Applied Energy 231 (2018) 116–126

Contents lists available at ScienceDirect

Applied Energy

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

Fast and experimentally validated model of a latent thermal energy storage device for system level simulations

R. Waser[a,*], F. Ghani[b], S. Maranda[a], T.S. O'Donovan[b], P. Schuetz[a], M. Zaglio[c], J. Worlitschek[a]

[a] Competence Centre Thermal Energy Storage, Lucerne University of Applied Sciences and Arts, Lucerne, Switzerland
[b] School of Engineering & Physical Sciences, Heriot-Watt University, Edinburgh, United Kingdom
[c] Sunamp Ltd, Macmerry, United Kingdom

HIGHLIGHTS

- Computationally efficient method proposed to characterise latent storage units.
- Model validated using two different salt hydrate based latent storage devices.
- Model applicable with analytic equations for effective conductivities.
- High accuracy proven without calibration.
- Approach suitable for annual energy system simulations with latent storages.

ARTICLE INFO

Keywords:
Latent thermal energy storage
Numerical model
Thermal characterisation
Phase change material
Energy system simulations

ABSTRACT

Latent storages utilising phase change materials (PCM) to store thermal energy offer a considerably higher energy density at a nearly constant temperature level in comparison to sensible storage systems. Despite this advantage, only a few latent storage technologies have been integrated successfully to the market. This may be due several engineering challenges and in particular the lack of a computationally fast and accurate mathematical model to facilitate the optimal incorporation of latent heat storages into an energy system. The presented study fills this gap and proposes a new, fast and experimentally validated mathematical modelling approach for latent heat storage units. The numerical model proposed combines high accuracy, low computational effort and numerical stability. The validation was performed with two different commercial latent storage units supplied by Sunamp Ltd. with a nominal phase change temperatures of 34 °C and of 58 °C. Both units use a salt hydrate based phase change material in combination with a fin-tube heat exchanger. The proposed model may be used for both fast system level performance investigations as well as latent storage design for a given application. It may therefore be implemented in commercial software packages such as TRNSYS [1] or Simulink [2].

1. Introduction

According to the International Energy Agency [3], heat accounted for a third of the world energy consumption in 2011. Around three-quarters of final energy use for heat was provided by fossil fuels [3]. Since final energy consumption of heat is much larger than electricity, especially in domestic dwellings [4], the end user's flexibility and self-consumption of renewables may be significantly increased using thermal energy storage. Thermal energy storage systems are hence regarded as a key technology for enabling increased share of renewable energy in the supply system [5].

The main advantage of latent storages systems is to store heat compactly in a narrow temperature range [6]. This allows the effective storage in applications, which include isothermal or nearly isothermal processes such as refrigerant evaporation or condensation. The efficiency of air conditioning systems [7] heat pumps with defrosting of the air/refrigerant heat exchangers [8], heat pump water heaters [9] or industrial processes generating waste heat [10] can be increased using latent storage systems. Finally, they can be integrated in the space heating systems [11] or used to store thermal energy for domestic hot water supply [12] due to their higher volumetric energy density compared to sensible storages.

Research in the field of latent storage technology mainly focuses on the enhancement of the heat transfer or the optimization of phase

* Corresponding author.
E-mail address: remo.waser@hslu.ch (R. Waser).

https://doi.org/10.1016/j.apenergy.2018.09.061
Received 19 April 2018; Received in revised form 2 September 2018; Accepted 6 September 2018

change material properties. The optimal dimensioning and integration of latent storages in energy systems, however, is a key requirement to fully exploit the advantages of latent storage systems with regard to cost and energy savings. Dynamic computer models are a promising approach to tackle this challenge. Key requirement of such models is low computational effort, high accuracy and stability.

In this work, a new modelling approach capable of predicting the behaviour of the latent heat storage in an energy system is proposed. The model allows to conduct long-term system simulation (e.g. on a yearly basis) dependent on changing boundary conditions and may therefore be implemented in TRNSYS [1] or Simulink [2].

"Heat Batteries" manufactured by Sunamp Ltd. [13] were used for model calibration and validation. These Heat Batteries are salt hydrate based latent storage units. They are equipped with a fin-tube heat exchanger (HEX), which transfers heat from a heat transfer fluid to the PCM surrounding the HEX and vice versa.

In the following chapter, the modelling approaches for the design and dimensioning of latent heat storage systems will be reviewed.

2. Numerical modelling approaches

The modelling of latent storage systems is based on a mathematical formulation that describes the solid/liquid phase change. However, closed analytical solutions are not available, since the underlying equations are of nonlinear nature.

The numerical methods applied in research to describe phase changes can be divided in adaptive grid and fixed grid methods. Using the adaptive grid methods, the exact location of the solid/liquid interface is evaluated on every grid point for each time step and thus the grid has to be adopted for every time step. Fixed grid methods do not require an explicit treatment of the solid/liquid interface. Instead, the position is estimated by the calculated temperatures. However, fixed grid methods require a scheme able to cope with strong nonlinearities. The major advantage of fixed grid methods is that mass- momentum and energy equations may be applied independent on the present phase of the material. Accordingly, the mathematical calculation of the phase change can be achieved through simple modifications of existing heat transfer numerical methods [14].

The fixed grid approaches can be further categorised into the enthalpy method and the effective heat capacity method [15]. Governing equations are introduced that are applied for both, the discretised solid and the liquid phase. Using the enthalpy based method the enthalpy is described as a temperature dependent algebraic expression [16]. A phase change temperature range (the so-called mushy zone) is defined in which the phase change enthalpy is added or subtracted to the specific temperature dependent enthalpy of the PCM. Thus, the solid/liquid interface is not explicitly tracked but its location is defined by the mushy zone. In the effective heat capacity method, the mathematical function corresponding to the heat capacity, theoretically defined only in the sensible case, is extended to account for the latent heat [14]. Measurements (e.g. Differential Scanning Calorimetry DCS) may be used for both methods [15,17]. Neglecting natural convection, the governing energy equation reads

$$\rho \cdot \frac{\partial h}{\partial t} = \nabla \cdot (\lambda \nabla T) \tag{1}$$

for the enthalpy formulation and employs or uses ρ, λ and h as the temperature dependent density, thermal conductivity and enthalpy of the PCM and T as the PCM temperature. The effective heat capacity method is based on the following equation:

$$\rho \cdot c_{p,eff} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) \tag{2}$$

Here, $c_{p,eff}$ is the temperature dependent effective heat capacity of the PCM. The advantages of the enthalpy method is the better numerical stability, however, interims steps to calculate the temperature field are required. Contrary, the effective heat capacity method calculates the temperature field directly [17]. For both approaches, the finite volume method (FVM) as well as the finite element method (FEM) can be applied to solve numerically the equations using geometries such as finned heat exchangers. Both, the enthalpy and the effective heat capacity method are introduced in commercially available computational heat transfer codes [18]. Hence, the methods have been extensively used in the past to investigate the heat transfer in latent heat storages using fin-tube heat exchangers. Due to the high computational burden resulting from the high spatial resolution required to investigate complex HEX geometries, the methods presented have mostly been used for 2-dimensional geometries or only for small 3-dimensional geometries

Velray et al. [19] studied the solidification process of a tube heat exchanger with internal fins. A 2-dimensional enthalpy-based model was used. Experimental data of temperatures at fixed positions were compared to the numerical data. The comparison showed good agreement. Similar work was performed by Jmal et al. [20]. A numerical study of PCM solidification in a finned tube heat exchanger including natural convection was performed in their work. The 2-dimensional model, based on the enthalpy method, was validated with experimental data. Therefore, temperatures at fixed positions are compared in this work. Khalifa et al. [21] published a numerical and experimental study on solidification around axially finned heat pipes. The enthalpy-based method was used and again the 2- dimensional model was validated using temperatures measurement at fixed positions.

Neumann et al. [22] combined a complex 3-dimensional model based on the effective heat capacity method with a 1-dimensional model to investigate the heat transfer in a latent storage using a fin and tube heat exchanger. Within the former model, half a fin and a fin gap filled with PCM was modelled and the 1-dimenisonal model was then used to model the entire heat exchanger pipe. Using this approach, the computational burden could be considerably reduced. However, the computational time required was still around 30 min on a recent workstation for a charging process. Zauner et al. [23] modelled a discharging process of a finned tube latent heat storage unit using effective heat capacities. To reduce the computational effort, they exploited the rotational symmetry of the heat exchanger geometry.

The computational efficiency for a small 2-dimensional domain of a latent storage geometry was comprehensively investigated by Pointner et al. in [24]. Both, the enthalpy and the effective heat capacity method were investigated. The study showed that for a mesh size of 20x21, the computational time highly depends on the algorithm used but remains in any case considerable because of the relatively high number of elements resulting from the 2-dimensional geometry. A 1-dimensional model can lead to a considerable reduction of the computational time. However, an analytic source term for the description of the heat transfer from PCM to HTF or vice versa is required on this case.

To the best knowledge of the authors, no numerical model of a fin-tube latent storage exists in literature, which is suitable for system simulations over an extended period of time with low computational effort and high accuracy. In the next chapter, the proposed modelling approach will be explained in detail. The first section deals with the numerical model developed in the study. In the second section, the experimental apparatus developed by Heriot-Watt University and the experimental procedure are described.

3. Methods

3.1. Numerical modelling approach

3.1.1. Governing equation and discretisation

The basis of the numerical approach applied in the present study is a 1-dimensional energy governing equation that describes conductive heat transfer. Convective effects are tackled introducing an effective thermal conductivity of the material. The 1-dimensional governing equation is given in Eq. (3).