Numerical analysis and design optimization of multi-coil units for latent heat cold storage applications

J. Hastanin, L. Salvador
Centre Spatial de Liège,
B-4031, Angleur, Avenue du Pré-Aily, Belgium
Corresponding author: lsalvador@ulg.ac.be

***Abstract*—The latent heat cold storage technology is a proven way to match efficiently energy supply with fluctuating demand. In this paper, a rather simple cold storage (CS) module is exposed. It is developed for low-cost cold storages applications and consists of a multi-coil tubular heat exchanger (CTHE) integrated in a tank filled with a phase change material (PCM). The operation principle is that during charging, at night-time hours, the heat transfer fluid (HTF) pumped through the CTHE freezes the PCM. Then discharging occurs when electricity costs are higher. The energy (cold) accumulated in the PCM tank is extracted and used in an external cooling system. In this work the CTHE design optimization procedure is investigated using the COMSOL Multiphysics® software package. The developed numerical models involve a simplified approximation, in which the heat transfer in the PCM is dominated by conduction. The initial guess values of CTHE design parameters were obtained by solving the classical one-dimensional Stefan problem.**

Keywords—latent heat cold storage; multi-coil heat exchanger; cold storage; COMSOL

III. INTRODUCTION

The use of cold storage (CS) systems involving Phase Change Materials (PCM) in commercial applications has experienced a notable growth over the past few decades due to their advantages in terms of high energy storage efficiency, relatively low production and maintenance costs. This technology is a proven way to match efficiently energy supply with fluctuating demand [1]. It has certainly a great potential impact on energy savings at world level.

Among the various PCM-based cold storage techniques, approaches involving the coil tubular heat exchanger (CTHE) modules appear to be particularly well suitable for compact and cost-effective applications.

In this paper, we address a rather simple and low-cost latent thermal storage module dedicated for cold storage applications. The operation principle is that during charging, at night-time hours, the heat transfer fluid (HTF) at the inlet of the CTHE has a temperature lower than the PCM solidification point. This fluid is pumped through the CTHE and progressively freezes the PCM in the tank. Then during discharging, at the the on-peak load with more expensive electricity, the energy (cold) accumulated in the PCM tank can be extracted and used in an external cooling system (food storage, acclimatization, etc.). The charging/discharging cycle duration depends upon the job criteria and cold storage strategy selected by the user.

The main purpose of this work is to investigate the design optimization and the effect of different design parameters on the storage efficiency.

IV. CONCEPT OVERVIEW

The investigated heat storage module is depicted in Fig.1. It consists of a multi-coil tubular heat exchanger (1) placed into a cylindrical tank (2) filled with PCM. In order to simplify the simulations, we address a three-coil heat exchanger in our numerical study.

The practical implementation of the concept relates to solutions of the classical *direct* heat transfer problem, which deals with calculating the spatial and temporal temperature distribution into the PCM tank associated with selected parameter values. In practice, this problem can be solved only numerically using the heat transfer equation with the boundary and initial conditions as per the investigated setup configuration [3-4]. In our case, the amount of the PCM sample is relatively large and the PCM tank design includes a variety of auxiliary elements (such as a CTHE and its mounting assemblies etc.). The effect of these elements on the heat transfer is not negligible. Therefore we need a computational

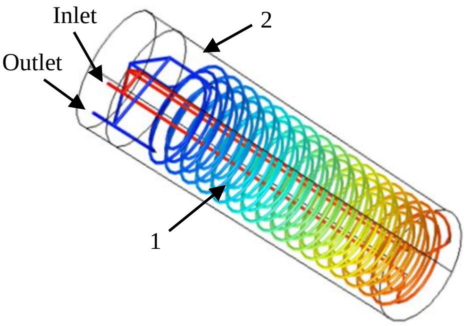

Fig. 1. Concept overview

tool to calculate accurately the temperature fields in computational domains having a complicated 3D geometry. We selected the COMSOL Multiphysics® software package to implement the design.

A. Heat transfer governing equations

Most commercial cold storage applications operate in a relatively narrow temperature range close to the PCM melting point. The viscosity of most low-melting temperature PCMs at temperatures close to the melting point is usually very large. Accordingly in practice, the heat transfer by convection can be neglected. Thus we use a simplified approximation in the numerical models, in which the heat transfer in the PCM is dominated by conduction. The mathematical formulation of this problem involves the classic heat transfer equation [3-4], with the symbols described in the appendix:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla\left(k \nabla T\right) + E \qquad (1)$$

In this equation:

$$\rho = \theta \rho_1 + (1-\theta)\rho_2 \qquad (2)$$

$$c_p = \frac{1}{\rho}\left(\theta \rho_1 c_{p.1} + (1-\theta)\rho_2 c_{p.2}\right) + L\frac{\partial \alpha_m}{\partial T} \qquad (3)$$

$$\alpha_m = \frac{1}{2}\frac{(1-\theta)\rho_2 - \theta\rho_1}{\theta\rho_1 + (1-\theta)\rho_2} \qquad (4)$$

$$k = \theta k_1 + (1-\theta)k_2 \qquad (5)$$

The initial conditions are:

$$T_{PCM}(x, y, z, t=0) = Const > T_{melting} \qquad (6)$$

In our study, we investigate time-independent and time-dependent boundary conditions. In the former case, the inlet of the CTHE is kept at a fixed temperature and HTF volumetric flow rate value:

$$T_{inlet} = Const(t)\,;\; q_{v,inlet}(t) = Const(t) \qquad (7)$$

while, in the latter case:

$$T_{inlet} = T(t);\; q_{v,inlet}(t) = Const(t) \qquad (8)$$

In both cases, the PCM tank wall is assumed to be thermally insulated:

$$-\mathbf{n}\cdot\left(-k\nabla T\right) = 0 \qquad (9)$$

B. CTHE design optimization

In our work the objective function in the CTHE design optimization is the cold storage efficiency, defined as the ratio of the amount of PCM frozen at the end of the charging period to the entire volume of the PCM in the tank:

$$\eta = \int_0^{\tau} Q(t)dt \Big/ (\lambda \cdot m) \qquad (10)$$

, where λ is the latent heat of the PCM phase transition, m is the mass of PCM in the tank, $Q(t)$ is the instantaneous heat flux from the PCM to the cooling fluid and τ is the charging period duration.

Since the numerical simulations in a 3D computation domain require significant computational resources, an appropriate choice of the initial guess of tube density in the PCM container can significantly reduce the total time needed to optimize the design. Simple mathematical models involving the classical one-dimensional Stefan problem solutions can be employed to specify the initial guess values of the CTHE tube-to-tank fill density.

V. NUMERICAL MODELLING

A. Three-dimensional model of the phase change process

The practical implementation of a high-efficient CTHE module requires an appropriate numerical approach to simulate the temperature field as function of time, as well as the melting and solidification front evolution in computational domains having a complex three-dimensional geometry (Fig.1).

We use the COMSOL Multiphysics® software package. It is then easy to estimate the effect of different design parameters (such as the temperature and flow rate of the HTF, coil tube radius, axial pitch, number of turns, etc.) on the objective function of the design optimization procedure defined by Eq. (10). The materials data is selected from the software built-in material library. The mentioned concept is investigated numerically using the apparent heat capacity method. We use the time-dependent solver. An analysis of the numerical results reveals that the most optimal mesh in terms of computation time is the "Normal Physical" one, suggested in the software. Finally the design optimization procedure of the cold storage module involves additional numerical models to estimate the PCM tank thermal isolation.

B. Stefan problem

As mentioned above, our design optimization procedure involves initial guess values for the CTHE geometry parameters, such as coil-to-coil tube distances and the number of turns in the coils, generated by solving the classical one-dimensional Stefan problem in finite-slab geometry with Dirichlet boundary conditions. The dimensionless formulation of this problem in an invariant domain ($0 \le x \le 1$) is, [5]:

$$\frac{\partial^2 T(x,t)}{\partial x^2} + xR(t)\frac{dR(t)}{dt}\frac{\partial T(x,t)}{\partial x} = R^2(t)\frac{\partial T(x,t)}{\partial t} \qquad (11)$$

$$0 \le x \le 1$$

$$R(t)\frac{dR(t)}{dt} = -Ste\frac{\partial T(x,t)}{\partial x}, \quad x = 1 \tag{12}$$

With the initial and boundary conditions:

$$\begin{aligned} &R = 0, \quad t \le 0 \\ &T = f(t), \; x = 0, \; t > 0, \\ &T = 0, \; x = 1, \; t > 0, \end{aligned} \tag{13}$$

, where *T(x,t)* is the temperature distribution, *R* is the position of the moving phase interface, *Ste* is the Stefan number. In this study, the Stefan problem solutions have been numerically investigated using the finite difference method in the Matlab software.

VI. RESULTS AND DISCUSSION

The following figures show an example of the results obtained during the charging process for the cold storage module presented in Fig.1. In the first study phase, we address the most common materials with well-known thermal proprieties, such as salt-water solutions (PCM), ethylene glycol aqueous solution (cooling fluid), etc. The physical properties of the used materials are summarized in Table 2 (Appendix).

Fig. 2, 3 and 4 depict the temperature field (a) and the solidification front evolutions (b) during the charging phase, calculated at different times (t = 20min, 1h and 3h20min) for the volumetric flow rate of the cooling fluid q_v=0,75 *l/s*, and an inlet temperature of the cooling fluid equal to -10°C.

Fig. 5 illustrates the thermal gradient of the cooling fluid between the outlet and the inlet of the CTHE, obtained with COMSOL numerical models. In Fig. 6 the instantaneous heat power from the PCM to the HTF is displayed as function of time. It is calculated with the thermal gradients shown in Fig.5. The effect of the HTF volume flow rate on the amount of the energy (cold) stored in the CS multi-coil module is illustrated in Fig.7 and Fig. 8. Fig. 7 depicts the temporal variation of the energy (cold) accumulated in the CS module during the charging cycle calculated by integrating the power shown in Fig.6, over the charging cycle duration. Finally in Fig. 8, we illustrate the energy stored in the PCM at the end of the charging cycle as a function of the cooling fluid volumetric flow rate.

Thus, our numerical investigations reveal that an increase of the HTF flow rate improves the charging process. However, this effect exhibits saturation. As it is illustrated in Fig.8, the amount of the cold stored in the CS module increases progressively with the HTF volumetric flow rate and reaches saturation at some critical value of the flow rate. In practice, since this critical value is very sensitive to many design parameters, it can be estimated only numerically.

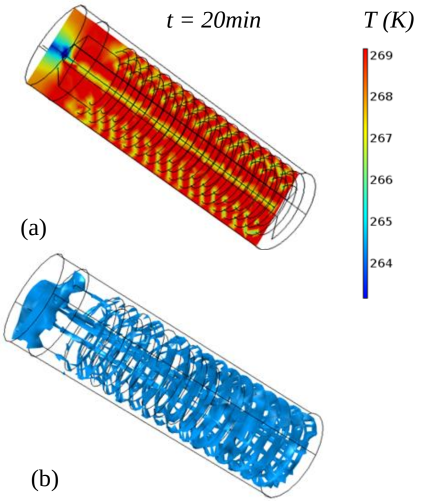

Fig. 2. Temperature field in the PCM (a) and solidification front (b), after 20 minutes.

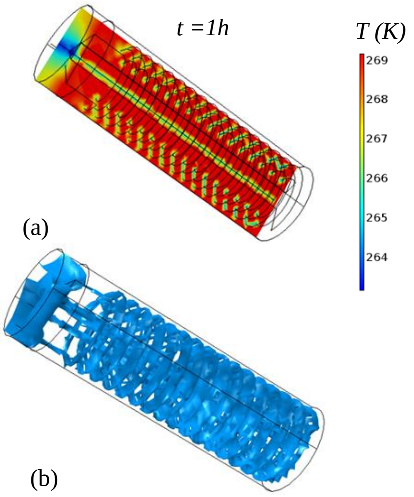

Fig. 3. Temperature field in the PCM (a) and solidification front (b), after 1h.

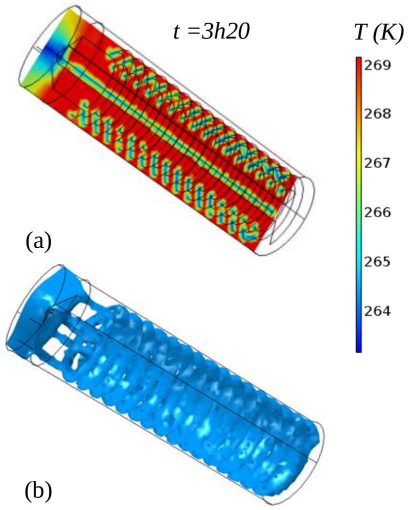

Fig. 4. Temperature field in the PCM (a) and solidification front (b), after 3h20.

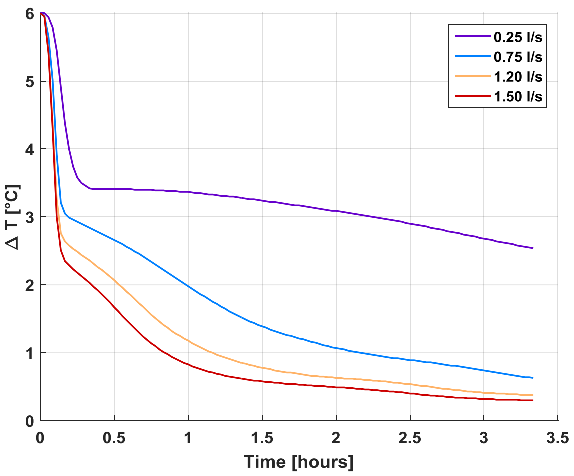

Fig. 5. Temperature gradient ($\Delta T = T_{outlet} - T_{inlet}$), for cooling fluid with different volumetric flow rates and inlet temperature of -10°C.

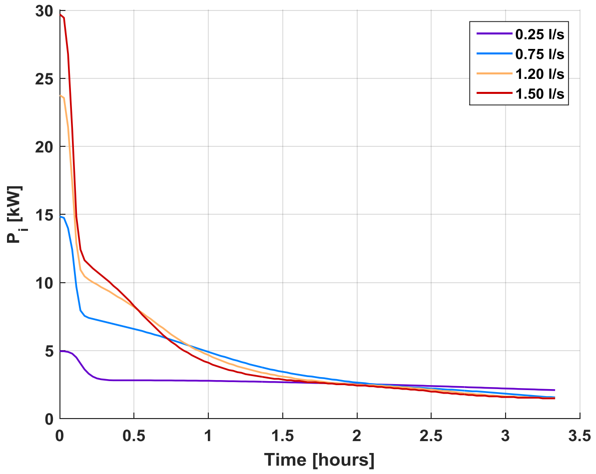

Fig. 6. Instantaneous power from the PCM to the HTF, for cooling fluid with different volumetric flow rates and inlet temperature of -10°C.

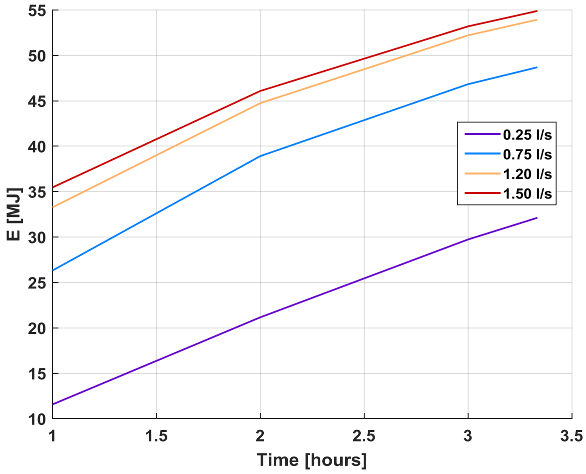

Fig. 7. Energy stored in the CS module during the charging cycle, for cooling fluid with different volumetric flow rates and inlet temperature of -10°C.

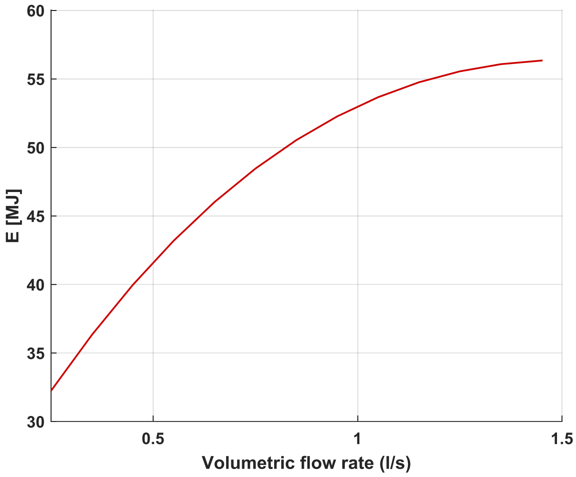

Fig. 8. Energy stored in the CS module as function of the volumetric flow rate of the cooling fluid and inlet temperature of -10°C, calculated after charging 3h20.

Fig. 9 depicts the gradient of the cooling fluid between the outlet and the inlet, calculated for different temperatures of the HTF at the inlet and a volumetric flow rate of 0.75 l/s. Fig. 10 shows the temporal variation of the instantaneous power from the PCM to the HTF calculated with the curves shown in Fig.9. Fig. 11 and 12 illustrate the evolution of the amount of the energy stored in the module for different temperatures of the HTF at the CTHE inlet. As mentioned above, the energy accumulated in the CS module as function of time, during the charging cycle (Fig.12), can be calculated by integrating the graphs of the instantaneous power over the charging duration (Fig.11).

As follows from Fig. 8 and Fig. 12, the efficiency of the CS module depends on both the HTF volumetric flow rate and its temperature. However, in contrast to the simulation results shown in Fig. 8, the graph of the energy stored in the module versus the cooling fluid temperature does not indicate saturation. Accordingly, to shorten the charging duration of the battery and to achieve a better solidification of the PCM, it would be more advantageous to reduce the HTF temperature at the CTHE inlet than to increase its volumetric flow rate. Yet it is noteworthy that in practice, an increase in the HTF volumetric flow rate typically provides a more cost-effective solution than a reduction of its inlet temperature. Thus one should find a reasonable compromise between these two parameters and maximize its cost-effectiveness. It is necessary to take into account not only the physical characteristics of the cooling equipment available on the market, but also its cost.

Finally our numerical study reveals that for a relatively long period of charging time, the temperature difference between the outlet and the inlet of the CTHE exhibits a very slight drop or even remains almost constant due to the heat absorption by phase transition in the PCM (Fig. 9). Therefore the amount of energy accumulated in the CS module can be approximated accurately enough by polynomial extrapolation,

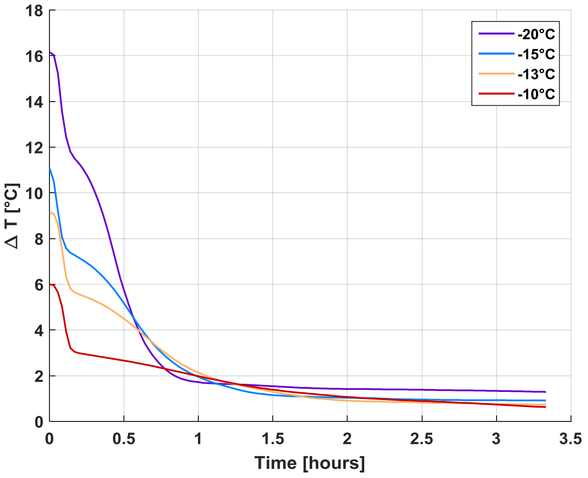

Fig. 9. Temperature gradient ($\Delta T = T_{outlet} - T_{inlet}$), for cooling fluid with different inlet temperatures and volumetric flow rate of 0.75 l/s.

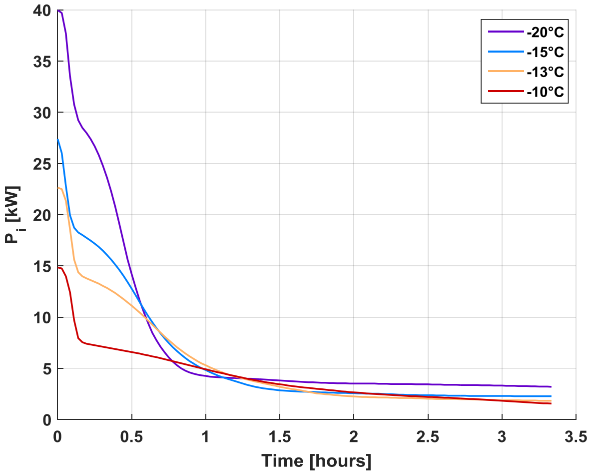

Fig. 10. Instantaneous power from the PCM to the HTF, for cooling fluid with different inlet temperatures and volumetric flow rate of 0.75 l/s.

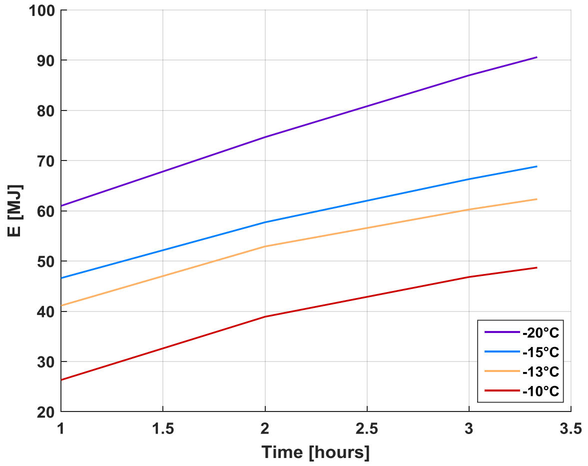

Fig. 11. Energy stored in the CS module during the charging cycle, calculated for different inlet temperatures of the cooling fluid.

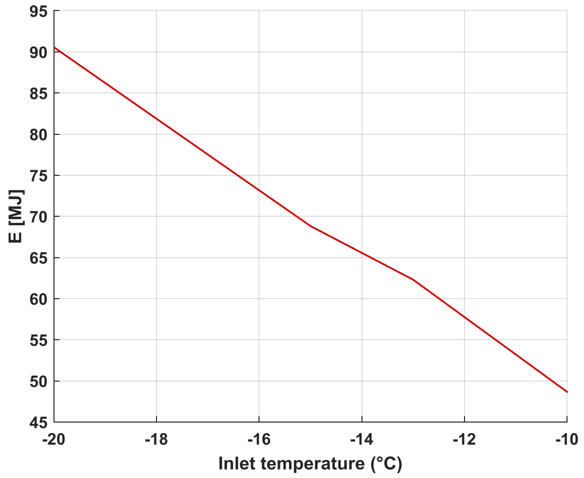

Fig. 12. Energy stored in the CS module as function of the inlet temperature of the cooling fluid and volumetric flow rate of 0.75 l/s, calculated after charging 3h20.

which is much easier to perform than numerical simulations. It provides an elegant way to considerably simplify the optimization procedure of the CS module design and of the cold storage strategy.

VII. CONCLUSIONS

In this paper, we address a simple and low-cost CTHE module dedicated to cold storage applications. The simulations are solved using the apparent heat capacity method. The inherent advantage of this approach is its relative simplicity. In this study, we investigate the temperature history of the PCM sample using the COMSOL Multiphysics® software. Some intermediate results of the numerical analysis have been reported and discussed. We limit ourselves to the description of the cold storage module design optimization, without the refrigeration loop. The concept example shown, as well as the numerical simulation results are for illustrative purposes only and do not represent the performance of any specific product.

VIII. APPENDIX

TABLE I. NOMENCLATURE

Symbol	Meaning
λ	Latent heat of fusion, [J/kg]
ρ	Density, [kg/m^3]
k	Thermal conductivity, [W/m^{2}K]
$c_{p,s}$	Specific heat in solid state, [J/kg K]
$c_{p,L}$	Specific heat in liquid state, [J/kg K]
T_m	Melting temperature, [K]
θ	Liquid-solid fraction, [A.U.]
T	Temperature, [K]

Symbol	**Meaning**
t	Time, [s]
Q	Heat energy, [J]
m	Mass, [kg]

TABLE II. PARAMETER VALUES IN NUMERICAL SIMULATIONS

Symbol	**Meaning**
PCM (salt-water solution)	c_{pL}=4200; c_{pS}=3800 [J/(kg·K)]
	k_L=0.36; k_S=0.56 [W/(m·K)]
	ρ=1100 [kg/m^3]
	λ=278 [kJ/kg]
	T_m=267 [K]

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