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Research Paper

A simplified approach for modelling latent heat storages: Application and validation on two different fin-and-tubes heat exchangers

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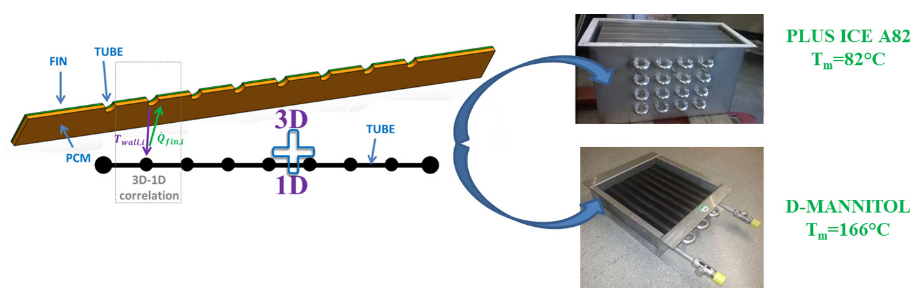
HIGHLIGHTS

- A validated modelling approach for simulating latent heat storages is presented.
- The model is suitable for fin-and-tubes heat exchangers using PCMs.
- The model combines 1D components for tubes and simplified 3D for fins.
- Validation has been realised on 2 systems with different exchangers and materials.

GRAPHICAL ABSTRACT



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ABSTRACT

Latent thermal energy storage systems represent a promising alternative to traditional sensible storages, but their exploitation requires a careful design of the system. The present paper reports a mathematical model for the simulation of thermal energy storage systems with phase change materials (PCMs). The model is suitable for the description of a latent heat storage using a fin-and-tube heat exchanger. Accuracy and computational effort are both taken into consideration, by coupling a 1D model for the tubes of the heat exchanger and a reduced 3D model for the material and fin domains. The developed model has been validated for two systems, realised at ITAE and ISE, differing for the PCM employed and the constructive characteristics of the heat exchanger. Results show that the model has a good accuracy and could predict the behaviour of the storages within 40 W error in case of powers and 1 K in case of heat transfer fluid temperatures. When a stable PCM was used, the average deviation between the PCM temperature in experiments and simulation was lower than 0.6 K.

1. Introduction

One of the headline targets of the EU 10-year strategy Europe 2020 is the sustainable growth with a low carbon economy. By 2020, the EU aims at reducing its greenhouse gas emissions by at least 20%, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of 20% or more [1].

According to these general goals, the technologies for the use of renewable energy sources have been strongly developed during the last years. Among renewable energies, the use of solar thermal energy is now proposed for applications covering different fields like domestic solar heating and cooling [2], solar process heat [3], concentrated solar power (CSP) plants [4] and solar desalination [5]. In order to efficiently exploit the potential of this energy

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Nomenclature

A_c	cross section, m^2
c_p	specific heat, kJ/(kg K)
D	hydraulic diameter, m
f	factor area
g	gravitational constant, m/s^2
h	convective coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
l	length, m
N	number
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}$	heat flux, W/m^2
Ra	Rayleigh number
Re	Reynolds number
s	thickness, m
T	temperature, K
t	time, s
u	velocity, m/s
U	circumference, m

Greek letters

β	expansion coefficient, K^{-1}
ρ	density, kg/m^3
μ	dynamic viscosity, m^2/s

Subscripts

amb	ambient
ext	external
lam	laminar
sym	symmetry
turb	turbulent

Abbreviations

CFD	Computational Fluid Dynamics
CSP	Concentrated Solar Power
DSC	Differential Scanning Calorimetry
HEX	Heat Exchanger
HTF	Heat Transfer Fluid
LTES	Latent Thermal Energy Storage
PCM	Phase Change Material
TES	Thermal Energy Storage

source, the development of advanced thermal energy storage systems (TESS) is widely recognised as a crucial topic. In fact, an efficient TESS can increase the exploitability of solar thermal energy reducing the impact of the typical discontinuous behaviour of solar radiation and its unpredictable variability due to atmospheric conditions. One further application where TESS can help reducing energy consumption is conventional process heat. By storing and reusing waste heat, processes could become more energy efficient. The most common TESS technology for temperatures below 100 °C is based on storage of thermal energy in hot water tanks using only the sensible heat of the water and its temperature variation. Nevertheless, it is quite known that there are other opportunities to efficiently store heat. Among them, latent thermal energy storage (LTES), based on the employment of phase change materials (PCMs), where heat is stored in the phase change from solid to liquid, is an interesting alternative [6–8].

LTES are very promising because of the following properties:

- High energy density in a narrow temperature range.
- Isothermal heat exchange during phase change process.
- Solidification/melting temperature of PCM depends on the material, thus it is possible to tailor the proper material for each application in order to obtain the charge/discharge of the storage at the desired temperature.

Despite the advantage in use of PCM for TESS, their practical utilization is often limited by the low thermal conductivity of most PCMs [9]. Because of this, it is necessary to properly design the storage system in order to maximise the heat transfer efficiency (i.e. charging/discharging power) maintaining a high energy storage density. This implies the development of accurate dynamic simulation models that can take into account the complex heat transfer phenomena between the heat transfer fluid (HTF), flowing inside the heat exchanger, and the PCM and within the PCM itself. Since analytical solutions are available only for simple geometries, different approaches have been proposed which allow to define the same governing equations both for solid and liquid phase, taking into account the phase change either by specifically defined enthalpy evolutions (enthalpy method) or by an effective heat capacity (effective heat capacity method) [10]. These data are derived from experimental characterization of the PCM itself. These approaches, coupled to the commercial diffusion of CFD software, have further enlarged the possibility to simulate more complex LTES configurations with good accuracy [11]. In [12] Dutil et al. have reported a comprehensive review about different numerical approaches, simulated geometries and materials. As reported in [13], most of the existing numerical models of LTES have been developed for simplified geometries (e.g. 1D and 2D). Despite this approach allows to limit the computation time, it cannot properly represent real LTES configurations, which often require more accurate and detailed 3D simulations [14] Accordingly, different papers have been recently published, dealing with the 3D numerical simulations of LTES for different applications. In [13] a shell and tube heat exchanger filled with a ternary mixture of salts with melting temperature of 142 °C was numerically simulated by implementing a 3D model in COMSOL. The simulated results were experimentally validated with good accuracy. Starting from the validated model, a parametric study was conducted, by varying several operating parameters. Main results confirmed that the charging process is primarily dominated by convection, leading to a faster process than the discharging. The HTF inlet temperature is more influencing the charging/discharging phase duration than the HTF flow rate. Meng and Zhang [15] have experimentally and numerically investigated a tube-in-tank LTES, embedding copper foam into paraffin, in order to enhance the effective thermal conductivity. A detailed 3D simulation model, implemented in Fluent, was developed and validated to analyse the heat transfer mechanisms of the realised storage. The simulations confirmed that, thanks to the embedded copper foam, the temperature distribution inside the storage was uniform. Also in this case the natural convection was dominating the charging phase while the conduction was the main heat transfer mechanism during discharging phase. Zauner et al. [16] have developed and modelled a fin-and-tube heat exchanger employing high-density polyethylene (HDPE) as PCM. The model, implemented in Fluent, showed a good agreement with the experimental data. Particularly, due to the high viscosity of the molten HDPE and the small fin pitch, the natural convection inside the storage was reasonably neglected. Nevertheless, the problem