NUMERICAL MODELLING OF HIGH TEMPERATURE LATENT HEAT STORAGE

de Gracia A[1], Pointner H[2], Vogel J[2], Tay N.H.S[3], Liu M[4], Johnson M[2] and Cabeza L.F[5*].
*Author for correspondence

[1]Departament d'Enginyeria Mecanica, Universitat Rovira i Virgili, Av. Paisos Catalans 26, 43007 Tarragona, Spain
[2]Institute of Technical Thermodynamics, German Aerospace Center (DLR), Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
[3]School of Mechanical and Systems Engineering, Newcastle University International Singapore, 180 Ang Mo Kio Ave 8, Singapore 569830, Singapore
[4]Barbara Hardy Institute, University of South Australia, Mawson Lakes Boulevard, Mawson Lakes, South Australia 5095, Australia
[5]GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA Pere de Cabrera S/N 25001 Lleida, Spain
E-mail: lcabeza@diei.udl.cat

ABSTRACT

Numerical tools are widely used to optimize designs of latent heat storage systems as well as to control their operative conditions and control strategies. Within this context, the aim of the authors is to compare the performance of the different available numerical methodologies, which are used to model the phase change processes occurring in a high temperature heat storage system. The models are based on different types of discretization, use different methodologies to approach the phase change, and are implemented in different software platforms. Moreover, the numerical results are compared against experimental data from a test facility consisting of a flat plate latent heat storage tank with a measured PCM melting temperature at 219.5°C. The comparison of the different numerical methodologies presented in this research does not only focus on the agreement against experimental data, but on the computational cost, speed and convergence performance, as well. The results indicated that all four models provide good agreement in comparison to the experimental results. However, they differ significantly regarding convergence behavior. While a C-based model is recommended for simulation models with a small number of elements and small time steps, the models implemented in MATLAB perform better for simulation models with a high number of elements and large time steps.

INTRODUCTION

The phase change process within latent heat storage has been subject of study during the last decades [1-3]. Analytical solutions of the melting and solidification process require semi-infinite domains and specific boundary and initial conditions, which suppose important simplifications from the analysed case study. Within this context, numerical methods have been identified as a suitable tool to optimize designs and control strategies of latent heat storage systems [4]. There are several numerical methodologies which have been used to study the solid-liquid phase change phenomena, which can be found in purpose-built codes for specific situations (using platforms such as MATLAB or C compilers), or adaptations of commercial software packages (such as CFD codes). The use of the different numerical platforms usually depends on the boundaries and complexity of the problem and authors expertise, however, there are no comparative studies between them in terms of computational cost, accuracy and numerical efficiency.

Moreover, there are several approaches to overcome numerically the phase change process, in which there should be highlighted enthalpy method [5], the effective heat capacity method [6] and the source term method [7]. In addition, different discretization schemes can be found to discretize the domain of the solid-liquid phase change [8].

This research validates experimentally and compares the performance of four models, with different numerical platforms, phase change approaches and discretization schemes against experimental data. The numerical efficiency, accuracy, computational cost and convergence behaviour would be analysed and compared between the four models describing a solidification process within a flat plate storage system.

EXPERIMENTAL SET-UP

The four models analysed in this research are validated and compared against experimental data provided from a flat plate heat storage set-up at DLR [9], shown in Figure 1.

The storage tank presents four PCM chambers separated by channels through which the heat transfer fluid (HTF) flows (Mobiltherm 603). The two inner PCM chambers are 80 mm thick, while the other two have half of width. The purpose of these two outer chambers is to minimize boundary effects on the inner two chambers, were thermal evolution is measured using Type K (Class 1) thermocouples. Moreover, the tank has a height of 1010 mm and is well insulated. The used PCM is an eutectic mixture of technical grade quality $NaNO_3$ (46wt%) - KNO_3 (54wt%) with a measured phase change temperature of 219.5ºC.

Figure 1 Experimental set-up of flat plate latent heat storage at DLR [9].

NUMERICAL METHOD

A discharge process of 8 hours of the flat plate heat storage system is simulated using four different models. Symmetry is used to reduce number of elements to compute inside of one of the inner PCM chamber in the direction normal to HTF. On the other hand, no symmetry can be applied in the direction of HTF due to thermal gradient of fluid through the channel. The discretized domain is highlighted in red in Figure 2 and defined in Figure 3.

Adiabatic boundary conditions were applied to top and bottom surfaces of channel, due to use of insulation. Moreover, the HTF is not considered in the model, and constant heat transfer coefficient of 200W/m^{2}K was applied to the convective interface between HTF and PCM. This value was supported by experimental data [9].

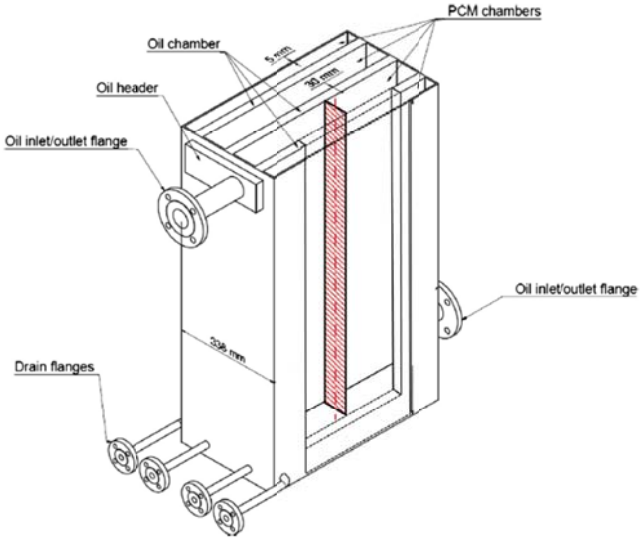

Figure 2 Sketch of storage tank and 2D-plane cut for simulation before applying symmetry condition [10]

The effect of natural convection inside the melted region of the PCM is considered using an effective thermal conductivity function correlating with the dimensionless Rayleigh number in all used models. This approach was developed by Farid and Husian [11] and is the same for all examined models, which makes the results comparable among each other. Moreover, a melting range of 4K was considered in all four analysed models, which are presented and classified in Figure 4 according to the approach to model the phase change and the used software.

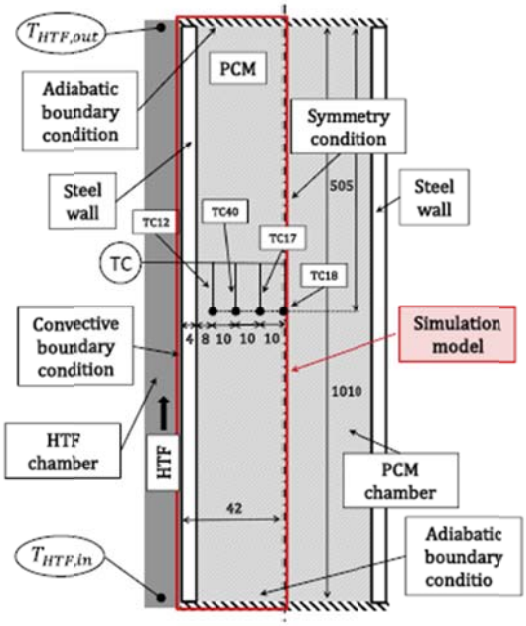

Figure 3 Sketch of discretised domain and boundary conditions [10]

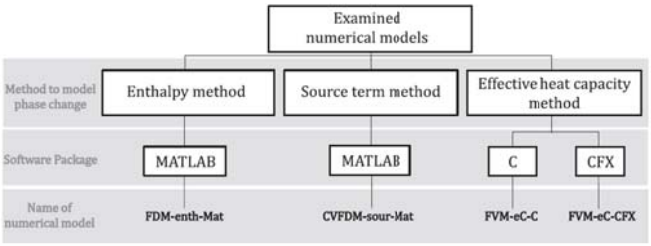

Figure 4 Sketch of storage tank and 2D-plane cut for simulation before applying symmetry condition [10]

The *FDM-ent-Mat* uses a finite difference method (FDM) to discretise the domain, and the phase change is modelled using the enthalpy method which allows the model to overcome the numerical problems related to constant phase change temperature. The model followed a fully implicit scheme and was implemented in MATLAB R2012b, where Gauss-Seidel iteration scheme was used to solve the set of linear equations.

On the other hand, the discretization of the domain is achieved using a control volume based finite difference method in the *CVFDM-sour-Mat* model. This model used the source term method, where the source term is linearized which reduces the iteration counts per time step and leads to a fast and robust convergence of iterative models. The linear equations were solved using the mldivide function.

The *FVM-eC-C* used a fully implicit scheme and discretised the domain with finite volume method. The phase change was modelled by the effective heat capacity method, which requires small time steps for simulation; otherwise the phase change can be partially skipped. The model uses Gauss-Seidel iterative method for solving the equations and was implemented in C programming language, using the free-licenced software DevC++ 4.9.9.2.

Finally, the *FVM-EC-CFX* implemented the equivalent heat capacity method using finite volume method in the commercial package, CFX-PRE version 15 within ANSYS.

The thermo-physical properties of the used materials and more detailed description of the compared numerical models can be found in Pointner et al. [10]

RESULTS AND DISCUSSION

Validation of Numerical Models

Four different sensors are used to measure the thermal evolution of the charging and discharging process of the PCM flat plate heat storage tank, as shown in Figure 3. The temperature in the inner symmetry axis (TC18 in Figure 3) will be used for the validation of the previously described four models. Figure 5 shows the thermal evolution at this location of PCM, comparing the experimental (uncertainty of ±2.65 K due to accuracy of sensors and uncertainty due to positioning and material properties) and numerical data. The validation process shows a good agreement in all analysed numerical models.

Furthermore, Table 1 shows the average deviations from experimental measurements at the 4 four locations shown in Figure 3 and share of simulation results within uncertainty interval of each model. It can be seen that four models behave similarly in terms of validations, having deviations around 1K and percentages inside uncertainty levels around 95%. From the small differences between models, FVM-eC-CFX shows the highest average deviation in comparison to experimental measurements (1.16 K), while FVM-eC-C is the one with less percentage inside the uncertainty levels (94.28%).

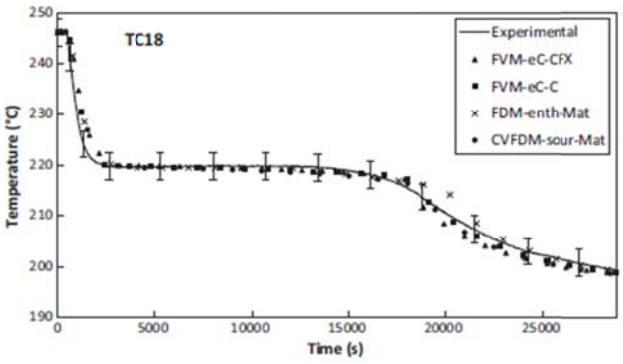

Figure 5 Sketch of storage tank and 2D-plane cut for simulation before applying symmetry condition [10]

Table 1 Temperature deviation and share inside uncertainty for all models and measuring point

Model	Deviation (K)	Inside uncertainty (%)
FVM-eC-CFX	1.16	97.11
FVM-eC-C	1.13	94.28
FDM-enth-Mat	1.11	94.77
CVFDM-sour-Mat	1.07	96.98

Computational efficiency

In this section, the computational efficiency of the different models is evaluated and compared under different mesh sizes and time steps. The simulations of each model are carried out in different CPU, hence in order to be able to compare the time required to achieve convergence of the full process, a scaled time is used with a scaling factor based on a CPU benchmark [12]. Table 2 shows the required scaled time of each model depending on the number of elements. It can be seen that the model FVM-eC-CFX, which is the only one implemented in a commercial package, is the slowest with all analysed number of elements. On the other hand, FVM-eC-C is the fastest model in all cases, except in case of highest number of elements, where CVFDM-sour-Mat is the fastest due to the use of the mldivide Matlab function instead of using Gauss-Seidel after linearization of non-linear equation.

Table 2 Scaled time (s) of each model with different number of elements

Model/Number Elements	**420**	**2100**	**10605**	**42420**
FVM-eC-CFX	1933	2277	3933	11228
FVM-eC-C	3	13	104	4844
FDM-enth-Mat	113	163	679	4257
CVFDM-sour-Mat	15	28	120	622

This section also analyses how the discretization in the time domain affects the computational resources required by each model. For this purposes, the two sets of simulations were compared using the same mesh size (420 elements) but different time steps (1 and 5 s). It can be noticed that the CVFDM-sour-Mat has the highest potential for reducing its computational time when increasing the time step.

Table 3 Scaled time (s) of each model with different time step

Model/Time step	Δt=1s	Δt=5s	Decrease (%)
FVM-eC-CFX	4248	1933	54.5
FVM-eC-C	3.8	2.7	27.9
FDM-enth-Mat	162	113	30
CVFDM-sour-Mat	63.5	14.6	77

CONCLUSION

This paper presents four different numerical models to analyse the performance of a flat plate heat storage system using PCM. The numerical models are experimentally validated and their accuracy and computational efficiency are evaluated and compared. The four models use different discretization methods (FVM, CVFDM and FDM), approach for modelling the phase change (enthalpy, equivalent heat capacity and source method), solver method (Gauss-Seidel or linearization) and are implemented in commercial software (ANSYS CFX) or coded in MATLAB or C language.

All the analysed numerical models showed good agreement in comparison to the experimental data describing a discharge process of a high temperature latent heat storage system. However, different computational resources were required, also depending on the mesh size and time step definition. The required time to achieve convergence of the C-based model is the lowest in all cases except when using an extra fine mesh definition, on the other hand, the models implemented in MATLAB are faster with this mesh since they can solve equations systems efficiently. The model implemented in the commercial software requires the highest computational effort than Gauss-Seidel iterative methods, however, it shows high potential of computational resources savings in case of increasing the time step.

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ACKNOWLEDGEMENTS

This work was partially funded by the nextPCM project supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Moreover, the work was partially funded by the Spanish government (ENE2015-64117-C5-3-R and ENE2015-64117-C5-3-R). The authors Luisa F. Cabeza would like to thank the Catalan Government for the quality accreditation given to their research group (2014-SGR-123). The research leading to parts of these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement PIRSES-GA-2013-610692 (INNOSTORAGE). Alvaro de Gracia would like to thank Ministerio de Economia y Competitividad de España for Grant Juan de la Cierva, FJCI-2014-19940.