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Design of a finned plate latent heat thermal energy storage system for domestic applications

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Abstract

In order to reduce the required volume for thermal energy storage, a finned plate latent heat thermal energy storage system for domestic applications is presented in this paper. This innovative design allows the exchanging of energy between water and the RT60, used as the phase change material. The simulation of that system is covered by a validated mathematical model. The model, based on a simplified numerical approach, is used for the optimal design of the final prototype, which is compared with a conventional 500 l hot water tank usually integrated in domestic heating and domestic hot water applications. It is obtained that the resulting design is in the order of one half of the water tank volume, resulting in a more compact configuration which can be easily integrated in the space. This solution will bring a great opportunity for thermal storage especially in those applications where there is a lack of available space, as it is the case of residential flats.

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Nomenclature

c_e	Effective specific heat of the finned-plates (J/kgK)
c_{HTF}	Specific heat of the heat transfer fluid (J/kgK)
e	Thickness of the finned plates (m)
f	Fin separation (m)
T_e	Effective temperature of the finned-plates (ºC)
T_{HTF}	Temperature of the heat transfer fluid (ºC)
U_e	Effective heat transfer coefficient (W/m^{2}K)
$U_{e,c}$	Effective heat transfer coefficient for charging (W/m^{2}K)
$U_{e,d}$	Effective heat transfer coefficient for discharging (W/m^{2}K)
w	Width of the HTF channels (m)
Z	Height of the plates (m)
ρ_e	Effective density of the finned-plates (J/kgK)
ρ_{HTF}	Density of the heat transfer fluid (J/kgK)

1. Introduction

Thermal energy conservation and management is a key issue for energy savings in any field with intensive thermal demands. One of these fields is the building sector, which nowadays accounts for 40% of the European energy consumption. There are many technologies in the building sector where the presence of thermal energy storage imply a more efficient and profitable operation. Amongst these technologies, one can found thermal solar systems, residential cogeneration, etc., where usually conventional hot water tanks are included in order to couple the generation and the demand. However, these tanks require big water volumes and high aspect ratios, which can be a problem in domestic applications where there is usually a lack of space.

This can be avoided by Phase Change Materials (PCMs), which use the latent thermal exchange taking place during the liquid-solid phase change as the thermal storage mechanism allowing a higher thermal storage density [1]. However, it should be considered that PCMs present some disadvantages over conventional Thermal Energy Storage (TES) systems. They generally present low thermal conductivities (between 0.2 and 0.7 W/m·K), which reduce the effective power in the charging and release of the thermal energy. Moreover, the specific price of these systems is significantly higher. Therefore, the designer plays a very important role based on the two main following considerations:

- It is necessary to adapt the power of the TES system to the requirements of the plant where it is integrated.
- It is necessary to find a geometry which allows reducing the complexity of the system and, consequently, its price.

Therefore, there is an implicit need for optimizing the design of different Latent Heat Thermal Energy Storage (LHTES) configurations. Mathematical modeling is the best approach for applying any optimization method to the design of these systems, and a wide number of modeling approaches have been used for the simulation of LHTES systems of different nature [2]. It includes exact analytical solutions [3-5], numerical methods [6-11], simplified analytical approaches [12-13] and simplified numerical methods [14-15].

In this paper, amongst all the possible LHTES configurations, an innovative finned-plate heat exchanger-based system is selected, where water runs as the Heat Transfer Fluid (HTF). This system and its modeling were already covered by the author in a previous paper and it was concluded that, amongst the previous stated methods, the simplified numerical method is the most suitable one for optimization purposes [16]. That model is included in a parametric optimization routine in order to reduce the volume as much as possible for given operating conditions. The resulting design is compared with a 500 l conventional hot water storage system.

This paper is organised in seven different sections, as follows: Section 2 presents the innovative finned-plate LHTES system, both the configuration and the PCM used as the storage medium. In Section 3 the modeling approach is presented. The conventional hot water tank is presented in Section 4 and the comparative framework is presented. Thus the optimal LHTES system design is obtained and its performance during the charging and discharging process is evaluated. The discussion of the results is carried out in Section 5 and finally, the main contributions of the study are summarized in Section 6.

2. Description of the latent thermal storage system

Amongst all the possible combinations between shapes and heat enhancement techniques for LHTES systems, the compact finned flat plate configuration was chosen, which from now on will be referred to as finned plate technology. This technology presents the next advantages:

- It is based on compact flat plate heat exchangers, which is regarded as the most effective heat exchanger technology.
- The manufacturing process is simple, due to the fact that only straight surfaces are employed.
- By the definition of single plates, it presents high modularity.
- It presents a high surface to volume ratio, which allows getting significant storage and release powers.
- The whole LHTES system shows a rectangular shape, which makes its space integration easy.

The system is based on the definition of the single finned plate presented in Fig. 1 where a cut has been made in order to show the inner finned structure. The aim of the finned structure is to enhance the heat transfer between the HTF and the PCM.

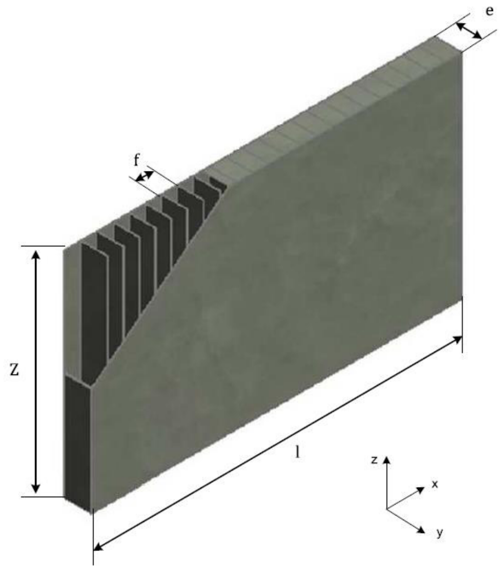

Fig. 1. 3D view of a single finned plate

The space between the fins within the plates is filled with PCM. RT60 paraffin from Rubitherm GmbH was selected as PCM. Its phase change temperature is around 60ºC, which results very suitable for the application under analysis. A sample of this material was analyzed by means of a Mettler Toledo DSC1 differential scanning calorimeter. The obtained thermal properties are presented in Table 1 along with some physical properties given by the supplier, being the latter the density, the conductivity and the dynamic viscosity.

Table 1.Thermophysical properties of the RT60 PCM

Property	Value
Temperature range for phase change	53-61 ºC
Latent heat	123506 J/kg
Thermal conductivity	0.2 W/mK
Density	880 kg/m^3 (solid) 770 kg/m^3 (liquid)
Specific heat	2660 J/kgK (solid) 2340 J/kgK (liquid)
Dinamic viscosity	3.705 x 10^{-5} kg/ms

The phase change does not take place at a constant temperature but through a temperature range. This is owed to the fact that the PCM is not homogeneous and contains additives which distort the phase change. The structure of the system (plates and fins) can be made by any metallic common material, such as stainless steel or aluminum, due to its high conductivity. For the present study, aluminum was considered owing to its lower density.

These plates are the modules that make up the whole system. They can be arranged in series or in parallel, giving rise to different LHTES system configurations that the designer should define in detail. In Fig. 2 it can be seen an example in 2D, consisting of 12 plates, arranged 6 in parallel and 2 in series. The HTF, water in this case, flows through the channels formed between the plates.

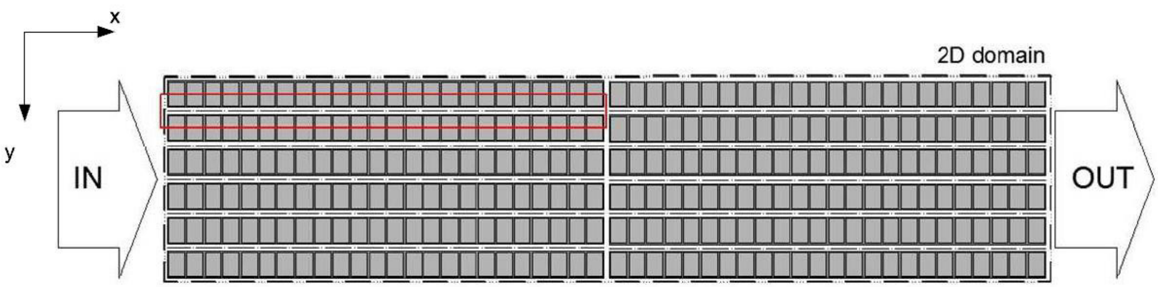

Fig. 2. 2D view of a generic LHTES consisting of 12 finned plates

3. Numerical modeling

The channels where the water flows through are very thin (in the order of few millimeters), as imposed by the compact heat exchanger technology in which the solution is based. Thus, these channels are modeled in 1D in the direction of the flow as presented by Eq. 1. By means of a hydraulic study, it was observed that the turbulent regime would increase significantly the pressure drop of the system. For this reason, only laminar regime is considered for the flow, selecting 2 mm as the optimal width of the channels.

$$\rho_{HTF}\, c_{HTF}\, wZ \frac{\partial T_{HTF}}{\partial t} + \dot{m}\, c_{HTF} \frac{\partial T_{HTF}}{\partial x} = -2U_e\, Z\left(T_{HTF} - T_P\right) \qquad (1)$$

Analogously, the finned plates are also discretized in 1D in the direction of the flow. Thus, T_P corresponds to the average temperature of the plate and U_e is the effective heat transfer coefficient between the HTF and the finned-plates. The modeling approach for the finned-plates is presented by Eq. 2.

$$\rho_e\, c_e\, e\, \frac{\partial T_P}{\partial t} = 2U_e\,\left(T_{HTF} - T_P\right) \tag{2}$$

Where c_e accounts for the effective specific heat which contains the specific heat of the PCM, the effect of the phase change derived from the enthalpy-temperature curve given by the DSC and the heat storage capacity of the enclosure and fins. The same occurs with the effective density. This approach allows considering the heterogeneous finned-plate as a homogenous medium (lumped capacity model).

These two equations are coupled and should be solved jointly by any non-linear resolution method. It should be noticed that both equation requires the determination of U_e, a term not known a priori. These should be calculated for the given configuration and materials and was presented in a previous paper by the authors where the modeling approach was developed, and validated by experimental means [16]. The U_e values vary from charging to discharging, as the process are different in nature, and are included as general analytical expressions in the model as follows:

$$\begin{aligned} U_{e,c} &= -52.61 + 96.7\sqrt{1 + 11.23\frac{e}{f}} + \left[15.97 + 86.31(e-f)\right]^2 \\ &+ \left(0.068 + \frac{8.8\times10^{-4}}{f^2} + 7.4\times10^{-3} f\right)^2 - \frac{4.26}{1 + ln\left(e^2 + f\right)} + \frac{199.021}{1 + 113.23(e-f)^2} \end{aligned} \tag{3}$$

$$\begin{aligned} U_{e,d} &= -55.45 + \frac{1.752}{f(1+f)} + 144.02\, exp\left[-85.415(e+f)\Big/\sqrt{e^2+f^2}\right] + \\ &75.14\sqrt{1 + 0.47\left(\frac{e}{f}\right)^2} - \frac{111.29}{1 - 1.76(e+f)\Big/\sqrt{e^2+f^2}} - \frac{259.49}{1 - 95.38\left(e^2 - f\right)} \end{aligned} \tag{4}$$

The whole model was programmed in FORTRAN allowing the quick simulation of different configurations of the LHTES system. Therefore, it is used in the next Section for design purposes.

4. Analysis of the storage systems and results

In this system, a conventional hot water storage tank is presented and compared with a specific design of the presented LHTES system. First, the hot water storage tank is described and secondly, the proposed system is detailed. For the analysis a constant temperature of 65ºC is selected for the charging and 50ºC for the discharging. These temperature levels are typical for domestic heating applications and DHW production. Although solar energy can lead to sensibly higher temperatures, this system stores the energy at the demand temperature level, which moreover, reduces the heat losses to the surroundings.

4.1. Conventional hot water storage tank

In many heating and Domestic Hot Water (DHW) residential applications where energy management is necessary, such as cogeneration or thermal solar systems, hot water storage tanks are used. A typical 500 l system is selected as a basis for the undergoing analysis. Specifically CV-500-R manufactured by LAPESA [17] is selected, whose main dimensions are summarized in Table 2.

Table 2.List of characteristics of the hot water storage tank

Height of the tank (m)	1.69
Diameter of the tank (m)	0.77
Overall volume (m^3)	0.787
Effective volume (m^3)	0.5
Maximum storage capacity (kWh)	8.7

4.2. Finned-plate LHTES system

For the design of the finned-plate LHTES system the afore presented simulation model is used. Apart from the mere design, one of the objectives of the paper is to compare it with a conventional storage solution. Thus, the design is constrained to provide approximately the same amount of storage capacity of 8.7 kWh. Moreover, a flow rate of 5 l/min is imposed and a maximum duration for the charging/discharging process is set at 3 hours, which is a common period for residential thermal solar or cogeneration installations. This information is used as input for a parametric optimization, where the simulations are carried out sequentially by the FORTRAN programming environment.

The simulations where made considering a 1 second timestep and a grid size of 1 cm in the x direction (as validated in [16]). The nature of the simulation allows carrying out a high number of simulations at a low CPU cost. Specifically more than 3000 simulations were carried out, using an AMD Turion Dual Core-Mobile 2.30 GHz with 6,00 GB RAM PC. Only a few hours were required to complete them. The optimal design for the imposed constraints is presented in Table 3.

Table 3.List of characteristics of the optimal finned-plate LHTES system

Plate length (m)	0.6
Plate height (m)	0.2
Plate width (cm)	3
Fin separation (cm)	4
Channel width (mm)	2
Plates in parallel	7
Plates in serial	8
LHTES system height (m)	0.9
LHTES system length (m)	0.6
LHTES system width (m)	0.5
Overall volume (m^3)	0.315
Maximum storage capacity (kWh)	8.5

The resulting system presents a cubic shape with a slightly lower storage capacity than the conventional system, but close enough to allow the comparison between them. The overall volume includes 5 cm of insulation in the external envelope of the system. Although 8 plates in serial would give rise to very long systems, the modular nature of the plates makes it possible to pile up the modules and get more regular shapes, which is one of the advantages offered by the proposed configuration. Thus, the resulting system consists of 56 finned plates as the one presented in Fig. 1.

As it could be predicted, the charging and discharging power are not constant, since they depend on the temperature difference between the finned-plates and the HTF which varies over the charging and discharging process. However, it was considered that the charging/discharging process should last less than 3 hours. The evolution of the power and the average power over time is shown in Fig. 3. There, the storage process starts when the whole system is at 50ºC and the water enters it at 65ºC and analogously, the release process starts when the whole system is at 65ºC and the water enters it at 50ºC.

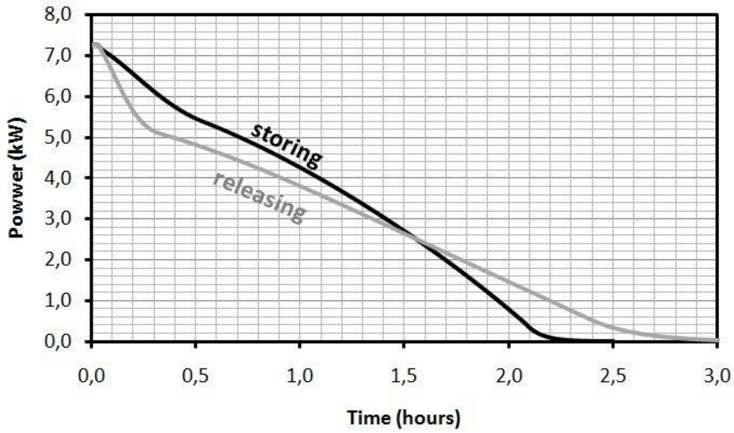

Fig. 3. Evolution of the charging/discharging power of the LHTES system

5. Comparison and discussion

In this Section the presented results are analyzed and discussed. The analysis can be carried out from different points of view; here it is made considering the volume, the size and some economic and functional considerations.

Regarding the overall volume, the proposed LHTES system allows reducing the required volume to less than the half of that of the conventional hot water tank. Here, the heat losses have not been included in the analysis but a lower volume gives rise to a lower external surface, reducing therefore the overall amount of heat losses. It should be noticed that the storage was considered to work between 50 and 65ºC, for higher temperature differences the volume difference between the LHTES system and the hot water tank would be decreased until being equal when a 45ºC temperature difference is considered. However, considering the temperature level of the heat demand (heating and DHW), storing the energy at a higher temperature would decrease the efficiency of the heat source (for instance when feeding the solar thermal panels at higher temperature) and would increase the thermal losses to the surroundings, decreasing the overall efficiency of the thermal process.

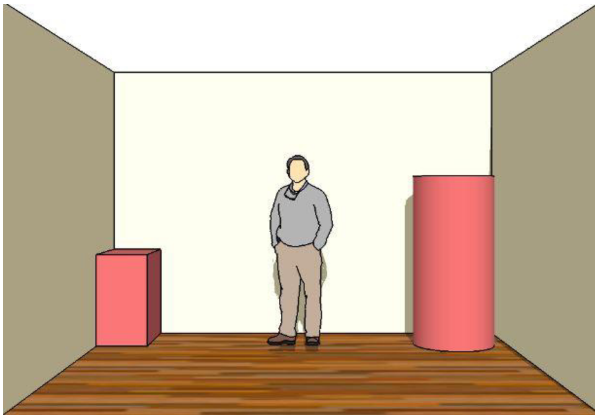

Fig. 4. Spatial view of both systems

A great advantage of the finned-plate LHTES system over the conventional hot water tank is that it is not subjected to specific shapes. One of the mechanisms that makes the thermal storage effective in hot water tanks is the stratification. To enhance the stratification and, therefore, the efficiency of the storage, high aspect ratios should be get. This fact makes the hot water tanks to be cylindrical and slender, which makes its integration more difficult in domestic flats. In contrast, the cubic shaped LHTES system can be easily integrated in several ways, even in the structure of the building or as simple domestic appliances. The combined effect of a more compact nature can be appreciated in Fig. 4, where the simplified volumes of both systems are depicted.

One of the most important issues to be considered is the final price of the system. According to the manufacturer, the 500 l hot water tank has an approximated catalogue price of 1600 €. On the other hand, at this stage of the development, is difficult to set an accurate prediction of the price for the finned-plate LHTES system. However, a rough estimation can be made using the prices of the raw materials. Thus, considering a price of 2.7 €/kg for the aluminum and 3.6 €/kg for the RT60 (given by Rubitherm for wholesale orders) a total price of 805 € would arise. However, to this price, the manufacturing and commercial costs should be added, resulting that the conventional hot water tank would be a cheaper solution. The feasibility of the LHTES system could be improved if cheaper PCMs were available and if an industrial manufacturing process were set up for the proposed LHTES system. Moreover, one should not forget that space is a problem in many residential flats, therefore, the modular and compact nature of the LHTES system can be in some cases the only alternative to provide storage capacity to this kind of installations.

Apart from this issues, it should be kept in mind the implicit benefits carried out by PCMs which are not contemplated under the scope of the proposed analysis. Mainly that the PCMs store the thermal energy over a narrow range of temperature. This fact avoids higher temperatures reducing the losses and stabilizes the working conditions, enhancing the operating performance of the system.

6. Conclusions

This paper proves that more compact thermal storage systems can be get using the benefits of the PCMs. Thermal modeling is a key issue to perform the design of the systems, especially when trying to get optimal configurations. The resulting LHTES system presents a very suitable alternative to conventional hot water tanks, especially when there is a lack of space. The costs of the LHTES should be still reduced to be economically competitive. This could be achieved using cheaper PCMs. Further investigations should be done in order to overcome this issue.

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