Applied Thermal Engineering 73 (2014) 975–983

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

The melting of phase change material in a cylinder shell with hierarchical heat sink array

Huawei Liu [a, b], Saiwei Li [a, b], Yu Chen [a, b], Zhiqiang Sun [a, b, *]

[a] School of Energy Science and Engineering, Central South University, Changsha 410083, China
[b] Hunan Key Laboratory of Energy Conservation in Process Industry, Central South University, Changsha 410083, China

HIGHLIGHTS

- We apply inner tubes of varying size for shell-and-tube latent heat storage system.
- The effects of the number of lower-hierarchy tubes and size ratio are studied.
- Size variation of inner tubes has a positive effect on the heat transfer of the device.
- The number of lower hierarchy tubes affects the device subtly.

ARTICLE INFO

Article history:
Received 19 June 2014
Accepted 26 August 2014
Available online 4 September 2014

Keywords:
Latent heat thermal storage
Phase change
Hierarchical structure
Shell and tube

ABSTRACT

Temporal and spacial mismatch between thermal energy supply and consumption occurs in many industrial processes, like harvesting thermal energy from intermittently ejected exhaust gas. To even out this mismatch, heat exchangers filled with phase change materials (PCMs) are widely accepted. Up till now, most of the heat exchangers take the shape of an annulus, or shell and tube design with uniform tubes, which may not be the ideal structures for their purpose. In this paper, a shell and tube design with hierarchical tube array in place of the uniform tubes is proposed and studied. The shell is assumed to possess a fixed temperature and negligible thickness. The tube arrays, where still water is stored, are assumed to be heat sinks with no fluid movement. Inside the shell, one tube is placed at the centre, forming the higher hierarchy; multiple other tubes encircle the central tube, forming the lower hierarchy. A paraffin blend, RT27, is filled in between. We investigate systematically the advantage of this new design over the annulus. Two structural parameters are explored numerically: the number of lower hierarchy pipes n and the ratio of higher hierarchy tube diameter to lower hierarchy tube diameter r. The results of changing the parameters are analysed in terms of paraffin melting time, water heating speed and exergy efficiency, in both dimensional and dimensionless forms. We show that the paraffin melting time is shortest for combination $n = 2$, $r = 2$. Also, during the unstable melting process, exergy efficiency fluctuates differently for different cases, but merges together ultimately.

1. Introduction

The necessity of thermal storage systems comes from the temporal and spacial mismatch between energy production and consumption [1]. Latent heat storage devices, which utilize phase change, are capable of providing high energy storage density while maintaining a relatively constant temperature during charging/discharging, making them a particularly attractive type of thermal storage system [2]. In order to lay down the foundation for optimized latent heat storage system design, the past decades see a great number of literatures on phase change mechanism, phase change in specific geometries, and performance evaluation of phase-change thermal storage systems. Researches in this field have been carried out extensively analytically [3–7], experimentally [8–18], and numerically [9–13,16,18–27], and are actively being continued today.

Due to the low thermal conductivity possessed by most phase change materials (PCMs), some kind of heat transfer enhancement technique is required to improve charging/discharging rates of the latent heat thermal storage system. One of these techniques is to apply an optimized geometry for the PCM container [14].

* Corresponding author. 932 Lushan Nanlu, Changsha 410083, Hunan, China. Tel.: +86 731 88876209; fax: +86 731 88879863.
E-mail addresses: zqsun@csu.edu.cn, sunzq86@foxmail.com (Z. Sun).

http://dx.doi.org/10.1016/j.applthermaleng.2014.08.062
1359-4311/

Nomenclature

ΔH	latent heat content in the mushy zone, J/kg
C_{mushy}	mushy zone constant
c_p	specific sensible heat at constant pressure, J/(kg K)
Fo	Fourier number
g	gravitational acceleration, 9.8 m/s^2
Gr	Grashof number
h	sensible enthalpy, J/kg
k	thermal conductivity, W/K
L	latent heat, J/kg
MF	melt fraction
n	number of lower-hierarchy heat sinks
p	pressure, Pa
S_i	source term
R	characteristic length, m
r	diameter ratio between higher and lower-hierarchy heat sinks
Re	Reynolds number
T	temperature, K
t	time, s
u	fluid velocity, m/s

Greek symbols

β	liquid fraction
Δ	difference
θ	dimensionless temperature
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
ψ_1	exergy efficiency, type one
ψ_2	exergy efficiency, type two

Subscripts and superscripts

*	dimensionless
HS	heat sink
i, j	dimension vectors
liquidus	the liquidus point
ref	reference value
W	shell
solidus	the solidus point
M	mean value

Considerable research has been done to explore the effect of various container geometries on latent heat thermal storage performance. The geometries usually took on the forms of cylinders (concentric or eccentric annulus) [24–27], spheres [9,11,13], rectangular/slabs [5,12,15–17], and shell and (multi-) tube design [6,7,14,18,20–22]. Among the container geometries, latent heat thermal storage systems with shell and tube design were the most prevalent one, accounting for more than 70% [2].

Multi-tubes were theoretically treated as a single tube by Ghoneim [6]. Using this assumption, variation of solar fraction with storage volume for gaseous based and liquid based systems were studied. Fully implicit finite difference method was used. Calculation for the two-dimensional model with natural convection was not done. However, natural convection during PCM melting plays an important role, and was proved later by Khodadi and Zhang [13]. Costa et al. [7] investigated theoretically a latent heat storage system with rectangular aluminum tubes that acted both as the PCM container and as a fin to help to enhance the rate of heat transfer in the PCM. Ismail et al. [20] studied PCM solidification inside a typical shell and tube container. The heat transfer fluid flowed inside the tubes and the PCM was filled in the shell around the tubes. The effects of varying Reynolds and Stefan numbers, different phase change temperature, system length and outer radius of fusion for the tubes were studied. They showed that only the phase change temperature was insignificant to system performance, all other investigated parameters had significant impact.

Hamada et al. [21] studied experimentally the effects of carbon-fibre chips and the carbon brushes, as additives, on the heat transfer rate in the PCM for a shell and tube type apparatus. The investigated apparatus had four identical tubes arranged axis-symmetrically. Hendra et al. [18] investigated a shell and tube design with many tubes using both experimental and numerical methods. However, in their numerical study, only a small region containing two one-quarter-of-a tube was used as the computational domain; the shell was not considered in the numerical procedure. The boundaries of the domain were defined as symmetry faces. Also, natural convection was not considered in the PCM region, assuming that conduction is dominant where the PCM layer was thin enough.

Agyenim et al. [14] made a comparison between two container geometries: a concentric annulus and a shell with four identical heat transfer tube. Their experimental results showed that the heat transfer rate during charging was improved using multi-tube in place of the single tube. By comparing the temperature gradients in the axial, radial and angular directions, they verified the validity of ignoring thermal conductivity in the direction parallel to the heat transfer fluids, and thus validating the representation of a cylindrical container two-dimensionally. Moreover, their study indicated that it is questionable to represent multi-tubes by a single tube at the centre of the shell. It has been pointed out that the emergence of hierarchy in the movement of mass on earth [28], is dictated by the constructal law [29–31]. The notion of hierarchical distribution, as in “few large and many small”, may be applied to the shell-and-tube thermal storage system design to yield superior results. However, to the knowledge of the authors, previous investigations on shell and tube container geometry had multi-tubes of uniform sizes. Size variation inside the same shell was not taken as an investigated parameter.

The present study proposes a hierarchical tube array design inside the shell. The multi-tubes are designed non-uniformly both in terms of arrangement and in terms of size, following the general concept of “few large and many small”. Moreover, to simplify the numerical simulation, the tubes are assumed to contain stationary heat transfer fluid. Thus, they only serve as heat sinks whose temperatures may vary in time. Diameter ratio of different tube hierarchy and various numbers of lower hierarchy heat sinks are investigated. The resulting velocity distribution, temperature field and melting pattern are solved numerically. Dimensional and dimensionless evaluation indices are used to evaluate the performance of different hierarchical combinations.

2. Numerical method

2.1. Physical model

In the present work, we study numerically PCM melting in a cylindrical storage device with hierarchical arrays of heat sinks within, as shown in Fig. 1. The system is akin to a tube and shell storage system, except that the tubes are replaced by a special array of heat sinks, which are structured in the following manner. Each array of heat sinks is divided into two hierarchical layers. The inner layer consists of one single heat sink, placed at the center of the