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Experimental study on the thermal performance of a new type of thermal energy storage based on flat micro-heat pipe array

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ABSTRACT

The thermal performance of an air-based phase change storage unit is analyzed and discussed in this study. The thermal energy storage uses flat micro-heat pipe array (FMHPA) as the core heat transfer component and lauric acid as phase change material (PCM). An experimental system is devised to test the heat storage–release property of the storage unit under different inlet temperatures and flow rates of the heat transfer medium. The performance of the storage unit and the melting/solidification curves of the phase change material are obtained based on extensive experimental data. Experimental results indicate that the flat micro-heat pipe array exhibits excellent temperature uniformity in the heat storage–release process, and the performance of the storage unit is efficient and steady.

1. Introduction

Phase change thermal energy storage can store discontinuous and unstable waste heat, thereby solving the mismatching problem in the time and intensity of heat supply and demand. Phase change thermal storage has a lot of advantages such as high density, stability, and controllability. However, the poor thermal conductivity of the phase change material (PCM) has restricted the performance of the thermal storage system [1]. Therefore, there is a necessity to study the heat transfer enhancement on phase change thermal storage. Many studies have been made to improve the performance of the phase change thermal storage systems.

Jegadheeswaran and Pohekar [2] reviews the implementation of the various techniques for enhancing the thermal performance of latent heat thermal energy storage (LHTES) units, including using extended surfaces, employing multiple PCMs method, thermal conductivity enhancement, and micro-encapsulation of PCM comprehensively. Their effort was realized to provide information on the relative merits and demerits of various possible enhancement techniques. Sharma and Shukla [3] deals with the thermal properties of the binary mixtures based on fatty acids and find that these materials have good thermal stability and can be potential applied for building application. Shamsundar and Srinivasan [4] described a heat exchanger with a latent heat thermal energy storage which uses an array of cylindrical tubes as fluid passage channels. They analyzed the two-dimensional phase change process of salt or other PCMs as storage medium. Shon et al. [5] investigated the thermal behavior of a fin-tube heat exchanger filled with solid PCM to improve the heat storage rate of an automotive coolant waste heat recovery system. Morrison and Abdel-Khalik [6] have presented four mathematical models to analyze a storage system consisting of one PCM of a similar geometry. Their research established the foundation of mathematical analysis of thermal storage. Dolado et al. [7] developed a model to simulate the performance of a thermal energy storage (TES) unit in a PCM-air heat exchanger. Their study used a kind of slab with bulges to enhance heat transfer between the air and the macro-encapsulated PCM. Although the bulges increase the area of the slab, the heat transfer enhancement of PCM side and air side is not satisfactory enough. Halawa and Saman [8] discuss the results of the numerical study on a phase change air-based flat slab thermal energy storage and investigate the effect of various parameters on the thermal performance of the storage. Their results enable the selection of appropriate design parameters for practical system for specific application to optimize the performance of system. Charvat et al. [9] investigated the possibility to employ latent heat of fusion in PCMs for TES in air-based solar systems using laboratory experiments and numerical simulations. The performed investigations showed the potential use of LHTES in air-based thermal systems with a narrow temperature operation range. Saman et al. [10] analyzed and discussed the thermal performance of a phase change thermal storage unit, which is a component of a roof-integrated solar heating system being developed for space heating of a house. So far, most of the studies on latent thermal storage using air as heat transfer medium mainly focus on simulations, while the experimental studies are relatively insufficient.

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Nomenclature

FMHPA	flat micro-heat pipe array
TES	thermal energy storage
PCM	phase change material
HTM	heat transfer medium
TST	thermal storage tank
ID	isolated duct
LA	lauric acid
Dimensional variables	
E	energy (kJ)
m	mass (kg)
c_p	specific heat capacity (kJ/kg °C)
T	temperature (°C)
H_m	latent heat capacity (kJ/kg)
V	volume flow rate (m^3/h)
t	time (min)
ρ	density (kg/m^3)
x	horizontal coordinate axis x (mm)
y	horizontal coordinate axis y (mm)
z	vertical coordinate axis z (mm)
Subscripts	
cold	cold HTM
hot	hot HTM
i	initial
f	final
in	inlet
out	outlet
st	stored
su	supplied
re	released

Heat pipe is a kind of heat transfer component with superior heat conduction performance. This component can be used to develop highly efficient heat exchangers because of its small size and excellent heat transfer capability. Naghavi et al. [11] review and critically discuss previous investigations and analysis on the incorporation of heat pipe devices into latent heat thermal energy storage with heat pipe devices. They aim at providing the necessary information on the features and limitations of each technique to enable further research in the area. They also draw the conclusion that the complementary use of the heat pipe and the PCM overcomes their disadvantages like overheating of heat pipe and low thermal conductivity of the PCM. Liu et al. [12] presented a new thermal storage system using heat pipe as the heat transfer elements. The performance of the new system under three basic different operation modes, the charging only, the discharging only and the simultaneous charging/discharging modes were studied. The extensive experimental results show that the thermal storage performs the designed functions very well and can both store and release the thermal energy efficiently. Robak et al. [13] investigated LHTES utilizing heat pipes or fins and identified that the heat pipe-assisted configuration transfers approximately twice the energy between a heat transfer fluid and PCM relative to both the fin-assisted LHTES and the non-heat pipe, non-fin configurations during solidification. Nithyanandam and Pitchumani [14] consider an approach to reducing the thermal resistance of LHTES through embedding heat pipes to augment the energy transfer from the heat transfer fluid (HTF) to the PCM. They also carry out the detailed parametric studies to assess the influence of the heat pipe and the LHTES geometric and operational parameters on the performance of the system during charging and discharging. Malan et al. [15] suggested a modular phase change storage (PCS) system using heat pipe with fins to improve heat transfer to and from the storage material. A storage system for solar tower technology, in which PCM needs to be exposed to sufficient heat transfer area to melt or solidify at sufficient rates, was achieved using heat pipes with metallic fins. The researches above developed the new thermal energy storage based on heat pipe and achieved prominent results. However, most of them used the traditional circular heat pipe which has many disadvantages like low efficiency, smaller contact area with the given volume, higher cost and technical complexity in manufacturing which limited the further development in thermal energy storage system.

This study presents a new type phase change TES based on flat micro-heat pipe array (FMHPA) [16] using air as the heat transfer medium (HTM). FMHPA is an excellent heat transfer component with many advantages, including lightness, larger contact area, higher efficiency, and excellent temperature uniformity. The actual performance of the storage is analyzed based on extensive experimental data, which provide basis for further investigating and practical applications.

2. Experimental setup and procedure

2.1. FMHPA-TES unit

An FMHPA-TES unit that uses air as HTM is designed and analyzed in this study. Fig. 1 shows that the size of the device is 388 mm × 105 mm × 740 mm. The FMHPA-TES unit mainly comprises four parts, namely, (1) thermal storage tank (TST), (2) FMHPA, (3) PCM, and (4) isolated duct (ID). The tank is welded together with a stainless steel plate. A total of 12 rectangular holes (82 mm × 5 mm) are machined on the top and base plates of the TST. FMHPA is inserted into the holes of the base and top plates (and extended 130 mm in length) as the heating and cooling sections, respectively. A rubber seal gasket is installed in the hole to avoid the leaking of PCM. The TES surface is covered with a heat insulation layer.

As depicted in Fig. 2, an FMHPA with fin is used as the core heat transfer component. This component measures 80 mm × 19 mm × 740 mm and weighs 421 g. FMHPA is an excellent heat transfer component; its structure is a multi-channel microgroove flat tube with a working medium (acetone, with 20% of liquid filling ratio). Fin is welded on the surface of FMHPA using the flat welding technology to decrease the thermal contact resistance significantly.

FMHPA can be divided into three sections depending on its operating principle (cooling, storage, and heating sections). When warm air flows across the bottom duct of TES, heat can be transferred to the heating section of FMHPA. The working medium in the heating section correspondingly absorbs heat and evaporates. The vapor forced by pressure differential flows up to the storage section, releases energy, and then condenses to the liquid. The heat is transferred across the wall of FMHPA and is absorbed by PCM, which then undergoes a phase change and stores energy. The liquid working medium in FMHPA returns to the heating section by means of gravity and capillary force. When heat is needed, the cold air flows across the top duct of TES, and FMHPA absorbs the heat from PCM and transfers it to the cooling section. Thereafter, the