Energy Conversion and Management 135 (2017) 188–199

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance investigation of a lab–scale latent heat storage prototype – Numerical results

Hakeem Niyas, Sunku Prasad, P. Muthukumar *

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India

ARTICLE INFO

Article history:
Received 15 September 2016
Received in revised form 2 December 2016
Accepted 26 December 2016

Keywords:
Latent heat storage
Thermal modeling
Effective heat capacity method
Optimization
Performance prediction

ABSTRACT

In the current study, numerical analysis of the charging and discharging characteristics of a lab-scale latent heat storage (LHS) prototype is presented. A mathematical model is developed to analyze the performance characteristics of the LHS prototype of shell and tube heat exchanger configuration. Effective heat capacity (EHC) method is implemented to consider the latent heat of the phase change material (PCM) and Boussinesq approximation is used to incorporate the buoyancy effect of the molten layer of the PCM in the model. For proper modeling of velocities in the PCM, Darcy law's source term is added. The governing equations involved in the model are solved using a finite element based software product, COMSOL Multiphysics 4.3a. The number of embedded tubes and fins on the embedded tubes are optimized based on the discharging time of the model. Various performance parameters such as charging/discharging time, energy storage/discharge rate and melt fraction are evaluated. Numerically predicted temperature variations of the model during charging and discharging processes were compared with the experimental data extracted from the lab-scale LHS prototype and a good agreement was found between them.

1. Introduction

Design and optimization of latent heat storage (LHS) prototypes require an extensive analysis of the heat transfer characteristics between the phase change material (PCM) and heat transfer fluid (HTF). The number of embedded HTF tubes in the heat storage prototypes and fins on the HTF tube's outer surface play a significant role in transferring the heat between them. Un-optimized prototype with more number of the HTF tubes and fins would lead to higher material inventory. Additionally, the overall weight of the system will increase too. Hence, a detailed optimization study is needed to have a cost-effective LHS system. To achieve this, many experiments with different geometric configurations, by varying the number of the HTF tubes and fins, need to be conducted. This approach has two major disadvantages; (i) the development cost of the different prototypes to be tested is high and (ii) for up scaling, new prototypes need to be developed for getting the optimized module.

Development of a numerical tool for the optimization of geometric configuration and performance evaluation of LHS prototype is an ideal solution to overcome the above limitations. But the mathematical modeling of the LHS prototypes, especially in the multidimensional case is complex [1]. The major problems involved in the modeling are (i) inclusion of latent heat of PCM, (ii) natural convection of the melt and (iii) conjugate heat transfer between the PCM and HTF. Because of these complications, initially, researchers developed the relatively simplified analytical models for LHS systems including melting and solidification [2–5]. Huang [4] presented an analytical solution to the 1D momentum equation considering the buoyancy flow during the melting of a vertical semi-infinite region. The author found that the upward flow has slightly greater velocity than the downward flow. Lamberg [5] developed an approximate 1D analytical model to study the solidification process in a finned LHS system. It was found that the solidification process was dominated by heat conduction, while the natural convection flow occurs only during the commencement of the solidification process. Although these analytical results aid in getting the theoretical concepts of the phase change process, they are not able to solve the real-time practical problems.

With the advent of CFD, several authors performed the 2D and 3D transient numerical analyses on LHS system. Hu and Argyropoulos [6], Verma et al. [7], Dutil et al. [8] and Al-abidi et al. [9] presented detailed review of the various mathematical models of LHS systems, their application, and limitations.

---

* Corresponding author.
E-mail addresses: pmkumar@iitg.ernet.in, pmuthukkumar@yahoo.com (P. Muthukumar).

http://dx.doi.org/10.1016/j.enconman.2016.12.075
0196-8904/

Nomenclature

A_{MUSH}	mushy zone constant
C_P	specific heat (J kg^{-1} K^{-1})
E_L	latent energy stored/discharged (J)
E_S	sensible energy stored/discharged (J)
F	body force (N m^{-3})
g	gravitational acceleration (m s^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
L_F	latent heat of fusion (J kg^{-1})
P	pressure (Pa)
S	source term (N m^{-3})
T	temperature (°C)
T_M	phase change temperature (°C)
t	time (s)
v	velocity (m/s)

Greek symbols

β	thermal expansion coefficient (K^{-1})
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)
γ	kinematic viscosity (m^2 s^{-1})
θ	melt fraction

Subscripts

C	charging
D	discharging
EFF	effective
ini	initial
L	liquid/liquidus
S	solid/solidus

Symbols

∇	differential operator

Abbreviations

BDF	backward differentiation formula
EHC	effective heat capacity
FEM	finite element method
HTF	heat transfer fluid
LHS	latent heat storage
PCM	phase change material

Phase change phenomena such as melting and solidification come under the category of moving boundary problems in CFD. Two types of the solution techniques were developed to handle the moving interfaces numerically, viz. time-dependent grid method and fixed grid method. In the time-dependent grid method, the melt front is tracked continuously, and the latent heat release/absorption during melting/solidification is treated as a moving boundary condition. This type of boundary condition demands the incorporation of a deforming/moving mesh so that the melt interface coincides with the grid elements. Fixed grid method found wide application due to its simplicity and ease of implementation. The primary advantage of fixed grid approach is that the latent heat evolution is accounted in the governing equation by defining either an enthalpy or an effective specific heat or a heat source [10]. Some researchers compared the various fixed grid methods for accurate solutions. Lamberg et al. [11] and Zhang et al. [12] compared the numerical results of both effective heat capacity (EHC) method and enthalpy method with their experimental data. They found that the results of EHC method were found to be more accurate than the enthalpy method. Farid et al. [13] developed a 2D numerical model for simulating a case of successive solidification and melting using EHC method. They concluded that the EHC method was successful in analyzing 2D heat transfer with phase change and predicting the heat transfer rate during the phase change of materials which have narrow as well as wide melting ranges.

Several researchers reported the numerical analyses of the LHS systems of various contours. Vyshak and Jilani [14] numerically studied the melting of PCM for three geometrical configurations namely rectangular, cylindrical and cylindrical shell using a 1D Crank-Nicholson finite difference scheme. They found that for same volume and surface area, the cylindrical shell took less time to melt and this effect was prominent at increased mass of PCM. Esen et al. [15] theoretically compared two models of a cylindrical shell based LHS system, viz. model 1 (PCM kept in the tube) and model 2 (PCM kept in the shell). They studied the effects of various geometric and thermal parameters; *viz*., cylinder radius, PCM volume, mass flow rates and inlet temperatures of HTF on the charging time. They found that the model 2 recorded a shorter charging time than model 1. They concluded that as the thickness of PCM increases, charging time of the PCM also increases due to higher thermal conduction resistance.

Lacroix [16] developed a 2D theoretical model to analyze the transient behavior of a shell-and-tube LHS system. A series of numerical experiments were undertaken, and the results showed that for a selected PCM, the geometric parameters must be carefully chosen in order to improve the performance of the storage system. Ng et al. [17] formulated a 2D numerical model to study the melting behavior of PCM in a horizontal cylindrical annulus isothermally heated from the inner wall. They observed that melting rate is enhanced by the increase in natural convection. Meanwhile, the melting of the PCM in the bottom part of the annulus is very inefficient due to the convective flow in the melt. Seddegh et al. [18] developed two numerical models for evaluating the performance of the shell-and-tube LHS systems, viz. conduction model and combined conduction-convection model. They found that the results of combined conduction-convection model agreed well with the experimental data than the conduction model. They also concluded that charging is a natural convection dominant process and discharging is a conduction dominant process.

Esapour et al. [19] formulated a 2D numerical model to analyze the influence of the number of HTF tubes in an LHS system during the charging process. They reported that by increasing the number of HTF tubes, the bottom region of the shell is influenced by the additional heat transfer surface thereby reducing the total melting time by about 29% for the four tubes system. Recently, Allouche et al. [20] developed a 3D numerical model to study the phase change heat transfer of a microencapsulated PCM slurry in a tube-bundle type heat exchanger. But, the number of tubes used in the heat exchanger was not optimized. Also, they have not incorporated any heat transfer enhancement technique such as adding fins to the tubes.

The direction of HTF flow during the charging and discharging processes also impacts the performance of the LHS systems. Gong and Mujumdar [21] developed a 2D FEM based model to investigate the effects of two alternative operation modes, introducing the cold and hot fluid from the same and opposite ends of HTF tube. Numerical experiments showed that injecting the cold and