and retrieval processes. In addition, melting and solidification per unit mass of the phase change material took longer when the void was present. The thermal characteristics of a volumetric solar absorption system were examined by Siddiqui and Yilbas [6]. They demonstrated that the performance parameter attained the highest value for the absorber plate location at the top of the channel, which was about 10% higher than those corresponding to the other locations. This was more pronounced with increasing Reynolds number and solar concentration. The characterization study of a nano-fluid volumetric solar absorber was carried out by Taylor et al. [7]. They indicated that concentrated thermal radiation energy could cause localized phase change in a nano-fluid, which resulted in non-uniform heating in the absorber. The metal-foam enhanced phase change material storage system was examined by Dukhan et al. [8]. They showed that the use of metallic foam improved the low thermal conductivity of the phase change material, which drastically increased the charging/discharging times of the process. The presence of nanofluids with encapsulated nanoparticles in a thermal energy storage system was investigated by Cingarapu et al. [9]. They demonstrated that the volumetric thermal energy storage could be further improved if thermal cycling was conducted in a narrower temperature range. The phase change material with graphite foam in relation to high-temperature latent heat storage systems of concentrated solar power plants was studied by Zhao et al. [10]. They showed that the graphite foam could improve the heat transfer performance as well as the exergy efficiency of the latent heat thermal energy storage systems. A numerical analysis of melting process in a shell-and-tube latent heat storage for concentrated solar power plants was carried out by Fornarelli et al. [11]. They demonstrated that the enhanced heat flux, due to natural convective flow, lowered about 30% of the time needed to charge the heat storage unit. Thermal energy storage using phase change material coupled to a solar receiver was investigated by Verdier et al. [12]. They presented the thermal protection of the central receiver of concentrated solar power plant using a tower, which was subject to considerable thermal stresses. Heat transfer analysis pertinent to triplex concentric tube with phase change material for thermal energy storage was carried out by Jian-you [13]. He developed the relation among fluid temperature and interface of solid and liquid phase of phase change material versus time and axial position. The time-wise variation of energy stored/released by the system was also presented. The thermal and rheological properties of hybrid nanocomposite phase change material for thermal energy storage were investigated by Parameshwaran et al. [14]. They demonstrated that the increased mass proportion of hybrid nanocomposites resulted in the increased viscosity indicating the presence of relative dependencies between the thermal properties and the viscosity of the hybrid nanocomposite phase change material. Numerical study on thermal energy storage performance of phase change material under non-steady-state inlet boundary was carried out by Tao and He [15]. They showed that when the average heat transfer fluid inlet temperature in an hour was fixed at a constant value, the melting time (time required for PCM

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