Energy Conversion and Management 153 (2017) 362–373

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental study of a latent heat thermal energy storage system assisted by a heat pipe network

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ARTICLE INFO

Keywords:
Latent heat
Thermal energy storage
Heat pipe network
Phase change material
Experimental study
Charging
Discharging

ABSTRACT

The charging and discharging processes of a latent heat thermal energy storage system assisted by a heat pipe network was experimentally studied. Rubitherm RT55 was chosen as the phase change material (PCM) and was enclosed within a vertical cylindrical container. A network of simulated heat pipes was embedded within the PCM to enhance the heat transfer. The heat pipe array consisted of a primary central heat pipe with an array of secondary heat pipes. The primary heat pipe transfers the thermal energy from the heat source to the heat sink while the secondary heat pipes transport the extra thermal energy into to the phase change material during the charging process or retrieve it from the phase change material during the discharging process. The heat pipe network was simplified by employing an arrangement of copper and acrylic pipes. Water was used as the heat transport fluid, which was circulated through the pipe network with a relatively high velocity to decrease the temperature drop, similar to what happens inside a real heat pipe. The effects of different heat transfer fluid flow rates and temperatures on the thermal performance of the latent heat energy storage system were studied. The results indicated that the heat transfer fluid flow rate and temperature have significant impacts on the total charging time of the system. It was also found that the while the flow rate of the heat transfer fluid has minimal effect on the discharging process, the temperature of the heat transfer fluid plays a significant role.

1. Introduction

Thermal energy storage (TES) systems are promising solutions for the intermittency issues associated with renewable energy resources, especially solar energy. Latent heat thermal energy storage (LHTES) has the advantages of a larger energy storage density, nearly isothermal operation, and a wide range of operational temperatures in comparison to sensible heat thermal energy storage (SHTES). These advantages not only make LHTES systems a good option for solar power generation but also qualify them for other applications such as waste heat recovery [1], electronic cooling [2] and domestic heating and air conditioning [3,4].

Despite the above-mentioned advantages, the inexpensive and commonly used phase change materials (PCMs), which are used as storage media, have relatively low thermal conductivities. This leads to much longer charging and discharging processes which limit the performance of LHTES systems. Different heat transfer enhancement techniques have been studied and developed to resolve this issue and improve the heat transfer within the PCMs. Numerous studies have been conducted on employing fins and extended surfaces as an effective method to enhance heat transfer within LHTES systems. Urschitz et al. [5] investigated the functionality of a bimetallic finned tube for a LHTES system with $NaNO_3$ as the PCM. Sheikholeslami et al. [6] studied the utilization of snowflake shaped fins to enhance the solidification of a PCM enclosed in a square container. The influence of internal horizontal fins on the melting process of octadecane was reported by Sharifi et al. [7]. Kabbara at al. [8] experimentally studied the charging and discharging processes of a dodecanoic acid based LHTES system assisted by a finned tube heat exchanger.

Another method to improve the heat transfer in LHTES systems is the impregnation of highly conductive porous materials within PCMs. Mesalhy et al. [9] numerically investigated the melting process within a high thermal conductivity porous matrix saturated with PCM. Martinelli at al. [10] experimentally tested the thermal behavior of RT35HC enhanced by copper foam. Zhao et al. [11] used graphite foam to enhance the thermal conductivity of a magnesium chloride when used as a PCM. Meng and Zhang [12] experimentally and numerically studied the impregnation of copper foam with a paraffin wax PCM. The melting process of a eutectic mixture of Li_2CO_3 and K_2CO_3 in a LHTES unit partially filled with porous media was numerically investigated by Xu et al. [13].

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http://dx.doi.org/10.1016/j.enconman.2017.10.019
Received 26 June 2017; Received in revised form 17 September 2017; Accepted 7 October 2017
0196-8904/

Nomenclature

Latin

c_p	specific heat, $J\,kg^{-1}\,K^{-1}$
h_{sl}	latent heat of fusion, $kJ\,kg^{-1}$
L	length, m
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
$\dot{Q}$	power, W
t	time, s
T	temperature, °C

Greek

ΔT	temperature difference, °C
ρ	density, $kg\,m^{-3}$
λ	thermal conductivity, $W\,m^{-1}\,K^{-1}$

Subscripts

HTF	heat transfer fluid
m	melting

A similar approach to enhance the heat transfer in LHTES systems is the dispersion of high thermal conductivity particles into the PCM. Dhaidan et al. [14] studied the melting of n-octadecane enhanced with CuO nanoparticle both experimentally and numerically. Yuan et al. [15] analyzed the thermal performance of palmitic-stearic acid enhanced by graphene nanoplatelets and expanded graphite. Das et al. [16] numerically investigated the thermal performance of a LHTES unit with n-eicosane enhanced with graphene nanosheets. Ghalambaz et al. [17] studied the effects of nanoparticle dispersion on the melting process of octadecane enclosed in a square container. The solidification process of n-octadecane enhanced with dispersed titanium dioxide (TiO_2) nanoparticles was experimentally studied by Motahar et al. [18]. An extensive and comprehensive review of the thermal conductivity enhancement methods in LHTES systems is presented by Gasia et al. [19] and Fan and Khodadadi [20].

Another proposed a technique to enhance the heat transfer within the latent heat thermal energy storage systems is the use of metallic alloys as phase change materials. Risueño et al. [21] studied the structural characterization and thermal stability of three alloys with different aluminum content ($Mg_{71}Zn_{28.9}$ $Al_{0.1}$, $Mg_{70}Zn_{24.9}$ $Al_{5.1}$ and $Mg_{70}Zn_{24.4}$ $Al_{5.6}$) as the phase change material for latent heat storage application. In Birchenall et al. [22,23] work, the CuMgSi ternary alloys were used as promising phase change materials for latent heat thermal energy storage. Blanco-Rodríguez et al. [24] analyzed the possibility of using magnesium based eutectic alloys as PCM for latent heat thermal energy storage in concentrated solar power generation applications.

Utilizing passive heat transfer devices such as heat pipes to enhance the heat transfer within the PCM is another technique which has been investigated in experimental and numerical studies [25–28]. Robak et al. [29] experimentally investigated a LHTES system enhanced by heat pipes or fins. It was found that employing heat pipes leads to significant improvement in both the charging and discharging processes of the system. Shabgard et al. [30] used a thermal resistance network model to analyze the thermal response of a heat pipe assisted LHTES with potassium nitrate as the PCM. Liu et al. [31,32] experimentally studied the thermal performance of a heat pipe assisted LHTES system with paraffin wax as the PCM. They analyzed the charging and discharging processes individually as well as a simultaneous charging/discharging operation mode of the system. Mahdavi et al. [33,34] developed a new heat pipe configuration for a specific application in concentrated solar power generation. They optimized the geometry of the heat pipe to enhance the performance of the system. Sharifi et al. [35] used a novel heat pipe-metal foil approach to enhance the thermal performance of a LHTES system with n-Octadecane. Murray and Groulx [36,37] experimentally investigated the phase change heat transfer of a LHTES with dodecanoic acid as the PCM during consecutive and simultaneous charging and discharging operations. Nithyanandam and Pitchumani [38] numerically studied the influence of quantity and orientation of embedded heat pipes on the thermal performance of a LHTES system during charging and discharging. Lohrasbi et al. [39] employed a two-dimensional numerical model to analyze the discharging process of a heat pipe assisted LHTES system with nano-enhanced water as the PCM. Wu et al. [40] experimentally studied the thermal performance of a heat pipe assisted PCM based battery thermal management system. It was shown that combining forced air convection with a heat pipe assisted PCM enhances the cooling process of the system significantly. Krishna et al. [41] reported the results of their experimental study on heat pipe assisted nano-enhanced Tricosane PCM for electronic cooling applications. They investigated the effects of PCM fill volume, heat input, and nanoparticle concentration on the thermal performance of the system. The charging and discharging processes of a finned heat pipe assisted LHTES system with potassium nitrate were studied by Tiari et al. [42,43] using a two-dimensional numerical model. It was found that heat pipe spacing is an important parameter to the thermal performance of the system during both melting and solidification of the PCM. Tiari and Qiu [44] developed a transient three-dimensional model to evaluate the charging process of a heat pipe assisted LHTES system with a eutectic mixture of sodium nitrate and potassium nitrate as the PCM. The results indicated that heat pipe network arrangement and natural convection within the molten salt play key roles in the thermal response of the system during the charging process.

In this paper, thermal performance of a LHTES system assisted by a novel heat pipe network is studied experimentally. This novel network of heat pipes consists of a primary heat pipe and four secondary heat pipes. The primary heat pipe transfers the thermal energy from the heat source to the heat sink. The secondary heat pipes transport the surplus thermal energy into the PCM during the charging process while retrieving the stored energy from the PCM during the discharging process. The main components of the test rig, shown in Fig. 2, are the cylindrical container filled with the PCM and embedded primary and secondary heat pipes, water tank and a pump to circulate hot or cold Heat Transport Fluid (HTF), the flow and temperature measurement devices, and data acquisition system. The experimental study was conducted to demonstrate the functionality of the suggested heat pipe network and to examine the effects of the HTF temperature and flow rate on the thermal performance of the LHTES system during the charging, discharging, and partial charging processes.

2. Experimental setup

2.1. Phase change material

RUBITHERM RT55 was chosen as the PCM for the experiment due to its relatively low cost, lab safe melting temperature, stable thermophysical properties during experiment testing, and relatively high latent heat of fusion. The thermophysical properties of RUBITHERM RT55 are listed in Table 1.

2.2. Apparatus

The PCM container was made of a 30.48 cm (1 ft.) long, 21.59 cm (8.5 in) outer diameter clear cast acrylic tube with a 0.635 cm (0.25 in) wall thickness. The container was wrapped by a 3.81 cm (1.5 in) thick